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Diagnosing grid's service quality issues: the virtual microgrid and the digitization and innovations in the power distribution grid.

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Abstract

Power quality issues from small and medium-sized grid-integrated solar photovoltaic systems (PMGD), whose plant capacity is less than or equal to 9 MW, challenge electric power distribution companies like ENEL Distribución S.A. in Chile. To tackle these challenges, leveraging rapidly configurable, scalable, and easily deployable distributed energy resources (DER) through a virtual power plant (VPP) is crucial. This paper introduces a "virtual microgrid," a specific VPP design and functional specification that swiftly diagnoses and resolves power quality issues. Virtual power plants use renewable energy sources, energy storage, and smart energy management to provide ancillary services to the grid. With the expanding PMGD market in Chile and globally, there is an urgent need for deployable DER to energize feeder sub-sections during reliability events and create grid pathways between DER and loads. Thus, DER are essential for enhancing grid flexibility, reliability, and maintaining the stability and integrity of electric supply quality standards. VPPs can reduce high costs associated with utility grid power capacity deficiencies in areas with unstable power supply, enhancing resilience and flexibility without compromising system stability. This study presents a novel approach—currently at the conceptual development stage—for diagnosing service quality issues related to grid supply through the rapid deployment of a configurable and fully scalable virtual microgrid. This solution is particularly relevant for zones in Santiago, Chile, where ENEL Chile faces challenges due to the increasing presence of PMGD—independent solar farms injecting all their production into the grid for profit, as permitted by current Chilean electric law (N°88/2019 of Ministry of Energy). Such practices negatively impact grid service quality standards, which can be mitigated through the deployment of virtual microgrids. The concept of a "virtual microgrid" emphasizes rapid configurability, scalability, and ease of deployment, tailored to address specific grid quality issues. Unlike previous efforts, this approach focuses on seamlessly integrating DER with existing grid infrastructure to quickly address and mitigate power quality issues caused by PMGD.

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1. Introduction

The DOE report says deploying 80 to 160 gigawatts of virtual power plants by 2030 could save about \$10 billion in annual grid costs and would direct grid spending back to electricity consumers. At that scale, virtual power plants could meet between 10 and 20% of peak electric demand [1]. The integration of distributed energy resources (DER) into the power grid has been a subject of extensive research in recent years, especially in the context of enhancing grid flexibility and reliability [2]. Next, we provide a brief literature review with a comprehensive overview of recent advancements, focusing on the role of virtual power plants (VPP) and the concept of virtual microgrids, addressing recent advancements in distributed energy resources (DER). Regarding DER and Grid integration issues, the increasing penetration of DER, including solar photovoltaic (PV) systems, has been extensively studied [3]. A key focus has been on how DER can be integrated into existing grid infrastructure without compromising stability and reliability. Recent studies have demonstrated various strategies for integrating DER, highlighting the need for advanced energy management systems and grid support services [4]. In regards to the impact of Small and Medium-sized PV Systems (PMGD) research has shown that these can cause significant power quality issues such as voltage fluctuations, frequency deviations, and harmonics [5]. These issues necessitate innovative solutions for maintaining grid stability. Studies have highlighted the specific challenges faced in regions with high PMGD penetration, such as in Chile [6]. A potential solution to address these issues—although at a conceptual development stage at present—is the virtual power plant (VPP) and virtual microgrids [7]. VPPs have emerged as a viable solution for managing the complexities associated with DER integration [7]. VPPs aggregate multiple DER units to operate as a single power plant, providing grid support services such as frequency regulation, voltage support, and demand response [8]. Recent research has focused on optimizing VPP operation for enhanced efficiency and reliability [8]. Although the concept of virtual microgrids is relatively new and has been proposed as an extension of VPPs [9]. Virtual microgrids are characterized by their ability to rapidly configure, scale, and deploy DER to address specific grid issues. Studies have explored the design, functionality, and potential applications of virtual microgrids, emphasizing their role in improving grid resilience and flexibility [9]. Recent technological advancements, including advanced metering infrastructure, smart inverters, and energy storage systems, have been pivotal in the development of VPPs and virtual microgrids [10]. Case studies from various regions have demonstrated the practical benefits and challenges of implementing these systems [11]. The rapid growth of PMGD in Chile and similar markets necessitates innovative solutions to maintain grid quality standards [12]. Traditional grid management approaches are insufficient to cope with the dynamic nature of DER, particularly in regions with high renewable energy penetration. Hence, the motivation for this study stems from the need to develop rapidly deployable, scalable, and efficient solutions that can address these challenges. The proposed virtual microgrid concept builds on recent advancements in VPP technology, offering a targeted approach to mitigating power quality issues caused by PMGD.

