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TRABAJO FIN DE GRADO

TEMPORAL VARIABILITY OF SENSITIVITY COEFFICIENTS IN EMERGING LOCAL ELECTRICITY MARKETS

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Co-Director: Marco Galici

Madrid, July 2025

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Temporal Variability of Sensitivity Coefficients in Emerging Local Electricity Markets

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VARIABILIDAD TEMPORAL DE LOS COEFICIENTES DE SENSIBILIDAD EN LOS MERCADOS LOCALES DE ELECTRICIDAD EMERGENTES

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VARIABILIDAD TEMPORAL DE LOS COEFICIENTES DE SENSIBILIDAD EN LOS MERCADOS LOCALES DE ELECTRICIDAD EMERGENTES.

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RESUMEN DEL PROYECTO

Este estudio evalúa la variabilidad espacial y temporal de los coeficientes de sensibilidad en redes de distribución activas. El análisis revela cómo la topología y la penetración fotovoltaica influyen en los flujos bidireccionales y en las necesidades críticas de flexibilidad. Los resultados respaldan estrategias adaptativas para los mercados locales de flexibilidad

Palabras clave: coeficientes de sensibilidad, mercados locales de flexibilidad, flexibilidad, redes de distribución.

1. Introducción

La integración masiva de recursos energéticos distribuidos, en particular la generación fotovoltaica, está redefiniendo las redes de distribución, transformándolas de infraestructuras pasivas en sistemas altamente dinámicos. Esta transición plantea importantes desafíos operativos, como la gestión de la congestión y la estabilidad de tensión, derivados de la variabilidad y la naturaleza bidireccional de los flujos de potencia. Los coeficientes de sensibilidad, que cuantifican la influencia de las perturbaciones de potencia activa y reactiva sobre las variables de la red, han emergido como indicadores fundamentales para evaluar la flexibilidad de la red y apoyar las estrategias operativas.

A pesar de su potencial, la dinámica espaciotemporal de los coeficientes de sensibilidad en redes de distribución activas sigue estando insuficientemente explorada. Abordar esta laguna de conocimiento es esencial para desarrollar mecanismos avanzados de flexibilidad y posibilitar la implementación de mercados locales de flexibilidad alineados con las necesidades evolutivas de los sistemas eléctricos modernos [1].

2. Metodología

Este estudio presenta un marco metodológico diseñado para analizar la variabilidad espacial y temporal de los coeficientes de sensibilidad en redes de distribución activas. El enfoque combina simulaciones horarias de flujo de carga con análisis estadísticos para caracterizar los coeficientes de congestión activos (CMdSdP) y reactivos (CMdSdQ), así como indicadores de sensibilidad de tensión (VMP y VMQ).

El análisis se llevó a cabo en tres configuraciones de red representativas. El Escenario A corresponde a una topología radial con generación fotovoltaica en seis nodos, mientras que el Escenario B amplía la configuración radial para incluir generación fotovoltaica distribuida en todos los nodos. Por su parte, el Escenario C representa una topología ramificada con generación fotovoltaica presente en todos los nodos.

3. Resultados

3.1 Análisis espacial

Los resultados del análisis espacial revelan que la topología de la red y la distribución de la generación fotovoltaica moldean significativamente los patrones de sensibilidad. En el **Escenario A,** caracterizado por una estructura radial y una implantación limitada de fotovoltaica, los flujos de potencia permanecen consistentemente unidireccionales durante todo el año. La sensibilidad a la congestión se concentra en las áreas periféricas, especialmente en los puntos eléctricamente más alejados del transformador principal y que carecen de generación local. Estas zonas presentan valores elevados de coeficientes de sensibilidad, lo que indica su potencial como objetivos para intervenciones de flexibilidad centralizadas dirigidas a mitigar caídas de tensión y sobrecargas en las líneas.

En el **Escenario B**, la generación fotovoltaica distribuida en todos los nodos convierte la red en un sistema plenamente activo, con flujos de potencia bidireccionales durante gran parte del día. La Figura 1 muestra los boxplots de CMdSdP, donde el eje X representa las líneas de la red (Line_x_y) y el eje Y los coeficientes de sensibilidad, que cuantifican el impacto de perturbaciones en la demanda sobre la corriente de cada línea.

Los colores distinguen los distintos nodos de carga, y las barras reflejan la variabilidad de los coeficientes a lo largo del año. La dispersión y los valores tanto positivos como negativos evidencian la naturaleza bidireccional de los flujos y la aparición dinámica de áreas críticas, lo que subraya la necesidad de estrategias de flexibilidad adaptativas [2].

