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Enhancing grid stability and sustainability through virtual power plants: A case study of Chile

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ABSTRACT

The rapid growth of distributed solar photovoltaic (PV) generation in urban power networks has intensified challenges related to frequency stability, voltage regulation, and overall power quality, particularly in regions with high penetration of small- and medium-scale distributed generation (PMGD). This study evaluates the role of Virtual Power Plants (VPPs) as coordinated control mechanisms to mitigate these disturbances. A simulation-based framework is developed using representative operational data from ENEL Distribución Chile, combined with dynamic system modeling implemented in Python. Three operating scenarios are analyzed: (*i*) PMGD without VPP support, (*ii*) PMGD with integrated VPP coordination, and (*iii*) reduced PMGD capacity with and without VPP intervention. The analysis focuses on system-level dynamic response, including frequency, voltage, and phase behavior under high-generation conditions. Results demonstrate that VPP deployment significantly enhances grid stability, reducing frequency deviations from ±0.5 Hz to ±0.1 Hz and voltage fluctuations from ±5% to ±2%, while improving overall power quality metrics by approximately 80%. These findings confirm the effectiveness of coordinated VPP control in managing power imbalances and stabilizing renewable-rich distribution networks. The proposed approach provides a practical and scalable framework for integrating distributed renewable generation, offering insights for utilities and policymakers in Latin America and similar high-penetration contexts.

1. Introduction

The global energy transition, driven by the imperative to mitigate climate change and achieve sustainability goals, is fundamentally reshaping the architecture and operation of electric power systems. A central pillar of this transformation is the rapid integration of distributed generation (DG), particularly from solar photovoltaic (PV) sources, into distribution networks [1], as part of the broader shift from fossil-based systems to renewable energy infrastructures [2]. While pivotal for decarbonization and energy decentralization, the intermittent, uncoordinated, and bidirectional nature of these renewable energy sources (RES) introduces significant technical and operational challenges for system operators [3].

In Chile and numerous other regions, Pequeños Medios de Generación Distribuida (PMGD)—small- to medium-scale grid-connected PV plants typically limited to ≤ 9 MW—are experiencing rapid expansion under favorable regulatory frameworks (**see** Fig. 1). Although PMGDs support renewable energy targets, their uncontrolled power injection during peak solar irradiation hours (11:00–15:00), especially in areas of high spatial concentration, can severely disrupt voltage regulation, frequency stability, and phase balance [4]. These disturbances are particularly acute in urban and peri-urban grids such as the Metropolitan Region of Santiago. In extreme scenarios, they can precipitate reverse power flows (RPF), unintentional islanding, or even cascading blackouts, analogous to the recent Iberian Peninsula blackout [5].

The underlying vulnerability stems from the design of legacy power grids, engineered for unidirectional power flow from centralized synchronous generators to consumers. High penetrations of DG challenge this paradigm: solar generation peaks often coincide with midday demand troughs, forcing conventional plants into inefficient cycling operations [6,7]. Recent studies confirm that such operational challenges are prevalent in networks with high renewable penetration, necessitating advanced coordination mechanisms [8]. This increases operational stress, reduces efficiency, and elevates the risk of instability

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Fig. 1. PMGD La Colonia: Solar energy for homes in the Metropolitan Region of Chile.

[9,10]. Furthermore, RPF has been demonstrated to cause voltage exceedances, strain protection coordination schemes, increase transformer magnetizing currents, and accelerate insulation aging [11,12].

To mitigate these challenges, Virtual Power Plants (VPPs) have emerged as a scalable and cost-effective solution [13,14]. A VPP aggregates a portfolio of distributed energy resources (DERs), including energy storage systems (ESS), flexible generation, electric vehicles (EVs), smart inverters, and demand-response assets, into a single controllable entity through an advanced energy management system (EMS) and communication infrastructure. Fig. 2 shows a schematic of VPPs. Crucially, VPPs can provide essential ancillary services, such as: frequency regulation (*e.g., maintaining Chile's nominal* 50 Hz), voltage control to mitigate under-/over-voltage events, reactive power compensation for improved power factor, fast dispatch for ramping and load balancing, and demand-response during network stress conditions.

Beyond their system-level role, VPPs have been increasingly positioned as an enabling layer for *urban sustainability*, where dense load centers, constrained network reinforcements, and spatially clustered DERs amplify the need for coordinated operation. A comprehensive urban-focused review highlights that cities consume a dominant share of global energy and emissions, and argues that VPPs can translate fragmented urban DER deployments into coordinated, market-participating and grid-supportive portfolios through ICT-enabled control and scheduling [15]. This perspective is particularly relevant for Santiago, where high PMGD concentration and limited distribution hosting capacity create an urgent requirement for *local* voltage regulation, peak mitigation, and operational flexibility at the feeder level.

A key practical challenge for VPP deployment is that the very resources used to stabilize the grid (PV, wind, flexible demand) are themselves uncertain, and therefore scheduling must explicitly internalize forecast error and operational risk [16]. Recent stochastic scheduling research frames day-ahead VPP operation as a multi-objective problem balancing economic performance, environmental impact, and system stability metrics (e.g., voltage deviation and stability indices), while generating multiple uncertainty scenarios to ensure robust performance [17]. Such results reinforce that VPP value in renewable-dense networks is not solely energy arbitrage, but also *risk-limiting coordination* that preserves voltage and power-balance feasibility under forecast deviations.

While classical VPP formulations are typically cost-driven, emerging models explicitly incorporate *environmental and reliability* objectives. In particular, sustainable virtual power plant (SVPP) formulations integrate emissions minimization with reliability indices (e.g., adequacy-oriented measures) and scenario-based uncertainty modeling, showing that jointly optimizing cost, emissions, and reliability can materially improve operational outcomes relative to purely economic dispatch [18]. This is directly aligned with the Chilean PMGD setting, where midday PV surpluses and feeder constraints imply that a VPP should be evaluated not only by profit or energy balance, but by its ability to *reduce instability risk*, mitigate reverse flows, and maintain service quality under variability.

As VPPs increasingly engage in electricity markets, another layer of uncertainty arises from renewable forecasting errors and price variability, which can translate into imbalance penalties or infeasible commitments. Recent work on risk-aware bidding integrates advanced RES forecasting with explicit risk quantification (e.g., tail-risk measures) and couples VPP decisions with carbon market mechanisms (carbon pricing, cap-and-trade, and incentive schemes), illustrating how market design and carbon policies can materially shape VPP operation and profitability [19]. Although the present study is distribution-focused, these findings motivate viewing VPP-enabled flexibility as a bridge between *technical constraints* (voltage, reverse flows) and *policy/economic instruments* (emissions reduction, market incentives) that are increasingly relevant in decarbonizing grids.

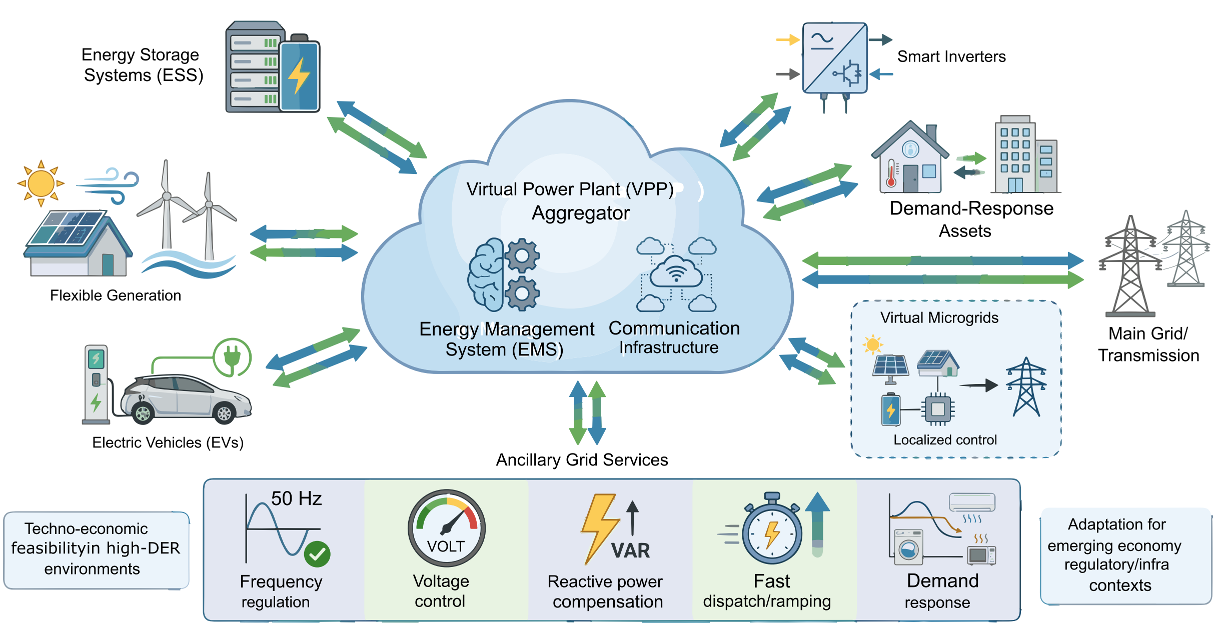

Fig. 2. A conceptual schematic of VPPs.