1.1. Overall Context and Description of the Main Grid issues

ENEL Distribución Chile S.A is the most important electricity distributing company in the country, which represents 48% of the total energy sold by distribution companies in the country, supplying more than 2 million customers. Therefore, modern and innovative solutions that ensure a safe, efficient, reliable and resilient service have a great impact on the Chilean energy market. It is in this context that the company proposes to carry out a technical and economic prefeasibility study for the installation of swiftly configurable and deployable virtual microgrids in

zones located in the outskirts of Santiago that sometimes present service quality issues like Colina and Lampa. At present, one of the main issues affecting service quality standards of electric companies like ENEL Chile and others is the rise of PMGDs, which operate in certain areas of the country. These PMGDs inject all their production to the grid, provided that the grid is active, and are paid approximately 70% of the standard price per kilowatt since they don't have the power transmission costs that the distribution companies do, as allowed by the current electric law (Decree N°88/2019 of Ministry of Energy and Technical Norm for Connection & Operation of PMGD (NTCO 2019)).

Virtual microgrids are an ensemble of distributed energy resources (DER) and/or microgrid networks that have agreed to operate on a common basis and provide a platform to keep power on and critical assets like healthcare services, water and power supply operating over prolonged periods of time when faced with blackouts. A microgrid, as defined by the U.S. Department of Energy, is “a group of interconnected loads and distributed energy resources (DER) within clearly defined electrical boundaries that act as a single controllable entity with respect to the grid”. A microgrid can connect and disconnect from the grid, enabling it to operate in both grid-connected or islanded mode. In that context, this project presents a new distributed generation model that incorporates intelligent control based on energy homeostasis for power and energy management applied to distributed generation systems such as on-grid microgrids and grid-connected microgrids [13]. It is expected that through the diagnostic system and the application of the digital twin and the smart meta-tool, a micro-grid will be configured in the area of interest, drawing the virtual boundaries of the micro-grid. The role of the intelligent meta-tool will be to configure the microgrid in the intervention area, and once configured, it will proceed to its execution and simulation to achieve optimal results of operation and quality of service. In this way, the intelligent system, through the homeostatic control of energy, using artificial intelligence resources, will make decisions in real time regarding the power and energy consumption of the industrial consumer systems connected to the micro grid. ENEL Distribución wishes to improve the quality and continuity of electric service supply to its customers connected to a medium voltage feeder, located north of the city of Santiago; given the fact that, during peak demand hours, the feeder that connects industrial loads with the network, becomes congested, causing considerable voltage- frequency variations. In addition, disturbances in the voltage activate the protection relays, interrupting service repeatedly, leaving its customers without electric supply. To solve this issue, there arises the possibility of developing a diagnostics method that can determine the requirements and correct implementation of a grid-tied microgrid with energy storage systems, which would be mainly composed of diverse small and medium size renewable and non-renewable energy sources, isolating the feeder during the day, satisfying its demand most of the time with the microgrid's supply and the rest of the time with the grid's supply.