El **Escenario C** presenta un comportamiento diferente debido a su topología ramificada y a la generación distribuida. La red exhibe una distribución más equilibrada de los flujos de potencia, lo que atenúa los picos de sensibilidad espacial y reduce los riesgos de congestión. La homogeneidad de los coeficientes de sensibilidad a lo largo de la red sugiere que los enfoques de flexibilidad basados en zonas pueden ser más efectivos que las intervenciones altamente localizadas en este tipo de sistemas.

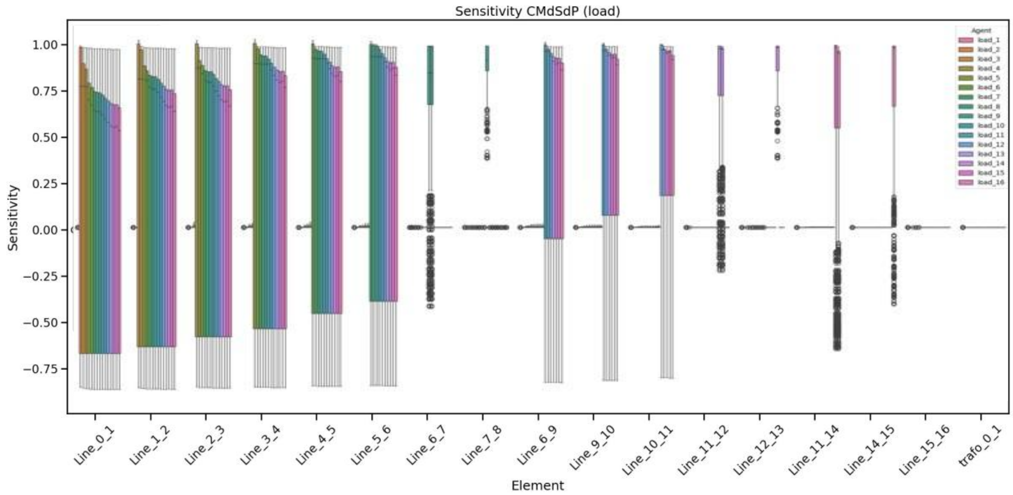

Figure 1.Boxplots de CMdSdP en el Escenario B que ilustran los flujos bidireccionales de potencia y la variabilidad espacial.

3.2 Análisis temporal

El análisis temporal pone de relieve cómo los patrones de sensibilidad evolucionan a lo largo del día. En el **Escenario A**, la variabilidad es limitada, con coeficientes de sensibilidad relativamente constantes que reflejan la operación estable de una red con flujos unidireccionales y penetración moderada de fotovoltaica. En cambio, el **Escenario B** presenta una dinámica temporal mucho más pronunciada. La evolución horaria de CMdSdP (Figura 2) identifica dos ventanas operativas críticas: las horas centrales del día, donde los flujos inversos causados por los excedentes de fotovoltaica modifican los patrones de congestión, y los picos de demanda vespertinos, en los que la reducción de la generación fotovoltaica incrementa la susceptibilidad de la red a las perturbaciones de carga. Estas fluctuaciones subrayan la importancia de desplegar recursos de flexibilidad de forma sensible al tiempo. El **Escenario C** muestra una variabilidad temporal más moderada. Aunque las horas centrales del día aún presentan flujos inversos que alteran ligeramente la sensibilidad, la topología ramificada y la generación fotovoltaica distribuida suavizan las fluctuaciones en comparación con la red radial plenamente activa.

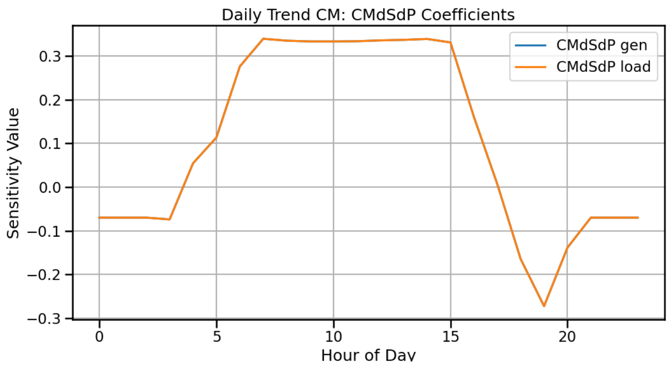

Figure 2. Curva diaria de CMdSdP en el Escenario B que identifica ventanas temporales críticas para el despliegue de flexibilidad.

El análisis combinado espacial y temporal confirma que los coeficientes de sensibilidad no son estáticos ni uniformes. Su variabilidad depende en gran medida de la interacción entre la estructura de la red, la distribución de la generación renovable y los patrones diarios de carga. Estos hallazgos tienen implicaciones directas para los mecanismos de flexibilidad operativa y basados en el mercado. Identificar áreas críticas permite priorizar los recursos donde tendrán el mayor impacto técnico, mientras que la detección de ventanas temporales críticas respalda el diseño de productos de flexibilidad dinámicos y adaptativos. Además, reconocer la influencia de la topología de la red sugiere diferentes paradigmas operativos: intervenciones altamente localizadas en sistemas radiales frente a una coordinación basada en zonas en configuraciones ramificadas.