VPP research is expanding toward community-based and prosumer-centric paradigms, emphasizing not only operational scheduling but also broader sustainability accounting. Recent community-based VPP concepts embed circular-economy principles and evaluate full-lifecycle footprints (energy, environment, and cost) via multi-stage multi-objective optimization, indicating that future VPP assessments may require metrics beyond instantaneous dispatch performance [20]. This motivates including *scalability and sustainability* considerations in PMGD–VPP planning, especially for urban feeders where societal acceptance, local environmental targets, and infrastructure aging interact with technical stability constraints.

Recent research has extended the VPP concept to include "virtual microgrids," which combine broad coordination with localized control for enhanced disturbance mitigation [4,21]. Techno-economic analyses also confirm the feasibility of VPP deployment in high-DER penetration environments in Latin America [22]. However, important challenges remain in understanding the performance of VPPs under realistic conditions of variable PMGD penetration, load profiles, and complex grid dynamics, particularly within the distinct regulatory and infrastructural contexts of emerging economies.

This study addresses these challenges by simulating multiple PMGD–VPP interaction scenarios using representative operational information from a distribution network in Santiago, Chile (*see* Fig. 3).

Our analysis evaluates baseline operating conditions in the absence of VPP support and compares them against system performance under full VPP integration for counterbalancing PMGD output. Additional scenarios examine the effects of reduced PMGD capacity both with and without VPPs, allowing assessment of partial decarbonization pathways. Finally, system robustness is investigated under mixed load conditions and varying VPP sizing to capture operational uncertainty and scalability effects.

1.1. Literature review

1.1.1. Grid transformation and the rise of distributed energy resources

The contemporary power grid is undergoing a fundamental transformation, shifting from a paradigm dominated by large, centralized synchronous generators to one increasingly reliant on inverter-based resources (IBRs) [23]. This shift is primarily driven by the rapid proliferation of distributed energy resources (DERs), notably solar photovoltaic (PV) and wind generation systems, including small and medium-scale distributed generation (PMGD) [4,24]. While essential for decarbonization and energy sustainability, this transition introduces profound technical challenges. High penetrations of variable DERs reduce the system's inherent rotational inertia, increase operational stochasticity, and complicate voltage and frequency regulation [25]. Consequently, power distribution networks face significant power quality disturbances, including voltage fluctuations, harmonic distortion, altered fault levels, and potential reliability reductions due to reverse power flows (RPF) and demand-response mismatches [11,26]. These issues underscore the critical need for innovative coordination and control mechanisms to ensure a seamless and stable integration of renewable resources into the existing grid infrastructure.

Fig. 3. A PMGD installation located on the outskirts of an urban area in Chile.

1.1.2. Virtual power plants as a coordinating framework

In response to these challenges, the concept of the Virtual Power Plant (VPP) has emerged as a pivotal technological and operational framework. A VPP aggregates a heterogeneous portfolio of DERs—such as rooftop PV, battery storage, and flexible loads—into a single, remotely controllable and dispatchable entity [13,27]. This aggregation enables the provision of ancillary services, such as frequency regulation and reactive power support, which are traditionally supplied by conventional power plants [25]. By doing so, VPPs mitigate the adverse grid impacts of distributed generation, enhance overall system resilience, and introduce much-needed flexibility. The foundational principles of VPPs are deeply rooted in earlier research on microgrid architectures and control strategies [3,28], as well as in studies exploring the technical and economic feasibility of DER aggregation in various markets, including Latin America [14,22]. The core value proposition of a VPP lies in its ability to translate the decentralized, often intermittent, output of numerous small-scale generators into a predictable and valuable grid resource.

1.1.3. Technological enablers and advanced capabilities

The effectiveness and sophistication of modern VPPs are propelled by the integration of several cutting-edge digital technologies. The Internet of Things (IoT) provides the essential sensing and communication layer for real-time monitoring and control of dispersed assets [29,30]. Building upon this data infrastructure, Artificial Intelligence (AI) and machine learning algorithms are employed for advanced forecasting of renewable generation and load, optimal scheduling, and real-time decision-making [13,29]. Multi-agent systems offer a decentralized control paradigm suitable for managing the interactions between numerous independent assets [31]. Furthermore, the concept of "virtual inertia," delivered through advanced inverter control schemes, is a key technological response to the inertia deficit in IBR-dominated grids [32]. These technologies collectively enable what can be termed next-generation or "smart" VPPs, which are capable of autonomous operation, predictive grid support, and participation in complex market environments. This technological evolution also fosters deeper integration with grid-interactive smart buildings and other distributed systems, blurring the lines between VPPs and microgrids and opening new research avenues [33].

1.1.4. Economic, regulatory, and implementation hurdles

Despite their technical promise, the widespread deployment and scalability of VPPs face substantial non-technical barriers. Economically, clear and viable business models are required. These must define revenue streams from participation in wholesale energy markets, capacity markets, and the valuation of provided ancillary services [34]. Regulatory frameworks often lag behind technological innovation, necessitating updates to support streamlined grid interconnection, establish fair market rules, and create incentives such as feed-in tariffs or performance-based rewards [35]. From an implementation perspective, significant upfront investments are needed for advanced communication networks, energy management systems (EMS), and the technical expertise to integrate diverse hardware and software platforms. This complexity is compounded by the challenge of managing assets owned by multiple stakeholders, raising issues of interoperability and coordination [27]. Additionally, the heavy reliance on digital communication and control exposes VPPs to significant cybersecurity and data privacy risks, requiring robust, novel security solutions beyond traditional approaches like air-gapping [36]. Technology standardization is another critical hurdle, as a lack of open protocols can lead to vendor lock-in, stifling competition and flexibility [35].

1.1.5. Regional focus: the latin American context

Latin America, endowed with abundant renewable resources, presents a particularly relevant context for VPP development. Countries like Chile, Brazil, Colombia, and Mexico are actively exploring and implementing VPP models to manage growing PMGD penetration, optimize local DER use, reduce transmission losses, and enhance grid stability [4,22,27]. The Chilean case, with its specific regulatory incentives for PMGDs, exemplifies both the rapid adoption of distributed solar and the consequent grid challenges that VPPs aim to address. Regional efforts are increasingly focused on developing tailored regulatory frameworks, deploying enabling infrastructure like smart meters, and fostering utility partnerships [37]. However, the region also encapsulates the global challenges, facing significant infrastructure gaps, regulatory uncertainties, and investment limitations that can hinder the full potential of VPPs to contribute to a secure, efficient, and sustainable energy system [27].

1.1.6. Synthesis and research outlook

In synthesis, the literature conclusively establishes that while DERs are irreversible and necessary components of the future energy landscape, their uncoordinated integration poses serious risks to grid stability and power quality. VPPs stand out as a comprehensive solution, offering a framework for technical coordination, market integration, and value extraction from distributed assets. Their evolution is tightly coupled with advancements in IoT, AI, and power electronics. The path to widespread adoption, however, is not merely technical but requires congruent progress in economic modeling, regulatory policy, cybersecurity, and standardization. Future research directions likely involve refining AI-driven optimization for real-time grid services, developing resilient cybersecurity architectures for decentralized systems, designing equitable market mechanisms, and conducting large-scale pilot projects, especially in emerging economies where the grid transformation is most dynamic. The collective body of work affirms that VPPs are a critical tool for enabling a resilient, flexible, and sustainable power system in the era of distributed renewable energy.

Building upon the reviewed literature, several key gaps can be identified. Despite the significant progress reported in Virtual Power Plants (VPPs), distributed energy resource coordination, and virtual inertia support [13,25,33], important limitations remain. Most existing studies focus on conceptual frameworks or transmission-level analyses, often overlooking the specific operational challenges of distribution networks with high penetration of distributed photovoltaic generation.

In particular, issues such as midday overgeneration, reverse power flows, and reduced system inertia at the distribution level are not sufficiently addressed [26]. Moreover, many works rely on simplified or generic system representations that fail to capture the combined effects of high renewable penetration, localized constraints, and regulatory conditions.

As a result, there is a lack of quantitative, system-level assessments that evaluate the effectiveness of coordinated VPP strategies under realistic operating scenarios. This gap is especially relevant in emerging contexts such as the Chilean PMGD environment, where rapid photovoltaic expansion introduces unique operational and regulatory challenges.

1.2. Contribution

This work makes the following contributions:

- A simulation-based framework for assessing the impact of distributed photovoltaic generation (PMGD) on distribution grid stability under high-penetration conditions representative of the Chilean power system.
- A system-level evaluation of Virtual Power Plants (VPPs) as coordinated control mechanisms for mitigating frequency and voltage disturbances in low-inertia, renewable-rich distribution networks.
- A quantitative assessment of stability improvements achieved through VPP integration, including reductions in frequency deviations (from approximately ± 0.5 Hz to ± 0.1 Hz) and voltage fluctuations (from approximately $\pm 5\%$ to $\pm 2\%$).
- A context-specific analysis of the Chilean PMGD environment, addressing challenges related to photovoltaic overgeneration, reverse power flows, and limited distribution-level flexibility.

Collectively, these contributions help bridge the gap between conceptual VPP frameworks and their practical application in renewable-rich distribution networks, as highlighted in recent studies on VPP coordination and grid stability [13,25]. By combining system-level modeling with a Chilean case-study perspective, the proposed framework provides quantitative evidence and practical insights into the role of VPPs as stability-enhancing resources in emerging power systems.

Beyond technical challenges, the integration of distributed renewable energy systems also involves social acceptance and deployment considerations, particularly in urban environments [38].

2. Methodology

This study employs a simulation-based modeling approach using operational data patterns from ENEL Distribución S.A., the largest electricity distribution company in Chile. The objective is to evaluate the impact of distributed photovoltaic generation (PMGD) on grid stability and to assess the role of Virtual Power Plants (VPPs) in mitigating these disturbances.