2. The Virtual Microgrid Model

2.1. *The Virtual Microgrid Model: Digitization and Innovations in the Power Distribution Grid.*

Grid digitization and innovations in power distribution can help to improve the implementation and management of microgrids is also a major concern of electric companies like ENEL, considering that these technologies can be scaled up and adapted to different urban and rural environments to address different scenarios. Grid digitization and innovations in power distribution play a crucial role in enhancing the implementation and management of microgrids, with such technologies as IoT and sensor integration. Internet of Things (IoT) devices and sensors can be deployed to monitor equipment health, detect faults, and improve overall grid reliability [13]. This real-time data helps in predictive maintenance, reducing downtime and enhancing the overall performance of the microgrid. Likewise, advanced data analytics and artificial intelligence (AI) can be employed to analyze vast amounts of data, optimizing microgrid performance, predicting energy demand, and improving decision-making. AI algorithms can also help in predicting and mitigating potential issues, enhancing the resilience of microgrid systems [13]. Virtual microgrids are localized energy systems operating in conjunction with the main power grid and are ready to assist it in case there's need for intervention. The above solution opens the possibility of using energy resources in ways that haven't been used before, developing new technologies and new services, based on a strategy focused on grid digitalization, electric power distribution innovation and energy sustainability. It is necessary to satisfy the needs of the customers while advancing in its distributed generation and diversification objectives as well as its digital grid agenda. These areas of action represent important business opportunities, developing innovative products and specific digital solutions for

people, companies and cities. In general, micro grids can offer a decentralized and flexible approach to energy distribution, providing solutions to challenges associated with load and demand management in traditional power distribution systems. They enhance resilience, enable efficient integration of renewable energy, and contribute to overall grid stability.

Ancillary services are additional services beyond the basic supply of electricity that help maintain the balance of supply and demand, manage grid voltage and frequency, and ensure the overall reliability of the power system. Some of this services that micro grids can offer are: frequency regulation, where microgrids can adjust their power output quickly in response to frequency fluctuations in the main grid. Voltage support can also be provided by virtual microgrids to help stabilize grid voltage by injecting or absorbing reactive power as needed. This support enhances the overall voltage profile of the grid and minimizes voltage fluctuations. Load following is also provided by microgrids in response to changes in overall system demand by adjusting their power output accordingly. It helps to balance supply and demand in real-time, contributing to grid stability. Peak shaving is also a function of microgrids. They can help reduce electricity consumption during peak demand periods, helping to alleviate stress on the grid's supply during high load times. This can be achieved through energy storage systems and demand response strategies. Likewise, in the event of a grid-wide blackout or disruption, microgrids with energy storage and backup generation capabilities can serve as black start resources. They can independently restart and restore power to critical infrastructure, facilitating the recovery of the entire grid. They can disconnect from the main grid, continue supplying power locally, and then seamlessly reconnect once the main grid is restored. Additionally, microgrids can provide voltage and reactive power control to maintain a stable grid. This is especially important for addressing voltage sags and swells that can occur due to changes in load or intermittent renewable energy generation. Finally, microgrids can provide grid balancing with renewable energy. They can assist in balancing the variability of renewable generation, and with the support of advanced control systems, they can also help to optimize the integration of intermittent sources into the grid.

2.2. Mapping the Virtual Microgrid Solution onto the Grid.

An initial sustainable smart microgrid is identified for four sites (properties, houses, companies, others). Figure 1 shows the virtual microgrid consisting of 4 virtual microgrid subsystems (each associated with a site or property). Other configurations of microgrids are being explored with ENEL, according to real conditions of critical substations according to already defined indicators. The inputs to the micro grid are Renewable energy sources and communications network. The Subsystems that internally comprise the virtual micro grid are shown in Figure 2:

- Energy storage systems.
- Bidirectional communication system (internal in each site or property, between sites or premises, customers-network between the micro grid and the communications network, directly or through the twisted pair of energy).

2.3. Distributed Generation System

An important contribution of distributed generation systems, like the micro grid, to electric power distribution networks is the possibility to provide ancillary services such as maintaining load – generation balance through frequency control, maintaining voltage levels providing reactive power support, and always maintaining generation and distribution reserves. Traditionally, ancillary services were provided by the power distribution networks themselves, but with the possibility of having PMGDs and micro grids operating in tandem with the grid, where customers and independent actors may also be energy producers; these may be provided by both the electric power distribution company and the micro grid owners. When operating connected to the grid, micro grids can provide major ancillary services that can help the power system ensure the power supply and the quality and reliability of service, such as frequency regulation. This service is based on active power control which can be done by controlling the output of the various distributed energy resources that the micro grid employs. Adjusting generation to load demand continuously to maintain specified system frequency within the control limits, is known as frequency regulation, which is most important to maintain service quality. This service can be provided efficiently by micro grids, whose distributed energy sources are connected to the grid and, at the same time, located close to the loads. This also allows

for on-line generation equipment to track customer load variations and to control the load as required throughout the day [13].