4. Conclusiones

Este trabajo presenta un marco robusto para evaluar la variabilidad de los coeficientes de sensibilidad en redes de distribución activas y demuestra su papel crítico en el apoyo a estrategias avanzadas de flexibilidad tanto operativas como basadas en el mercado. Al integrar las perspectivas espacial y temporal, la metodología propuesta permite a los operadores de red y agregadores diseñar intervenciones que aborden proactivamente los desafíos de congestión y estabilidad de tensión.

Los conocimientos adquiridos permiten comprender mejor las sensibilidades en los mercados locales de flexibilidad, abriendo el camino hacia estrategias dinámicas y basadas en datos que alineen la activación de la flexibilidad con las necesidades en tiempo real de los sistemas eléctricos modernos y descentralizados. Estas contribuciones destacan la importancia del análisis de sensibilidad como piedra angular para la gestión eficaz de las redes activas. A medida que los sistemas de distribución continúan evolucionando, incorporando mayores niveles de energías renovables y complejidad operativa, la integración de enfoques basados en los coeficientes de sensibilidad será esencial para garantizar operaciones de red seguras, eficientes y sostenibles [3].

5. Referencias

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TEMPORAL VARIABILITY OF SENSITIVITY COEFFICIENTS IN EMERGING LOCAL ELECTRICITY MARKETS

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ABSTRACT

This study evaluates the spatial and temporal variability of sensitivity coefficients in active distribution networks. The analysis reveals how topology and PV penetration influence bidirectional flows and critical flexibility needs. The results support adaptive strategies for local flexibility markets.

Keywords: Sensitivity Coefficients (SCs), Local Flexibility Markets (LFMs), flexibility, distribution networks.

1. Introduction

The widespread integration of distributed energy resources (DERs), particularly photovoltaic (PV) generation, is redefining distribution networks, transforming them from passive infrastructures into highly dynamic systems. This transition introduces significant operational challenges, including congestion management and voltage stability, driven by the variability and bidirectional nature of power flows. Sensitivity coefficients, which quantify the influence of active and reactive power perturbations on network variables, have emerged as critical indicators for assessing grid flexibility and informing operational strategies.

Despite their potential, the spatio-temporal dynamics of SCs in active distribution systems remain insufficiently explored. Addressing this knowledge gap is essential for developing advanced flexibility mechanisms and enabling the deployment of local flexibility markets aligned with the evolving needs of modern power systems [4].

2. Methodology

This study introduces a methodological framework designed to analyse the locational and temporal variability of SCs in active distribution networks. The proposed approach combines hourly load flow simulations with statistical analyses to characterise active (CMdSdP) and reactive (CMdSdQ) congestion coefficients, as well as voltage sensitivity indicators (VMP and VMQ).

The analysis was conducted across three representative network configurations. Scenario A corresponds to a radial topology with PV generation at six nodes, while Scenario B extends the radial configuration to include PV generation distributed across all nodes. Scenario C, in contrast, represents a branched topology with PV generation present at all nodes.

3. Results

3.1 Locational Analysis

The results of the locational analysis reveal that network topology and the distribution of PV generation significantly shape sensitivity patterns. In **Scenario A**, characterized by a radial structure and limited PV deployment, power flows remain consistently unidirectional throughout the year. Congestion sensitivity is concentrated in peripheral areas, particularly in electrically remote locations lacking local generation. These regions exhibit elevated SC values, indicating their potential as targets for centralized flexibility interventions aimed at mitigating voltage drops and alleviating line overloads.

In **Scenario B**, the distributed photovoltaic generation at all nodes transforms the network into a fully active system, with bidirectional power flows dominating throughout key periods of the day. Figure 3 presents the CMdSdP boxplots, where the X-axis represents the network lines (*Line_x_y*) and the Y-axis shows the sensitivity coefficients, which quantify the impact of demand perturbations on the current in each line.

The colours distinguish the different load nodes, and the bars reflect the variability of the coefficients over the year. The dispersion and presence of both positive and negative values highlight the bidirectional nature of power flows and the dynamic emergence of critical areas, underscoring the need for adaptive flexibility strategies [5].

Scenario C presents a different behavior, owing to its branched topology and distributed generation. The network exhibits a more balanced distribution of power flows, which attenuates spatial sensitivity peaks and reduces congestion risks. The homogeneity of SCs across the network suggests that zone-based flexibility approaches may be more effective than highly localized interventions in this type of system.