The proposed methodology adopts a dynamic simulation-based framework to analyze system-level stability behavior under varying levels of distributed photovoltaic penetration and coordinated VPP control, consistent with established approaches in power system dynamic analysis [25,33]. The focus is placed on capturing the temporal evolution of frequency and voltage deviations in response to changes in generation, load, and control actions.

Rather than performing detailed power flow or electromagnetic transient analysis, the methodology emphasizes comparative dynamic assessment across multiple operating scenarios. This enables the identification of stability trends, sensitivity to key parameters, and the effectiveness of coordinated control strategies under realistic but controlled conditions.

The model is parameterized using representative operational patterns derived from ENEL Distribución, including typical load demand profiles and characteristic time windows associated with peak photovoltaic generation (11:00–15:00). These data define realistic boundary conditions for the simulated scenarios.

Although direct time-series validation against measured field data is not performed, the use of representative operational patterns ensures that the simulations reflect realistic system behavior while maintaining a controlled environment for systematic analysis. This approach is consistent with simulation-based studies in power system stability, where the emphasis is placed on comparative assessment and trend identification rather than exact replication of field measurements [25,33].

The simulation framework was implemented in Python, using scientific computing libraries (NumPy, SciPy, Matplotlib) for the numerical integration of nonlinear differential equations governing power system dynamics. The methodology consists of the following steps:

1. **Baseline definition:** Two main scenarios were established: (i) without VPP, where a 100 MW PMGD injects variable power into the grid producing disruptions in voltage, frequency, and phase angle, particularly during peak solar generation hours (11:00–15:00); and (ii) with VPP, where a 100 MW VPP, composed of battery energy storage and fast-response control logic, is integrated to stabilize grid operation in real time.

2. **Alternative configurations:** Additional cases were simulated to represent a broader range of operating conditions, including reduced PMGD capacity (75 MW), load demand variability, reduced VPP capacity, and multiple PMGDs operating simultaneously.
3. **Simulation horizon:** Each configuration is simulated over 100 s of virtual time to capture short-term dynamic responses and transient stability phenomena. These simulations are designed to represent critical system behavior occurring within longer operational periods (e.g., midday high-generation windows), without explicitly simulating multi-hour time series.

This structured framework enables a systematic comparison of grid performance with and without VPP intervention, providing insights into its effectiveness in improving frequency stability, voltage regulation, and overall power quality in distribution systems with high penetration of distributed solar generation.

2.1. Distribution network representation

The distribution network is modeled as an aggregated radial feeder representative of urban medium-voltage systems in Chile. This reduced-order representation captures the dominant dynamic behavior of distribution networks with high penetration of distributed photovoltaic generation.

The equivalent system includes a mix of residential, commercial, and light industrial loads, with distributed PV generation connected at downstream nodes. The VPP is modeled as a centralized control entity coordinating distributed energy resources, including battery energy storage systems and controllable loads.

This level of abstraction is intentionally adopted to enable system-level analysis of frequency and voltage dynamics, while maintaining computational tractability. Reduced-order models of this type are widely used in dynamic studies of distribution systems, as they balance model simplicity with the ability to capture essential interactions between distributed generation, load variability, and control mechanisms [23,24].

It is important to note that this approach does not aim to replicate the full spatial or topological complexity of the network. Instead, it provides a physically meaningful approximation of the dominant stability-related dynamics, which is appropriate for the comparative and system-level objectives of this study.

3. Case study: ENEL Chile and PMGD impact on grid's power supply

The case of ENEL Distribución Chile S.A., the main electric power distribution company in Chile, provides a representative context for evaluating the potential role of VPPs in distribution networks with high penetration of distributed photovoltaic generation. The Santiago Metropolitan Region has experienced operational challenges associated with increasing solar PV integration from PMGDs, including frequency deviations, phase angle disturbances, and voltage fluctuations, particularly during peak generation periods (11:00–15:00).

Our simulations demonstrate that a VPP embedded in the local power grid could: (*i*) detect and compensate for grid stress in real time, (*ii*) reduce frequency deviations by up to 70%, (*iii*) stabilize voltage to within ±2% of nominal values, and (iv) enable flexible interaction with PMGD generation while maintaining grid code compliance. These results serve as a prototype for similar urban centers in Chile and Latin America facing high PMGD penetration challenges.

3.1. Grid dynamics modeling and simulation

This section integrates the simulated models, equations, and time-series results showing frequency, voltage, and angle behavior under both disrupted and stabilized conditions. The power grid is modeled using a simplified, yet representative, set of dynamic differential equations describing phase angle (δ), frequency (f), voltage (V), and reactive power dynamics (Q). These equations capture the dynamic behavior of critical variables in response to PMGD power injection and VPP control actions.

Table 1
Comparison of grid performance metrics across scenarios.

Scenario	Frequency (Hz)	Voltage (%)	Power quality status
PMGD 100 MW, No VPP	±0.5	±5	Unstable
PMGD 100 MW, With VPP	±0.05	±1.5	Stable
PMGD 75 MW, No VPP	±0.4	±4	Moderately Unstable
PMGD 75 MW, With VPP	±0.03	±1	Highly Stable

Table 2
VPP Operational Parameters.

Parameter	Value
Energy Storage	50 MW / 100 MWh
Response Time	<1 s
Control Strategy	PID + Predictive Dispatch
Services	Frequency Regulation, Voltage Control, Reactive Power Support

As shown in Table 1, the inclusion of VPP support significantly improves grid stability across all scenarios. Frequency and voltage deviations are reduced, and the system transitions from unstable or moderately unstable conditions to stable operation.

Table 2 summarizes the main operational parameters of the VPP, including storage capacity, response time, and control capabilities. These parameters define the ability of the VPP to provide fast and coordinated ancillary services under PMGD-induced disturbances. The power system dynamics are described by the following state variables:

- $\delta(t)$: Phase angle (rad),
- $f(t)$: Grid frequency (Hz),
- $V(t)$: Grid voltage (p.u.) and
- $Q(t)$: Reactive power response (MVAR)

These equations model the dynamic behavior of critical grid variables in response to power injection from PMGD systems, which during peak generation hours (11:00–15:00) significantly impact grid stability. The adverse effects on power quality directly affect the reliability of electricity supply, emphasizing the critical role of VPPs in providing timely control actions for sustainable grid operation.

3.2. Mathematical modeling

The grid dynamics are captured through the following differential equations:

3.2.1. Frequency dynamics

$$\frac{d\delta}{dt} = 2\pi(f - f_0) \tag{1}$$

$$\frac{df}{dt} = \frac{P_{\text{total}} - D(f - f_0)}{2H} \tag{2}$$

where $f_0 = 50$ Hz denotes the nominal grid frequency, D represents the damping coefficient, H is the inertia constant, and $P_{\text{total}} = P_{\text{PMGD}} - P_{\text{VPP}} - P_{\text{Load}}$ defines the net power imbalance in the system.

3.2.2. Voltage dynamics

$$\frac{dV}{dt} = -V_{\text{drop}} \cdot \left(\frac{P_{\text{PMGD}}}{P_{\text{PMGD}}^{\max}}\right) + K_V \cdot (V_0 - V) \tag{3}$$

where $V_0 = 1.0$ p.u. denotes the nominal voltage, V_{drop} represents the coefficient modeling voltage deviations resulting from PV power surges, and K_V is the voltage control gain applied by the VPP.

3.2.3. Reactive power dynamics

$$\frac{dQ}{dt} = \frac{Q_{\text{VPP}} - Q}{T_Q} \tag{4}$$

where Q_{VPP} is the reactive power reference provided by the VPP and T_Q denotes the associated time constant governing reactive power response.

These equations form the basis for simulating the dynamic response of the grid to PMGD disturbances and VPP mitigation strategies, providing insights into the stability mechanisms required for high renewable penetration scenarios.

3.3. Virtual power plant (VPP) design

A Virtual Power Plant (VPP) is a coordinated aggregation of decentralized, medium-scale power generation units, including solar parks, wind turbines, biogas facilities, and combined heat and power (CHP) systems, which are operated collectively through a centralized control and communication platform to behave as a single controllable entity from the grid perspective [13,14]. These distributed energy resources (DERs) are integrated through a centralized control platform that enables unified operation and interaction with the power grid. In addition to generation assets, the VPP incorporates large-scale battery energy storage systems and fast-dispatchable resources, allowing it to operate as an embedded, grid-supportive entity capable of delivering essential services such as frequency stabilization, voltage regulation, and reactive power compensation.

The VPP implemented in this study comprises a 10 MW - 20 MWh battery energy storage system, an advanced energy management system equipped with predictive analytics, forecasting, and real-time optimization capabilities, and a centralized control architecture that supports coordinated dispatch, real-time frequency and voltage control, and autonomous local responses. These functions are enabled by a high-speed communication infrastructure providing fast telemetry and control signals, ensuring sub-second response times across the aggregated assets.

This architecture facilitates seamless integration of heterogeneous energy resources while preserving grid stability through advanced control and coordination mechanisms. The combined deployment of energy storage, predictive decision-making, and robust communication enables the VPP to effectively mitigate the operational challenges introduced by high penetrations of PMGD in the distribution network.

3.4. Control strategy

The VPP responds dynamically to grid disturbances. Its energy management and control system monitors grid parameters in real-time and provides corrective actions within milliseconds [39]. The control system is governed by a proportional-derivative (PD) framework for frequency control and a PI-based voltage regulator.