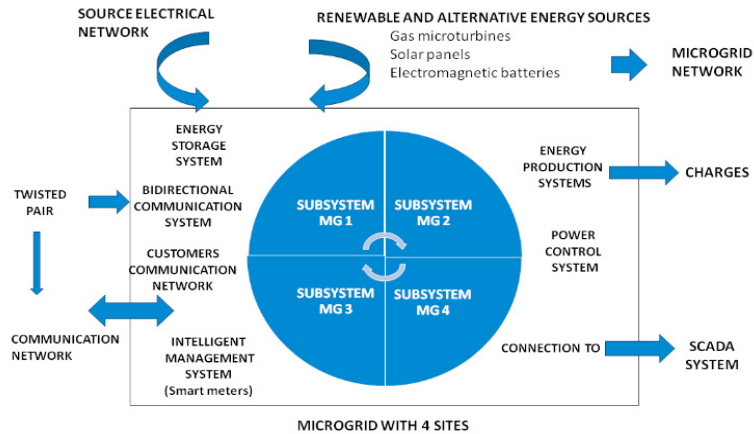


Fig.1. Model of a sustainable smart microgrid.

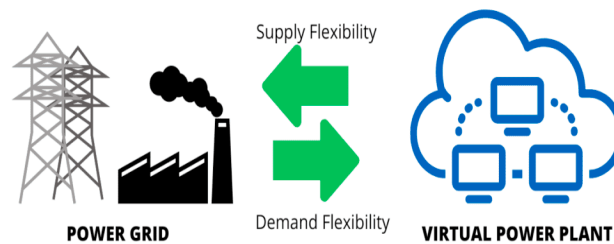


Fig. 2. Virtual microgrid (virtual power plant) helps to create a nimbler and more stable, secure power grid.

Another important benefit is voltage control, along with congestion management and grid losses' optimization can all be aided by ancillary services. Grid loss optimization and voltage control can be done by controlling the reactive power which not only depends on the control capability of the grid-coupling technology but also on the active power control capability of the distributed energy resources being operated by the microgrid. Hence, microgrids can perform smooth voltage regulation locally in response to specific controller settings. Moreover, local supply of real and reactive power from distributed energy resources that are part of the microgrid can significantly reduce grid losses and is useful for congestion reduction. Microgrids can provide three distinct ancillary services. These are frequency responsive spinning reserve, supplemental reserve and backup supply in an open competitive market. These services are aimed at restoring the real-time energy balance between generators and loads in case any sudden issues were to occur, such as power outage due to weather phenomena like strong wind or heavy rain [13].

3. The mathematical modeling of the PMGD problem and the role of the microgrid-on grid.

As we saw earlier, small means of distributed generation (PMGD) are installed in some rural areas of Chile. They are independent solar farms that inject all of their production to the electric power distribution network for a profit as allowed by current Chilean electric law. However, such injection of electric power into the grid negatively affects the service quality of the electrical energy supply of electric utilities like ENEL that see their service quality indicators being impacted by frequency distortions that affect voltage and electric supply service stability. The following model describes the mathematical equations that represent these distortions caused by PMGD, when injecting their electrical energy production to the grid. Modeling the impact of small-scale distributed generation, such as PMGD in Chile, on the electrical grid involves understanding the frequency distortions caused by these renewable energy sources. The

integration of intermittent sources like solar power can lead to fluctuations in the grid frequency, affecting voltage and overall system stability. One common way to represent these effects is through a simplified mathematical model.