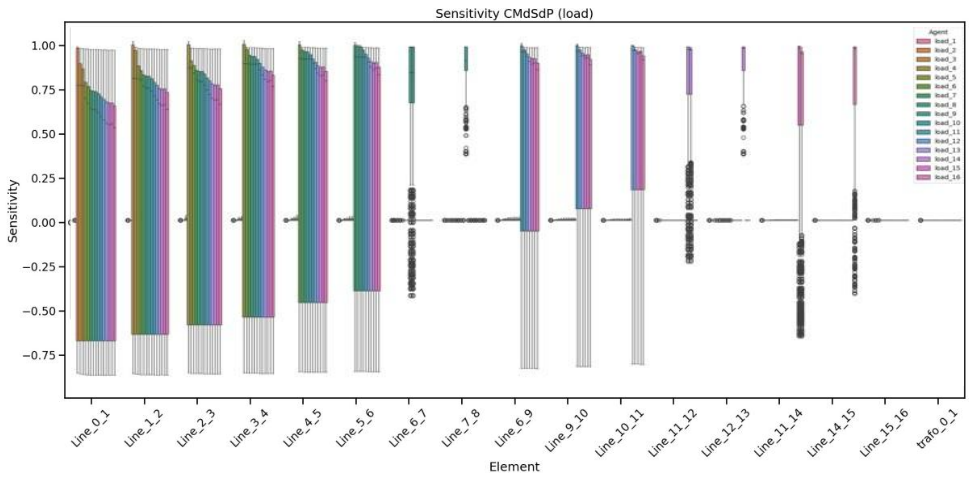

Figure 3. Boxplots of CMdSdP in Scenario B illustrating bidirectional power flows and spatial variability

3.2 Temporal Analysis

Temporal analysis further highlights how sensitivity patterns evolve throughout the day. In **Scenario A**, variability is limited, with SCs remaining relatively constant, reflecting the stable operation of a network with unidirectional flows and moderate PV penetration. **Scenario B**, however, exhibits pronounced temporal dynamics. The hourly evolution of CMdSdP (Figure 4) identifies two critical operational windows: midday hours, where reverse flows caused by PV surpluses modify congestion patterns, and evening demand peaks, where reduced PV output increases the network's susceptibility to load perturbations. These fluctuations emphasize the importance of deploying flexibility resources in a time-sensitive manner. **Scenario C** displays a more moderate temporal variability. Although midday hours still show flow reversals that slightly alter sensitivity, the branched topology and distributed PV generation smoothen fluctuations compared to the fully active radial network.

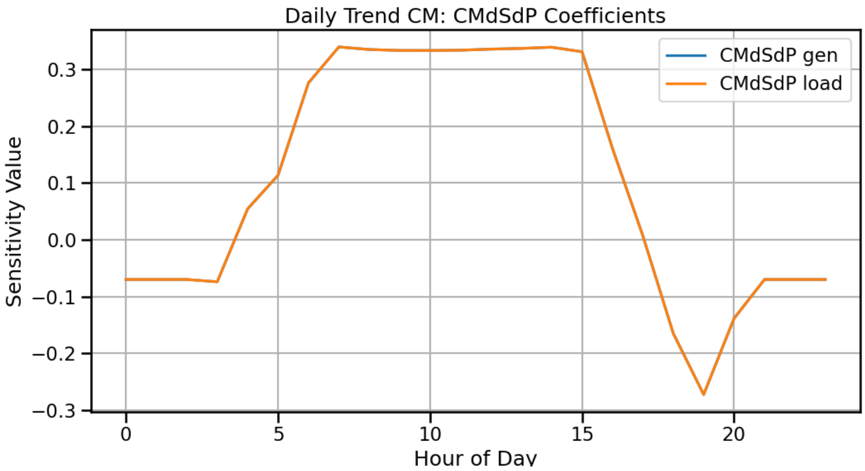

Figure 4. Daily trend of CMdSdP in Scenario B identifying critical time windows for flexibility deployment

The combined locational and temporal analyses confirm that SCs are neither static nor uniform. Their variability depends strongly on the interplay between network structure, renewable generation distribution, and daily load patterns. These findings have direct implications for operational and market-based flexibility mechanisms. Identifying spatial hotspots enables the prioritization of resources where they will have the highest technical impact, while detecting critical time windows supports the design of dynamic, adaptive flexibility products. Furthermore, recognizing the influence of network topology suggests distinct operational paradigms: highly localized interventions in radial systems versus zone-based coordination in branched configurations.

4. Conclusion

This work provides a robust framework for assessing SC variability in active distribution networks and demonstrates their critical role in supporting advanced operational and market-based flexibility strategies. By integrating locational and temporal perspectives, the proposed methodology enables network operators and aggregators to design interventions that proactively address congestion and voltage stability challenges. The insights gained bridge the gap between technical analysis and practical implementation in LFMs, paving the way for dynamic, data-driven strategies that align flexibility activation with the real-time needs of modern, decentralised power systems.