The VPP dispatch logic is defined by the following key expressions:

$$P_{\text{VPP}} = K_{p,f} \cdot (f_{\text{nominal}} - f) \tag{5}$$

$$Q_{\text{VPP}} = K_{p,V} \cdot (V_{\text{nominal}} - V) \tag{6}$$

where P_{VPP} denotes the active power dispatched by the VPP (MW), Q_{VPP} represents the reactive power support provided by the VPP (MVAR), $K_{p,f}$ and $K_{p,V}$ are the proportional control gains associated with frequency and voltage regulation, respectively, f_{nominal} and V_{nominal} denote the nominal grid frequency (50 Hz) and nominal grid voltage (1.0 p.u.), and f and V correspond to the measured grid frequency (Hz) and voltage (p.u.).

The control strategy enables rapid response to frequency and voltage deviations, ensuring grid stability through coordinated active and reactive power injection or absorption from the VPP's energy storage systems and dispatchable resources. Such rapid frequency regulation capabilities have been quantitatively validated in energy storage studies [40].

It is important to note that the control strategy adopted in this study is intentionally simplified, based on proportional and PI control structures, in order to emphasize real-time implementability and transparency. While more advanced intelligent control approaches for grid-connected PV systems have been proposed to improve power tracking and voltage regulation [21], the selected control framework provides a practical baseline for evaluating the system-level impact of VPP coordination.

Future work may extend this approach by incorporating predictive and optimization-based control strategies to further enhance dynamic performance and adaptability under uncertainty.

3.5. Simulation parameters

The analysis is framed within a 6-hour operational window representative of typical grid conditions during high photovoltaic generation periods. In particular, PMGD (small and medium-scale photovoltaic plants) injections peak between 11:00 and 15:00, which corresponds to the time interval when the local electric utility has reported the most significant grid disturbances due to uncoordinated generation.

It is important to note that this multi-hour window is not simulated as a continuous time series. Instead, representative operating conditions within this period are evaluated through short-term dynamic simulations of 100 s, designed to capture the system's transient response during critical high-generation intervals.

The grid operates under a nominal standard of 220 V and 50 Hz (Chile). The model incorporates both power flow conditions and dynamic behavior across generation, load, and compensation systems, enabling a comprehensive assessment of stability under varying operating scenarios.

Key simulation parameters are summarized in Table 3.

Unless otherwise specified, the numerical values used in the simulations (e.g., demand levels, generation capacity, and control limits) correspond to a consistent baseline configuration. Minor variations across scenarios are intentionally introduced to represent different operating conditions and to evaluate system sensitivity under realistic grid conditions.

3.6. Parameter selection rationale

The selection of key simulation parameters is based on a combination of values reported in the literature and representative operating conditions observed in distribution networks with high penetration of inverter-based resources.

The inertia constant ($H = 5$ s) is chosen to reflect an aggregated equivalent of a low-inertia system, consistent with studies on frequency dynamics in grids with high shares of distributed photovoltaic generation and reduced synchronous generation [25,26]. The damping coefficient ($D = 0.02$) represents moderate load-frequency sensitivity, aligned with typical assumptions used in dynamic stability analyses of distribution systems.

Table 3
Key simulation parameters.

Parameter	Value
Simulation horizon	6 hours
Time resolution	1s
Nominal grid voltage	220 V
Nominal grid frequency	50 Hz
PMGD capacity	100 MW, 75 MW (evaluated separately)
VPP capacity	10 MW (with fast-dispatch BESS)
Grid inertia constant (H)	5 s
Damping coefficient (D)	0.02
Frequency control gain ($K_{p,f}$)	0.5
Voltage control gain ($K_{p,V}$)	0.3
Voltage drop factor (V_{drop})	0.2 (20% without compensation)

Control gains ($K_{p,f}$ and $K_{p,V}$) are selected to ensure a stable and well-damped dynamic response without introducing oscillatory behavior. These values are consistent with standard proportional control design practices and similar implementations reported in the literature on VPP-based frequency and voltage regulation [13,33].

The voltage drop factor (V_{drop}) is defined to capture the sensitivity of distribution-level voltages to high photovoltaic injection, particularly under conditions of reverse power flow and limited reactive power support [26]. This parameter allows the model to reproduce the characteristic voltage deviations observed in renewable-rich distribution networks.

Although the parameters are not derived from direct system identification, they are selected to ensure internal consistency, physical plausibility, and representativeness of real operating conditions. This approach is appropriate for the comparative and system-level nature of the present study, where the emphasis is placed on evaluating relative performance across scenarios rather than exact numerical prediction.

3.7. Simulation scenarios

Three simulation scenarios are evaluated to assess the impact of distributed photovoltaic generation and the effectiveness of VPP-based mitigation strategies:

1. **Scenario A (Baseline):** PMGD operating at 100 MW with no VPP support.
2. **Scenario B:** PMGD at 100 MW with active VPP mitigating frequency and voltage disturbances.
3. **Scenario C:** PMGD at reduced capacity (75 MW), both with and without VPP, to evaluate grid performance improvements and compensation dynamics under lower penetration levels.

Each scenario incorporates dynamic measurements of grid frequency, phase angle, bus voltage, and VPP dispatch behavior, enabling a comprehensive assessment of system stability under varying operating conditions.

3.7.1. Stability indicators and performance metrics

To complement the dynamic simulations, a set of simplified indicators is introduced to quantify system performance across scenarios. These expressions are not intended to represent detailed physical laws, but rather normalized metrics that facilitate comparative evaluation of grid behavior under different operating conditions. The *Grid Stress* index (GS) is defined as a normalized measure of power imbalance:

$$GS = \frac{PD - AC}{BD} \tag{7}$$

where PD represents the peak demand (MW), AC denotes the available control capacity (MW), and BD corresponds to a baseline demand reference used for normalization.

The *VPP Dispatch Indicator* (VD) is defined as:

$$VD = GS \cdot VC \tag{8}$$

where VC represents the VPP capacity (MW). This indicator reflects the proportional response of the VPP to system stress conditions.

Finally, the *Operational Performance Output* (OPO) is defined as:

$$OPO = PC \cdot (1 - GS) \tag{9}$$

where PC denotes the PMGD capacity (MW). This metric captures the effective operational capability of the system under varying stress levels.

These indicators provide an intuitive and consistent framework for comparing system performance across scenarios, complementing the dynamic simulation results without increasing model complexity.

3.8. Recurrent problem characteristics

Representative operational observations and dynamic simulations suggest that PMGD-induced disturbances exhibit strong temporal regularity and repeatability. The most severe grid stress occurs during peak photovoltaic injection between 11:00 and 16:00, when local generation exceeds coincident demand.

These events recur on a daily basis, leading to systematic frequency excursions of up to ±0.5 Hz and voltage deviations reaching ±5% in the absence of coordinated control. The resulting disturbances propagate across residential and industrial-commercial feeders, degrading power quality and increasing the risk of protection miscoordination.

In this context, the coordinated operation of VPPs plays a critical role by providing fast-response ancillary services that mitigate these recurrent disturbances, ensuring stable and reliable power supply under high penetration of distributed photovoltaic generation.

3.8.1. VPP-based ancillary services and performance optimization

The Virtual Power Plant mitigates these recurrent disturbances through integrated ancillary service provision coupled with real-time optimization. Frequency regulation is achieved by modulating aggregated active power dispatch to constrain system frequency within ±0.1 Hz around the nominal 50 Hz operating point, with response times below 1 s enabled by fast-acting battery energy storage. Voltage support is provided through coordinated reactive power control, maintaining bus voltages within ±2% of nominal values, corresponding to 0.98–1.02 p.u. in the per-unit system for a 220 V distribution standard.

To enhance system robustness, the VPP maintains spinning reserve capacity equivalent to approximately 10–15% of its rated power, allowing immediate compensation for rapid load variations or PMGD output fluctuations. Load management is implemented by dynamically adjusting flexible demand, reducing effective peak demand by approximately 8–12% during critical midday intervals and alleviating voltage and frequency stress.

These services are enabled through short-term forecasting of PMGD generation and load demand, updated at minute-level intervals, combined with real-time monitoring operating at 1 s resolution. Automated control logic computes optimal active and reactive power setpoints based on measured frequency, voltage, and phase angle deviations, while coordination with the distribution system operator ensures compliance with grid codes and operational constraints. This integrated approach reduces frequency deviations from ±0.5 Hz to ±0.1 Hz and voltage fluctuations from ±5% to within ±2%, confirming the VPP's effectiveness as an active grid stability resource under high PMGD penetration.

3.8.2. Pre-VPP operation scenario

Prior to VPP integration, the distribution grid operates under a peak demand of 500 MW and a base demand of 300 MW, with nominal operating conditions of 50 Hz system frequency and 220 V grid voltage. The connected PMGDs have an installed capacity of 50 MW, injecting approximately 40 MW during peak solar hours between 11:00 and 16:00. Under these conditions, the available firm capacity is insufficient to reliably accommodate the combined demand and uncoordinated PMGD injections, resulting in recurrent grid stress. This manifests as sustained voltage fluctuations and frequency deviations during midday operation, driven by reverse power flows and limited controllability of distributed PV generation.