3.1. Description of the Mathematical Model Equations

Let $f(t)$ be the grid frequency (in Hertz) at time t , $P_{PMGD}(t)$ be the power injected by PMGD at time t , $K_{PMGD}(t)$ be a distortion function representing the detrimental impact of PMGD on the grid frequency as a function of time. Then, the rate of change of grid frequency can be expressed as:

$$\frac{df(t)}{dt} = -K_{PMGD}(t) \cdot P_{PMGD}(t) \quad (1)$$

This equation suggests that the change in grid frequency is proportional to the power injected by PMGD, with $K_{PMGD}(t)$ representing the proportionality function. K_{PMGD} is a function of time because, solar irradiation is not fixed but varies throughout the day, as the sun is changing its position with respect to earth, and thus photovoltaic generation is variable as well. Indeed, the power output from solar photovoltaic (PV) systems, such as those of PMGD is indeed variable and depends on factors such as sunlight intensity, angle, weather conditions, and time of day. Therefore, to account for the variable nature of solar power generation, we include in the equation a time-varying coefficient or factor that reflects the changing conditions of the solar PV system. One way to model this is to introduce a time-dependent function, denoted as $K_{PMGD}(t)$, representing the time-varying impact of PMGD on grid frequency: In this formulation, $K_{PMGD}(t)$ would capture the time-varying nature of the impact of PMGD on the grid frequency. This could be determined based on real-time measurements, historical data, or sophisticated control strategies that take into account the changing conditions of the solar resource. It's important to note however that accurately modeling the impact of variable renewable energy sources like solar PV on the grid is a complex task and may require advanced control and forecasting techniques, which we will obtain with the digitization of the power distribution grid. Nevertheless, incorporating a time-varying coefficient provides a more realistic representation than assuming a constant K_{PMGD} in scenarios where the power production from PMGD sources varies over time. In this model:

$K_{PMGD} > 0$ indicates that the presence of PMGD tends to decrease the grid frequency when injecting power, impacting stability negatively.

$K_{PMGD} < 0$ indicates that the presence of PMGD tends to increase the grid frequency when absorbing power, impacting stability negatively.

3.2. The Implementation of the Digital Solution known as a Virtual Microgrid

This study envisions the implementation of a digital solution known as a virtual microgrid, rather than a physical micro grid, to address the power quality and stability issues caused by PMGD installations. A virtual microgrid operates in the digital domain, utilizing advanced control and optimization algorithms to manage distributed energy resources (DERs) within a specific area of the grid. The proposed solution, in the form of a virtual micro grid is to work in the context of addressing frequency disturbances caused by PMGD and must consider digital control and optimization to coordinate the operation of DERs, such as solar panels, energy storage systems, and demand response resources, within the affected area of the distribution network. These algorithms ensure that energy flows are balanced and controlled to mitigate frequency disturbances. Then, a dynamic resource allocation allows resources based on real-time grid conditions and demand patterns. By intelligently deploying and dispatching DERs, ENEL Distribución can rapidly stabilize frequency and improve power quality within the affected area without the need for physical infrastructure upgrades. Grid support functions used by the virtual micro grid can provide including frequency regulation, voltage control, and reactive power compensation, to enhance the stability and reliability of the distribution network. Hence, by leveraging the capabilities of micro grids on-grid ENEL Distribución can actively manage grid conditions and respond to fluctuations caused by PMGD installations. A Real-time monitoring and analysis are also key services that the virtual microgrid can perform as it is equipped with real-time monitoring and analysis capabilities.

This proactive approach enables timely intervention and resolution of power quality and stability issues. Finally, the virtual microgrids can be designed and developed to extend their coverage to additional areas of the distribution network as needed scalability and adaptability accommodating the growth of PMGD installations over time.

3.3. Intervention of a Virtual Microgrid (virtual power plant) to solve the Power Quality and Stability issues caused by PMGD.

In order to represent the intervention of a virtual microgrid (virtual power plant) to address power quality and stability issues caused by PMGD installations, we can consider a set of equations that describe the dynamics of the distribution network and the control actions taken by the virtual microgrid. Here are some key equations and concepts.