These contributions highlight the importance of sensitivity analysis as a cornerstone for the effective management of active networks. As distribution systems continue to evolve, incorporating higher levels of renewable energy and increased complexity, the integration of SC-based approaches will be essential to ensure secure, efficient, and sustainable grid operations [3].

5. References

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Chapter 1. INTRODUCTION

The energy transition is radically transforming power systems worldwide. International commitments to mitigate climate change, such as the Paris Agreement and the United Nations 2030 Agenda, call for an accelerated decarbonization of the energy sector and the massive integration of renewable energy sources. In Europe, the Green Deal establishes climate neutrality as a target for 2050, and Spain has translated these goals into the National Integrated Energy and Climate Plan (PNIEC) 2021–2030, which anticipates that at least 74% of electricity generation by 2030 will come from renewable sources [9].

This effort is reflected in the evolution of the Spanish electricity system. According to data from *Red Eléctrica de España* (REE), by the end of 2024 renewable energies already represented 66% of installed capacity, with solar photovoltaic leading (25.1%), followed by wind (24.9%) and hydropower (14.1%) [8]. This structural change is evident in the distribution of installed capacity, as shown in Figure 5.

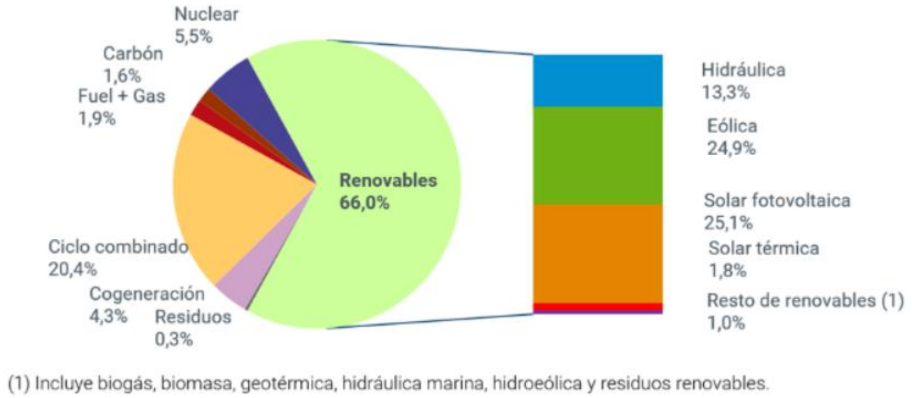

Figure 5. Structure of installed generation capacity in Spain at the end of 2024. Source: REE [8]

The continuous growth of renewable energy, especially variable technologies such as solar and wind, has profoundly modified electricity generation patterns. Figure 6 illustrates the annual evolution of renewable and non-renewable generation in Spain, highlighting the progressive decline of fossil fuel sources and the increasing contribution of distributed energy resources (DER).

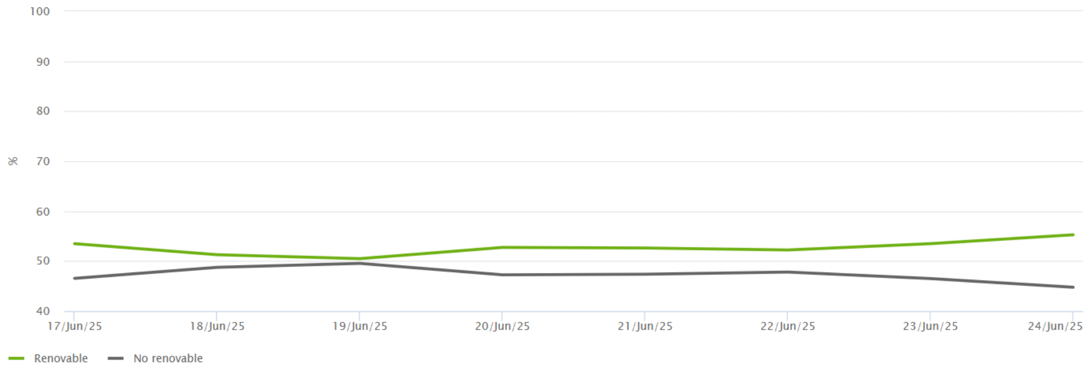

Figure 6. Annual evolution of renewable and non-renewable generation in Spain. Source: REE [7]

1.1 THE CHALLENGE OF ACTIVE NETWORKS

The massive deployment of distributed generation has turned distribution networks, traditionally passive, into active systems with bidirectional power flows [10]. This new paradigm brings technical challenges such as:

- Greater volatility and difficulty in predicting power flows.
- The emergence of local congestions and power quality issues.
- The need to dynamically manage flexibility in demand and generation.