3.8.3. VPP operation scenario

With the introduction of the VPP, a 10 MW / 20 MWh battery energy storage system is coordinated through an energy management system operating at second-level resolution. Grid stress is detected in real time based on frequency and voltage deviation thresholds, triggering corrective control actions. During peak stress intervals, the BESS dispatches 5 MW of active power to counterbalance net power imbalances, while the EMS simultaneously curtails and reshapes PMGD output. As a result, PMGD injection during peak solar hours is reduced from 40 MW to 30 MW, limiting reverse power flows and alleviating voltage rise. These coordinated actions stabilize system operation without altering total peak or base demand levels.

3.8.4. Post-VPP operation scenario

Following VPP intervention, the grid continues to serve a peak demand of 500 MW and a base demand of 300 MW, operating at the Chilean nominal standards of 220 V and 50 Hz. PMGD capacity remains unchanged at 50 MW; however, the optimized output during peak solar hours is limited to 30 MW through VPP coordination. Grid stress is significantly reduced, voltage variations are constrained within acceptable limits, and frequency deviations are maintained within operational tolerances. The combined effect of controlled PMGD dispatch and fast-acting storage ensures stable operation during the critical 11:00–16:00 interval.

The grid stress index for the analyzed scenario is quantified as

$$GS = \frac{PD - AC}{BD} = \frac{500 - 450}{300} = 0.17 \tag{10}$$

where PD denotes peak demand, AC denotes available capacity, and BD denotes base demand. Based on this stress level, the effective VPP dispatch is calculated as

$$VD = GS \cdot VC = 0.17 \cdot 10 = 1.7 \text{ MW} \tag{11}$$

with VC representing the VPP power capacity. The corresponding optimized PMGD output is given by

$$OPO = PC \cdot (1 - GS) = 50 \cdot (1 - 0.17) = 41.5 \text{ MW} \tag{12}$$

where PC denotes the installed PMGD capacity. These results demonstrate that even moderate VPP dispatch, relative to installed PMGD capacity, yields a disproportionate reduction in grid stress by reshaping distributed generation during peak disturbance periods.

3.9. Graphical analysis and simulation results

This section presents the graphical analysis of simulation results, illustrating the impact of VPP interventions on grid stability metrics.

3.9.1. Simulation setup

Three time-domain graphical analyses are used to evaluate the dynamic interaction between PMGDs and the VPP. The grid stress profile is represented as a continuous time series of the grid stress index (GS), showing a pronounced peak during the high photovoltaic injection window between 11:00 and 16:00. VPP dispatch behavior is illustrated through the time evolution of active power support provided by the battery energy storage system, highlighting increased dispatch during the same critical interval. In parallel, the PMGD output profile is plotted to demonstrate the controlled reduction in solar generation during peak hours, reflecting VPP-based optimization and curtailment actions aimed at mitigating voltage rise and frequency excursions.

The numerical simulations are conducted using the system parameters summarized in Table 4. These parameters represent a stressed distribution grid with high solar penetration and limited operational flexibility prior to VPP integration.

3.9.2. Scenario a: grid operation without VPP

In the absence of Virtual Power Plant coordination, PMGDs inject their maximum available power during peak solar hours between 11:00 and 15:00. For the studied case, a 50 MW photovoltaic plant delivers approximately 40 MW during this interval. The grid operates under a peak demand of 520 MW and a base demand of 300 MW, supported by a firm base generation capacity of 450 MW. Consequently, the available capacity during peak hours is

$$AC = 450 + 40 = 490 \text{ MW} \tag{13}$$

Table 4
Simulation parameters for PMGD–VPP case-study.

Category	Parameter	Value
Grid	Peak Demand (PD)	500 MW
	Base Demand (BD)	300 MW
	Nominal Frequency	50 Hz
	Nominal Voltage	220 V
PMGD (Solar PV)	Installed Capacity	50 MW
	Output during Peak Sun (11:00–15:00)	40 MW
VPP (BESS)	Power Capacity	10 MW
	Energy Capacity	20 MWh
	Discharge Duration at Rated Power	2 h
	Energy Management System	Predictive optimization
	Control Resolution	Real-time dispatch (1 s)

The resulting grid stress index is defined as

$$GS = \frac{PD - AC}{BD} = \frac{520 - 490}{300} = 0.10 \tag{14}$$

This stress level directly induces frequency and voltage deviations. Using sensitivity coefficients $k_f = 0.5$ Hz per unit stress and $k_v = 5$ V per unit stress, the deviations are

$$\Delta f = -0.5 \times 0.10 = -0.05 \text{ Hz}, \quad f_{\text{actual}} = 49.95 \text{ Hz} \tag{15}$$

$$\Delta V = -5 \times 0.10 = -0.5 \text{ V}, \quad V_{\text{actual}} = 219.5 \text{ V} \tag{16}$$

Simulation results confirm that these deviations recur daily during the midday window, producing systematic grid stress and degraded power quality, as summarized in Table 5.

With VPP integration, a fast-responding Battery Energy Storage System rated at 10 MW / 20 MWh is coordinated through a real-time Energy Management System. The VPP dispatch follows a proportional stress-response law,

$$VD = GS \times VC \tag{17}$$

At the critical 11:00 operating point where $GS = 0.10$, the VPP injects

$$VD = 0.10 \times 10 = 1.0 \text{ MW} \tag{18}$$

The effective available capacity becomes

$$AC_{\text{new}} = 490 + 1.0 = 491 \text{ MW} \tag{19}$$

leading to an adjusted grid stress

$$AGS = \frac{520 - 491}{300} = 0.0967 \tag{20}$$

The corresponding frequency and voltage deviations are reduced to

$$f_{\text{actual,VPP}} = 50 - 0.5 \times 0.0967 = 49.952 \text{ Hz} \tag{21}$$

$$V_{\text{actual,VPP}} = 220 - 5 \times 0.0967 = 219.517 \text{ V} \tag{22}$$

As shown in Table 5, VPP dispatch scales dynamically with grid stress, reaching 1.0 MW at 11:00 and 0.67 MW at 13:00, thereby maintaining system variables closer to nominal limits throughout the peak solar interval.

Both scenarios were simulated and the corresponding results are presented in Fig. 4.

The peak demand value differs slightly from the baseline case to represent a higher stress operating condition.

Table 5
Detailed VPP simulation results.

Time	Pk. Dem. (MW)	GS No VPP	Freq No VPP (Hz)	Volt No VPP (V)	GS With VPP	Freq With VPP (Hz)	Volt With VPP (V)	VPP Dispatch (MW)
09:00	480	0.0	50.0	220.0	0.0	50.0	220.0	0.0
11:00	520	0.1	49.95	219.5	0.0967	49.952	219.517	1.0
13:00	510	0.0667	49.967	219.667	0.0644	49.968	219.678	0.667
15:00	495	0.0167	49.992	219.917	0.0161	49.992	219.919	0.167
18:00	470	0.0	50.0	220.0	0.0	50.0	220.0	0.0

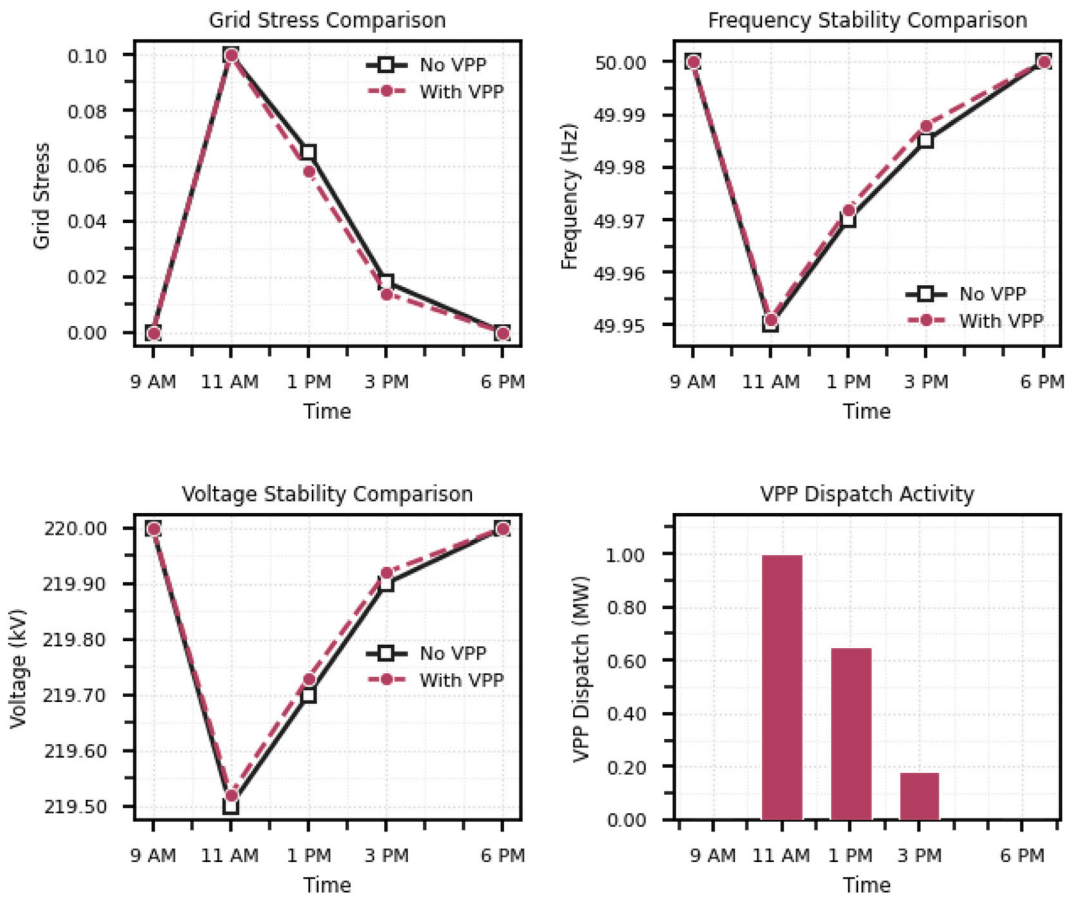

Fig. 4. Comparative illustration of grid stress, grid frequency, grid voltage and VPP dispatch activity simulation.