Power Flow Equations: which describe the flow of active (P) and reactive (Q) power through the distribution network, and also determine the voltage magnitude and phase angles at each node in the grid based on the power injections, line impedances, and network topology.

$$P_i = \sum_{j=1}^N V_i V_j [G_{ij} \cos(\theta_i - \theta_j) + B_{ij} \sin(\theta_i - \theta_j)] \quad (2)$$

$$Q_i = \sum_{j=1}^N V_i V_j [G_{ij} \sin(\theta_i - \theta_j) - B_{ij} \cos(\theta_i - \theta_j)] \quad (3)$$

Where P_i and Q_i are the active and reactive power injections at node i . V_i and θ_i are the voltage magnitude and phase angle at node i . G_{ij} and B_{ij} are the real and imaginary parts of the admittance between nodes i and j , respectively, and N is the total number of nodes in the network. With regards to voltage regulation, the virtual microgrid can regulate voltage levels within the affected area of the grid by controlling the reactive power output of DERs such as energy storage systems or capacitor banks. This can be represented by control algorithms adjusting reactive power injections based on voltage setpoints and feedback signals:

$$Q_{ctrl} = f(V_{measured}, V_{setpoint}), \quad (4)$$

where Q_{ctrl} is the reactive power output commanded by the control algorithm, $V_{measured}$ is the measured voltage magnitude at the point of regulation, and $V_{setpoint}$ is the desired voltage setpoint.

Frequency Regulation: The virtual microgrid can also contribute to frequency regulation by adjusting the active power output of controllable DERs such as energy storage systems or dispatchable loads. This can be represented by control algorithms that modulate the active power injections in response to frequency deviations from the nominal value:

$$P_{ctrl} = f(\omega_{measured}, \omega_{nominal}) \quad (5)$$

where P_{ctrl} is the active power output commanded by the control algorithm, $\omega_{measured}$ is the measured frequency deviation from the nominal value, and $\omega_{nominal}$ is the nominal frequency of the grid.

Dynamic Stability Analysis: dynamic stability analysis equations can assess the stability of the grid in response to disturbances such as changes in power generation or load. These equations typically involve the modeling of fast dispatching energy resources like synchronous generators, loads, and control systems to analyze the transient and dynamic behavior of the grid under different operating conditions:

$$\frac{d\delta}{dt} = \omega - \omega_s, \quad (6)$$

Here we have that δ is the rotor angle of the synchronous generator, ω is the angular velocity of the rotor, ω_s is the synchronous speed of the generator, and $d\delta/dt$ is the rate of change of the rotor angle. The equations shown help illustrate the model and provide a framework for representing the intervention of a virtual microgrid on grid to address power quality and stability issues caused by PMGD installations. The control actions taken by the virtual microgrid can be formulated based on these equations to achieve the desired objectives of voltage and frequency regulation within the distribution network.

4. Conclusions

Virtual microgrids can very well operate in the electric power distribution market as they can rapidly discharge power into the grid or charge power from the grid, as the case may be. Large batteries are usually the main resource although steadfastly-dispatchable resources are also required. In some cases, these batteries within these types of arrangements will not be able to discharge below a certain level as they need to have sufficient power on stand-by to meet grid's requirements. Overall, the versatile capabilities of virtual microgrids make them invaluable components of modern power systems, offering benefits in terms of efficiency, reliability, and resilience, especially in regions prone to natural disasters or harsh weather conditions. Leveraging rapidly configurable, scalable, and deployable distributed energy resources (DER) like the virtual microgrid can further grid's flexibility, reliability, stability and they are also essential to maintain the integrity of the electric supply service's standards. Their ability to provide fast, reliable and flexible solutions makes them essential components for meeting the evolving needs of both urban and rural communities, especially in regions where traditional grid expansion may be cost-prohibitive. In this regard, implementing a new approach for rapidly diagnosing service quality problems affecting the grid in a particular location, especially in areas with a high concentration of PMGD, can involve advanced monitoring and analysis through AI analytics, and the swift integration of configurable and scalable Distributed Energy Resources (DER) like the virtual microgrids whenever these are needed.

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