In this context, Distribution System Operators (DSOs) must evolve towards more dynamic roles, managing the integration of distributed resources and ensuring a constant balance between generation and demand to maintain the stability and efficiency of the network.

Local Flexibility Markets (LFMs) emerge as a key tool enabling DER to provide services such as congestion management and voltage regulation [15]. However, the effectiveness of these markets depends on having accurate information about how each resource impacts the network.

1.2 SENSITIVITY COEFFICIENTS AND THEIR IMPORTANCE

Sensitivity coefficients are parameters that quantify how a variation in active or reactive power at a given node affects critical system variables, such as voltage at other nodes or line currents. They are an essential tool for:

- Assessing the impact of flexibility resources on the network.
- Prioritizing nodes and lines in operational management.
- Designing flexibility products that are more efficient and aligned with technical needs.

Nevertheless, a common issue in most current approaches is the assumption that these coefficients are constant over time. Recent studies have shown that sensitivity coefficients can vary significantly throughout the day and year, depending on the operational state of the network, active topology, and weather conditions [15].

Operational decisions based on outdated or inaccurate values can lead to economic inefficiencies and, in some cases, result in over- or under-procurement of flexibility, leaving operational needs unresolved or creating new issues in the network.

1.3 OBJECTIVES

The main objective of this work is to analyse the temporal and locational variability of sensitivity coefficients in active distribution networks, evaluating their impact on technical operation and the design of local flexibility markets.

Specific objectives**:**

- Characterize the hourly and seasonal behaviour of congestion (CM) and voltage (VM) sensitivity coefficients in networks with high renewable penetration.

- Identify critical nodes based on their dynamic sensitivity to prioritize the activation of flexibility resources.
- Assess how the variability of coefficients affects the efficiency of operational decisions and participation in local markets.

1.4 ALIGNMENT WITH THE SDGS

This work contributes directly to the Sustainable Development Goals (SDGs) defined in the 2030 Agenda [16], proposing solutions for the efficient integration of renewable energy and advanced management of electricity networks.

In particular, it is aligned with SDG 7: Affordable and clean energy, by facilitating the incorporation of renewable resources into distribution networks through tools that optimize their technical operation. It also contributes to SDG 9: Industry, innovation and infrastructure, by developing innovative local flexibility strategies that improve the resilience of electricity infrastructure and reduce the need for physical reinforcements.

Finally, the work is linked to SDG 11: Sustainable cities and communities, by promoting the creation of smart grids capable of efficiently managing energy flows in urban and rural environments.

Chapter 2. STATE OF THE ART

2.1 ACTIVE NETWORKS AND THE NEED FOR FLEXIBILITY

The evolution of the electricity system towards a decentralized and sustainable model is driven by the increasing integration of Distributed Energy Resources (DER) such as photovoltaic generation, storage systems, and electric vehicles with bidirectional charging capabilities. This transformation is leading to a shift from traditional distribution networks, conceived as passive infrastructures with unidirectional power flows, to active networks where flows are dynamic and bidirectional [10].

In this new paradigm, Distribution System Operators (DSOs) face multiple technical challenges. The intermittency of renewable energy sources introduces high volatility in power flows, complicating real-time forecasting and balancing. Moreover, the proliferation of distributed generation can create local congestions in sections of the grid with limited capacity, as well as power quality issues, including voltage deviations and increased technical losses.

Flexibility emerges as a fundamental resource to address these challenges. According to the International Energy Agency (IEA), flexibility is defined as “the ability of a power system to modify electricity generation or consumption in response to an external signal, either technical or economic, to maintain grid balance and stability” [12]. In the context of active networks, flexibility allows managing the variability and uncertainty associated with renewable generation, optimizing network operation without systematically resorting to costly infrastructure reinforcements [15].

Flexibility can come from various sources, which are mainly grouped into three categories:

- Generation flexibility, which involves adjusting the output of conventional power plants and distributed renewable resources to meet real-time network needs.

- Demand flexibility, based on the temporal modification of electricity consumption by users through demand response programs, incentivized via price signals or contracts with operators.
- Storage flexibility, which uses technologies such as batteries to absorb or inject energy depending on the system's operational conditions.