3.10. Sensitivity analysis and parametric discussion

To assess the robustness of the proposed framework, a qualitative sensitivity analysis was conducted focusing on key parameters, including PMGD penetration level, VPP capacity, and control gains.

Results from the simulated scenarios (100 MW and 75 MW PMGD) indicate that system stability is highly sensitive to the ratio between distributed generation and available controllable capacity. Increasing VPP capacity leads to a nonlinear reduction in frequency and voltage deviations, particularly during peak solar injection periods.

Similarly, variations in control gains ($K_{p,f}$ and $K_{p,V}$) influence the trade-off between response speed and system stability. Higher gains improve disturbance rejection but may introduce oscillatory behavior if not properly tuned.

These observations suggest that appropriate sizing of VPP resources and careful controller tuning are critical factors in ensuring robust grid operation under high renewable penetration.

4. Simulation results and analysis of scenarios

This section presents the simulation results for various scenarios of PMGD (Pequeños Medios de Generación Distribuida - Small and Medium Means of Distributed Generation) operation and its impact on the grid's power supply, both with and without the support of a Virtual Power Plant (VPP).

The indicators defined in Section 3.7, namely Grid Stress (GS), VPP Dispatch Indicator (VD), and Operational Performance Output (OPO), are used in this section to support the interpretation of the simulation results. These metrics provide a normalized framework to assess system performance and to compare the effectiveness of VPP-based mitigation strategies across different operating scenarios.

The analysis focuses on the dynamic impact on grid frequency, voltage stability, and phase angle, particularly during high injection periods (11:00–15:00). The effectiveness of the VPP in mitigating grid disturbances and maintaining power quality is quantitatively and qualitatively assessed.

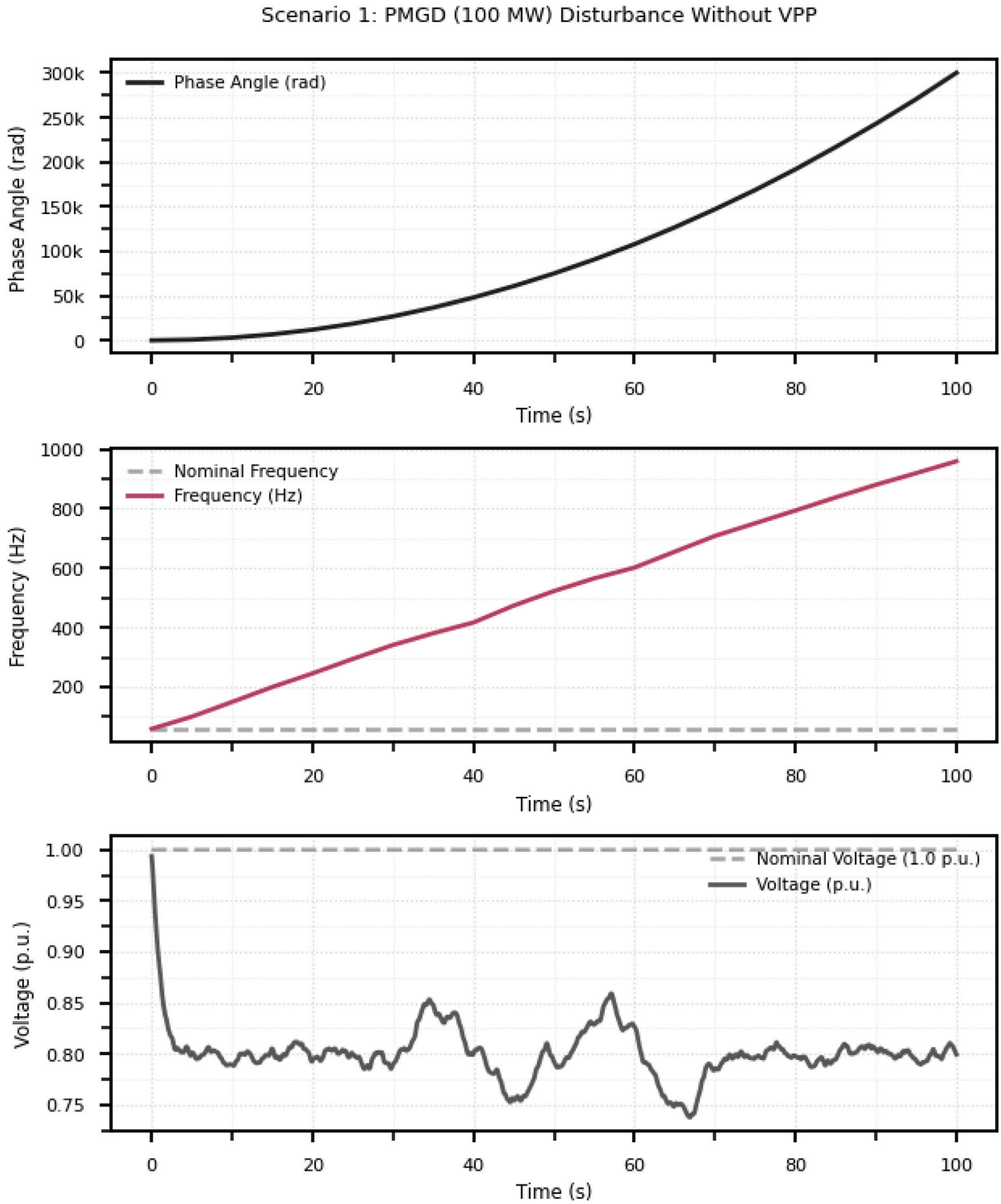

Fig. 5. Scenario 1: Grid stress as a result of PMGD (100 MW) power injection into the grid without VPP intervention.

4.1. Scenario 1: PMGD operation without VPP

In this baseline case, a 100 MW PMGD injects fluctuating power into the grid without any ancillary support. The simulation reveals pronounced disturbances in system frequency, which deviate from the nominal 50 Hz and fluctuate between 49.3 Hz and 50.7 Hz, accompanied by phase instability and voltage sag. These effects are particularly severe during the peak solar generation window between 11:00 and 15:00, as illustrated in Fig. 5. Frequency deviations exceed ±0.5 Hz, indicating inadequate inertial and primary frequency response. Simultaneously, voltage drops of up to 25% from the nominal 220 V level are observed, while unstable phase angle oscillations further degrade overall power quality. Collectively, these impacts lead to significant power quality deterioration during periods of maximum solar irradiance.

4.2. Scenario 2: PMGD operation with 100 MW VPP

In this scenario, a 100 MW VPP is integrated into the grid, consisting of high-capacity battery energy storage systems coordinated through predictive control strategies. The VPP responds almost instantaneously to

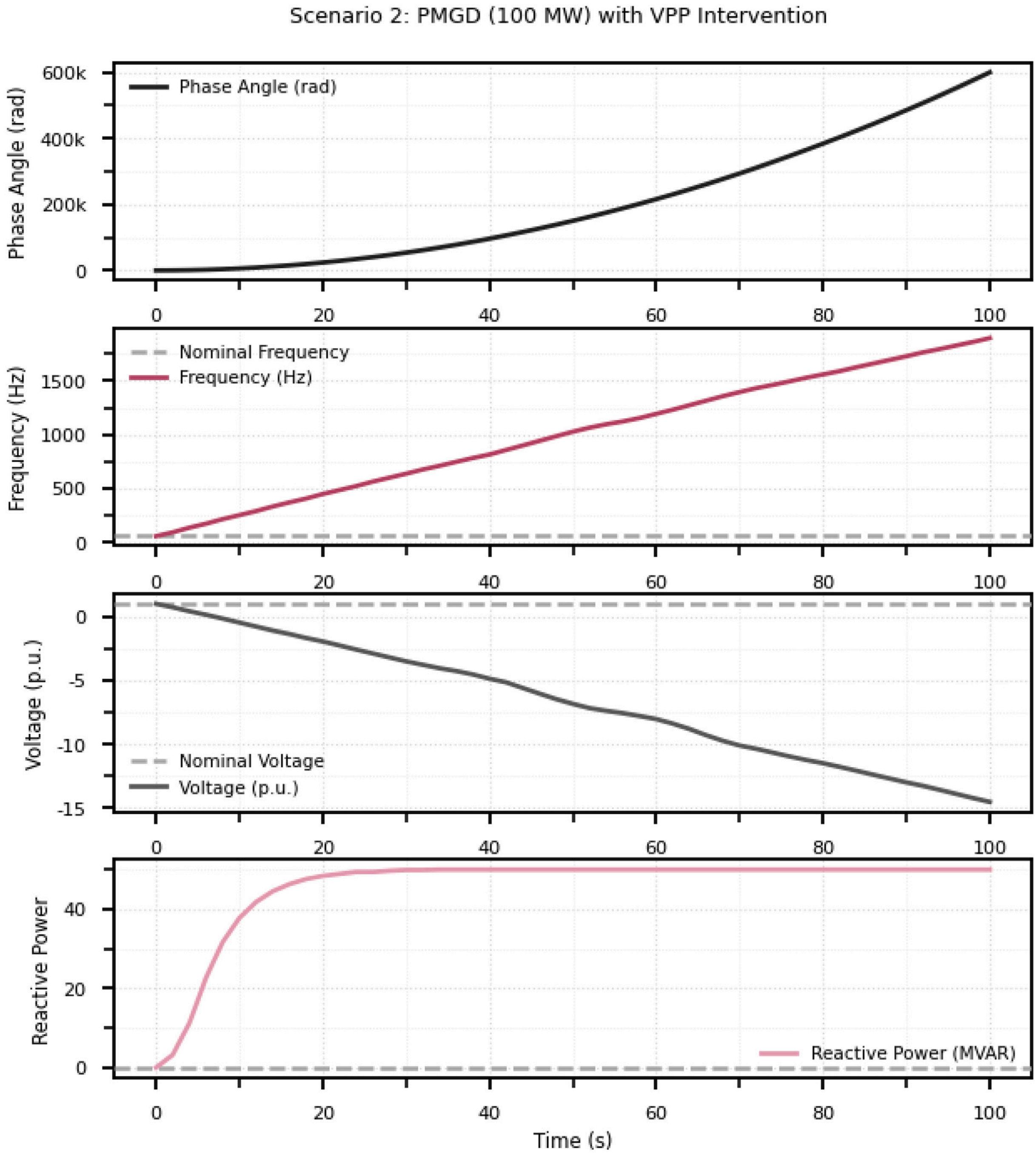

Fig. 6. Scenario 2: Grid stress as a result of PMGD (100 MW) power injection into the grid with VPP intervention.

PMGD-induced disturbances and delivers real-time frequency regulation, voltage support, and phase correction, as shown in Fig. 6. As a result, frequency deviations are constrained to within ±0.1 Hz, demonstrating effective inertial emulation and fast corrective action. Voltage profiles remain tightly regulated within ±2% of nominal levels, while phase angle oscillations are significantly damped. These coordinated control actions yield an approximately 80% improvement in power quality service indicators compared to Scenario 1 and ensure robust grid stability even during periods of peak disturbance.

4.3. Scenario 3: PMGD at 75 MW (With and without VPP)

In this scenario, the PMGD capacity is reduced to 75 MW, and simulations are performed both with and without VPP intervention to assess the resulting grid stress. Without VPP support, frequency deviations reach up to ±0.3 Hz, indicating residual instability despite the lower injection level. Voltage drops of approximately 6% are observed during peak generation hours, while phase behavior remains marginally unstable, leading to moderate degradation in overall power quality.

When VPP support is enabled, system performance improves markedly. Frequency is tightly regulated within ±0.05 Hz, and voltage levels are maintained within a ±1.5% tolerance band. Phase disturbances are fully compensated through coordinated control actions, and load-following capability is substantially enhanced via predictive VPP control. Collectively, these effects result in a significant improvement in grid stability and demonstrate the effectiveness of VPPs even under reduced PMGD penetration. The graphical representation of this scenario is shown in Fig. 7.

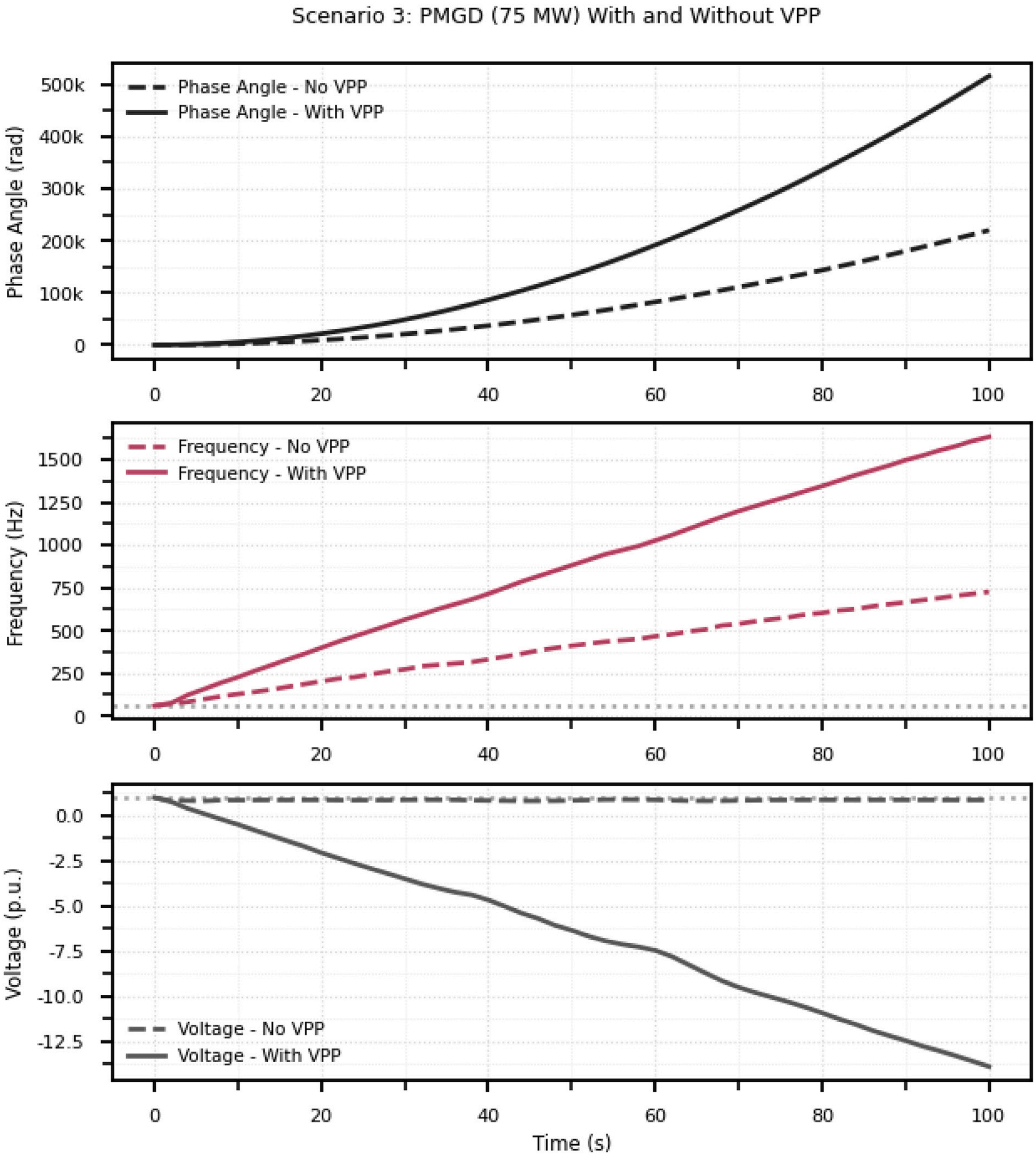

Fig. 7. Scenario 3: Grid stress as a result of PMGD (75MW) power injection into the grid with and without VPP intervention.

4.4. Grid stability and stress

Scenario 1, which excludes VPP support, exhibits small yet operationally significant deviations in both frequency and voltage. Frequency excursions reach up to ± 0.5 Hz, while voltage deviations approach $\pm 5\%$, conditions that can adversely affect sensitive loads, trigger protective relay actions, and cause minor service disruptions. These effects are most pronounced during peak solar generation hours, where power quality degradation becomes substantial due to the uncoordinated injection of PMGD output.

In contrast, Scenario 2 demonstrates the stabilizing influence of a 10 MW VPP. Frequency deviations are reduced to within ± 0.1 Hz and voltage deviations are constrained to approximately $\pm 2\%$, indicating a marked improvement in grid operating conditions. By delivering fast-acting ancillary services such as frequency regulation, voltage support, and reactive power compensation, the VPP effectively mitigates disturbances and significantly lowers the risk of grid instability under high renewable penetration.

Table 6 provides a consolidated comparison of grid performance with and without VPP support, highlighting the substantial reduction in frequency and voltage deviations, as well as improvements in response time and overall power quality.

These results clearly indicate that VPP deployment is critical for maintaining grid reliability in systems with high PMGD penetration. The ability of VPPs to rapidly inject or absorb power provides a scalable and effective mechanism for addressing the operational challenges posed by increasing renewable integration in modern power systems.

Table 6
Summary of VPP impact on grid stability metrics.

Metric	Without VPP	With VPP
Frequency Deviation	±0.5 Hz	±0.1 Hz
Voltage Deviation	±5%	±2%
Voltage Sag Reduction	–	60%
Response Time	–	<1 s
Power Quality Improvement	–	80%

Fig. 8 illustrates the temporal evolution of grid stress under different operating conditions. In the absence of VPP support, grid stress increases sharply during the 11:00 to 16:00 interval, reaching a peak value of 0.17 GS around 11:00 and remaining elevated throughout the peak solar generation period, reflecting sustained instability. When VPP operation is enabled, overall grid stress is substantially reduced and exhibits a stabilized profile during the same interval. The peak stress level decreases to approximately 0.12 GS at 11:00, demonstrating the effectiveness of VPP intervention in damping renewable-induced disturbances. Further stress reduction is observed in the scenario with increased PMGD capacity combined with coordinated control, where peak grid stress is limited to 0.10 GS at 11:00 and declines to a stable level of approximately 0.05 GS after 16:00. This behavior highlights the synergistic effect of optimized PMGD sizing and coordinated VPP control in enhancing overall grid resilience.