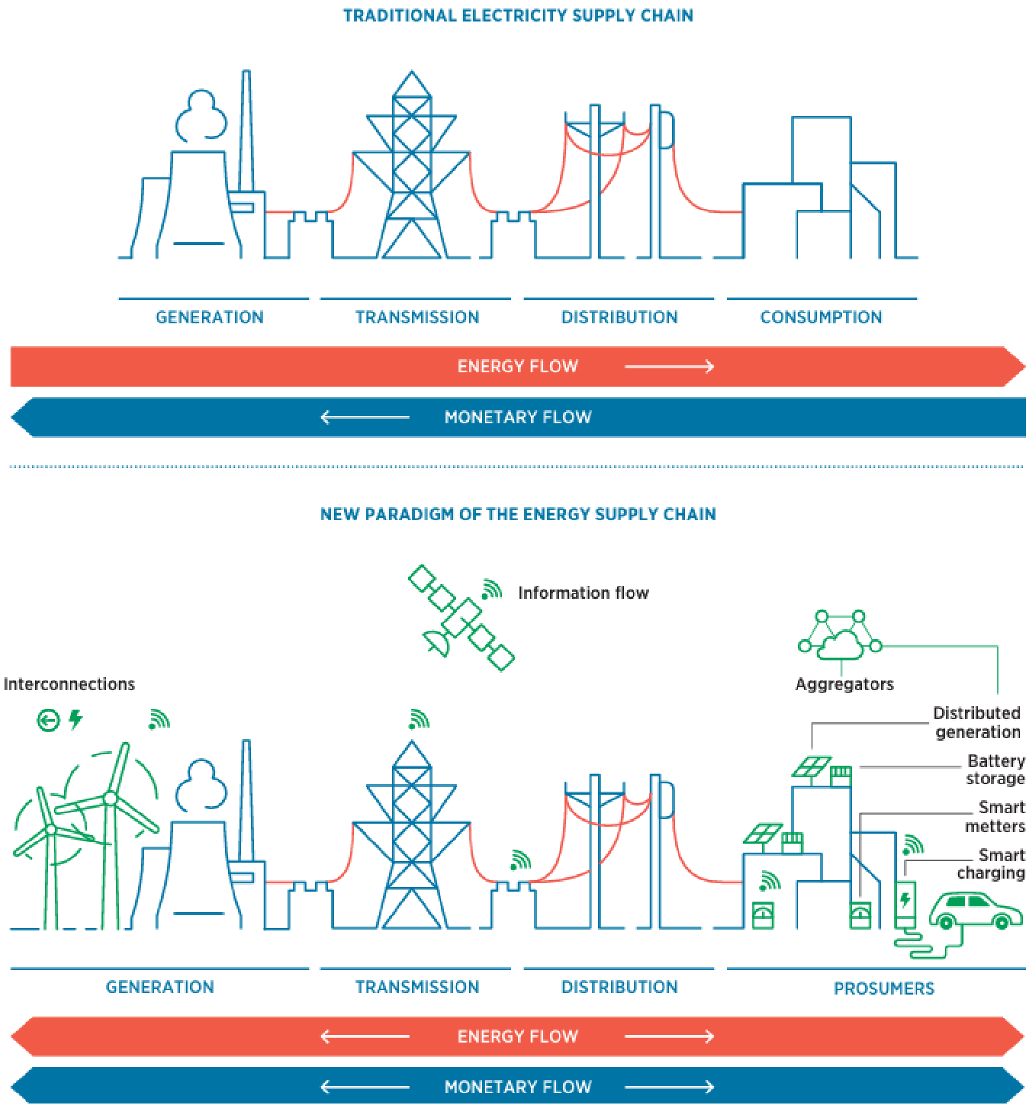

Figure 7. Conceptual diagram of an active network with distributed energy resources and bidirectional power flows. Source: IRENA [12].

The integration of these resources requires the deployment of advanced monitoring and control tools capable of providing real-time information on network status. Moreover, coordination among the various system actors, including prosumers and aggregators, is essential to maximize the potential of flexibility. In this context, Local Flexibility Markets (LFMs) emerge as an innovative mechanism to mobilize and coordinate distributed resources to resolve technical needs at the local grid level, facilitating an orderly transition towards a smarter and more resilient electricity system [14].

2.2 LOCAL FLEXIBILITY MARKETS (LFMS)

The increasing dynamism of distribution networks and the massive integration of Distributed Energy Resources (DER) have highlighted the need for new mechanisms to manage flexibility efficiently and locally. In this context, Local Flexibility Markets (LFMs) emerge as an innovative solution that enables Distribution System Operators (DSOs) to access resources within their area of influence to resolve technical issues such as congestions, voltage deviations, or power imbalances [18].

Unlike wholesale electricity markets, which operate at national or regional levels, LFMs function on smaller geographical scales and shorter time horizons [26]. Their goal is to coordinate the activation of distributed resources dynamically and efficiently, optimizing the use of the network without resorting to costly infrastructure reinforcements.

2.2.1 CONCEPT AND MOTIVATION

LFMs provide a platform where different stakeholders can offer and request flexibility to meet local operational needs. Through these markets, DSOs can identify where in the network there is a deficit or surplus of capacity and request adjustment services from participating agents. This mechanism allows technical and economic signals to be conveyed to end users, encouraging their active participation in system management.