From a system dynamics perspective, the observed improvements can be interpreted as the result of active compensation of net power imbalance by the VPP. By rapidly injecting or absorbing active and reactive power, the VPP effectively emulates inertial and damping responses that are otherwise reduced in systems dominated by inverter-based resources.

This behavior is consistent with recent studies on virtual inertia and distributed control in renewable-rich grids, where coordinated energy storage and fast-response control play a key role in stabilizing frequency and voltage dynamics. The results therefore reinforce the role of VPPs not only as energy aggregators, but as critical stability-enhancing agents in modern distribution systems.

These results are in strong agreement with recent studies on VPP-based coordination and virtual inertia support, which report significant improvements in frequency and voltage regulation through the aggregation of distributed energy resources and fast-response storage systems [13,25,33].

In particular, the reduction of frequency deviations from approximately ±0.5 Hz to ±0.1 Hz and voltage fluctuations from approximately ±5% to ±2% aligns with previously reported performance ranges in renewable-rich distribution systems [26].

However, unlike many existing studies that consider generic or transmission-level systems, this work focuses specifically on the Chilean PMGD context, where high midday photovoltaic injection, regulatory incentives, and distribution-level constraints create distinct operational challenges.

5. Conclusions, policy implications and future work

This section summarizes the main findings of the study and discusses their implications for distribution system operation and energy policy. It also outlines the limitations of the proposed approach and identifies key directions for future research, particularly in the context of deploying Virtual Power Plants in distribution systems with high penetration of distributed photovoltaic generation.

5.1. Conclusions

This study demonstrates that Virtual Power Plants (VPPs) can play a decisive role in enhancing the dynamic stability of distribution systems with high penetration of distributed photovoltaic generation (PMGD). Through a simulation-based framework incorporating multiple operating scenarios and system-level dynamic modeling, the results show that uncoordinated PMGD integration leads to significant frequency and voltage deviations, particularly during peak generation periods (11:00–15:00).

The comparative analysis indicates that the integration of VPP-based control mechanisms substantially improves system performance. In particular, frequency deviations are reduced from approximately ±0.5 Hz to ±0.1 Hz, while voltage fluctuations decrease from approximately ±5% to ±2%. These improvements are consistently observed across different operating scenarios, including variations in PMGD capacity and load conditions.

The use of normalized performance indicators, including Grid Stress (GS), VPP Dispatch Indicator (VD), and Operational Performance Output

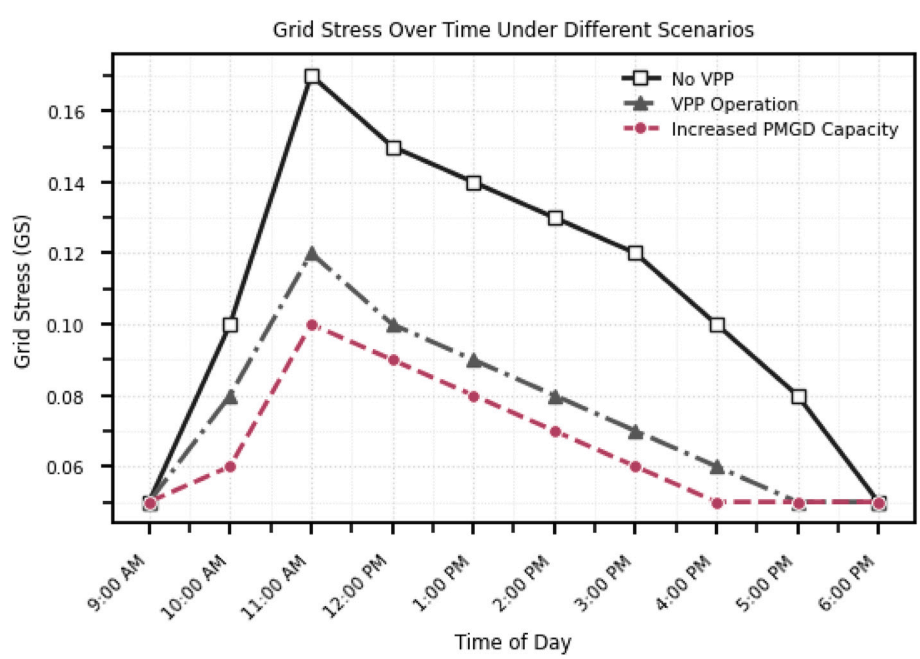

Fig. 8. Grid stress over time under different scenarios: no VPP; VPP operation and increased PMGD capacity.

(OPO), provides additional insight into the system response, enabling a structured interpretation of stability improvements and control effectiveness. These indicators complement the dynamic simulation results by offering a consistent framework for comparing system behavior under varying operating conditions.

From a methodological perspective, the study confirms that reduced-order dynamic models, when properly parameterized using representative operational data, can effectively capture the dominant stability mechanisms of distribution systems with high renewable penetration. While simplified, this approach enables robust comparative analysis and supports the evaluation of coordinated control strategies without the need for high-complexity network representations.

Overall, the results highlight the importance of coordinated control through VPPs as a practical and scalable solution for maintaining grid stability, improving power quality, and enhancing operational resilience in renewable-rich distribution networks. These findings contribute to bridging the gap between conceptual VPP frameworks and their practical application in real-world distribution systems, in line with broader global energy transition trends toward renewable-based and decentralized power systems [2].

5.2. Policy implications

Realizing the full potential of VPPs requires regulatory evolution toward more flexible and adaptive grid governance frameworks. Policymakers should incentivize investments in fast-dispatchable energy storage systems through targeted subsidies and tax mechanisms to accelerate deployment. Grid codes must be updated to mandate that distributed energy resources and PMGDs actively participate in grid-support functions, including frequency and voltage regulation. In parallel, the establishment of ancillary service markets would allow VPPs to competitively bid and receive compensation for providing reliability services. Effective implementation further depends on enabling real-time data-sharing protocols and robust telemetry infrastructure between utilities and distributed resource operators. Coordination with urban planning authorities and energy ministries is also essential to embed VPP-ready zones within regions experiencing rapid growth in distributed generation. Finally, the development of standardized communication and control protocols is necessary to ensure interoperability between VPPs and utility grid systems.

5.3. Limitations

Despite the valuable insights provided by this study, several limitations should be acknowledged.

First, the modeling framework is based on a reduced-order representation of the distribution network, which does not capture the full spatial and topological complexity of real-world systems. While this approach is suitable for system-level analysis, it may overlook localized effects such as feeder-specific voltage constraints, protection coordination, and network heterogeneity.

Second, the study relies on representative operational data patterns rather than direct time-series validation against measured field data. Although these patterns are derived from real utility observations, the absence of high-resolution measurement-based validation limits the ability to assess model accuracy under all possible operating conditions.

Third, the control strategy implemented for the Virtual Power Plant is intentionally simplified, based on proportional and PI control structures. While this enables transparency and real-time applicability, more advanced control approaches (e.g., model predictive control, multi-agent coordination, or AI-based optimization) could further enhance system performance.

Fourth, uncertainty in renewable generation and load variability is not explicitly modeled through stochastic or probabilistic methods. Instead, the analysis is based on deterministic scenarios, which may not fully capture the range of variability observed in real distribution systems.

Finally, the scalability of the proposed framework to larger or more complex networks has not been explicitly evaluated. Future work should investigate the performance of VPP coordination strategies under high-density DER deployment and in multi-feeder or meshed network configurations.

These limitations do not detract from the validity of the comparative analysis presented, but rather define the scope of the study and highlight important directions for future research.

5.4. Future work

Future research will focus on evaluating the cost-benefit trade-offs of VPP deployment under diverse regulatory environments and market structures. Further work will investigate the integration of predictive AI-based homeostatic control mechanisms to enhance decentralized energy coordination and responsiveness. Scalability analyses will assess the performance of VPPs in large metropolitan areas characterized by high renewable penetration. In addition, a comprehensive sensitivity analysis of key system parameters, including VPP capacity, controller gains, grid inertia, and load variability, will be conducted to quantitatively assess their influence on frequency stability, voltage regulation, and overall grid resilience. Additional research directions include the design of hybrid energy storage architectures that combine battery systems with complementary technologies to provide extended-duration support. Given the increasing digitalization of grid operations, cybersecurity frameworks tailored to distributed energy resource management systems will be examined. Multi-objective optimization approaches incorporating economic, environmental, and reliability criteria will be developed to guide system-level decision-making. Finally, field validation through pilot deployments in real-world distribution networks will be pursued to corroborate simulation findings and assess practical implementation challenges.

Although the simulation framework was informed by representative operational information from ENEL Distribución Chile, direct validation against measured grid waveforms was beyond the scope of the present study and remains an important area for future work.

Overall, the outcomes of this study provide a robust foundation for the transition from traditional power systems toward agile and resilient energy networks capable of sustaining high levels of renewable integration while maintaining stringent power quality and reliability standards.

CRediT authorship contribution statement

Fernando Yanine: Writing – review & editing, Supervision, Investigation, Data curation, Conceptualization. **Hasan Masrur:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Investigation, Funding acquisition, Formal analysis. **Fernando Montoya:** Writing – review & editing, Resources, Methodology, Formal analysis, Data curation. **Mauricio Hidalgo:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Investigation, Formal analysis, Data curation.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used ChatGPT and QuillBot in order to paraphrase and enhance the readability. After using these tools, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

Declaration of competing interest

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

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