The primary motivation behind the development of LFMs is the growing complexity of modern power grids. The intermittency of distributed renewable generation and the progressive electrification of demand (e.g., electric vehicles, heat pumps) require rapid and localized responses to maintain grid stability. LFMs facilitate this response by mobilizing flexible resources dispersed across the distribution network.

2.2.2 STAKEHOLDERS AND OPERATION

LFMs involve various agents with complementary roles:

- **Distribution System Operators (DSOs):** The main drivers of these markets, as they define the local technical needs (e.g., relieving an overloaded transformer) and validate the received offers in terms of technical feasibility.
- **Aggregators:** Combine the flexibility of multiple small resources (such as households or small businesses) and offer it in a coordinated manner, enabling the participation of individual agents who alone would not have a significant impact.
- **Prosumers:** Act as flexibility providers by modifying their generation or consumption according to market signals.
- **Transmission System Operators (TSOs):** In cases where there is interaction between the transmission and distribution networks, they collaborate with DSOs to ensure consistency between the two levels.

The typical operation of an LFM can be divided into four phases:

1. Detection of need: The DSO identifies a technical issue in the network.
2. Reception of offers: Flexibility agents submit their proposals to address the identified need.
3. Technical validation: The DSO verifies the feasibility of the received offers.
4. Activation and settlement: The selected resources are activated, and the corresponding financial transactions are managed.

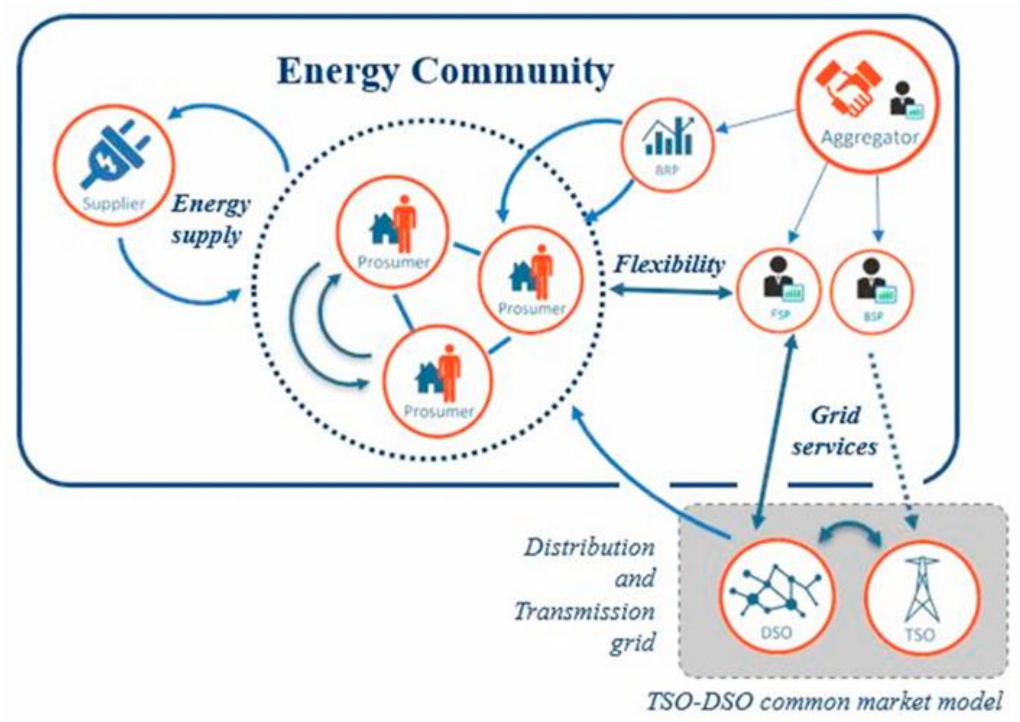

Figure 8. Diagram of the operation of a local flexibility market, showing interactions between DSOs, TSOs, aggregators, and prosumers [24].

2.2.3 RELEVANT EUROPEAN PROJECTS

Numerous projects funded by the European Commission have explored the feasibility and impact of LFMs:

- CoordiNet: Implemented in Spain, Greece, and Sweden, this project demonstrated DSO-TSO coordination to activate local flexibility for congestion management and renewable integration support [18].
- OneNet: Develops an integrated platform enabling flexibility management across Europe, creating standardized interfaces between the different system actors [20].
- INTERRFACE: Focused on developing digital tools to facilitate DER participation in flexibility markets and improve interoperability between networks [21].

These projects have demonstrated the potential of LFMs to transform active grid management but have also revealed regulatory, technological, and economic challenges that must be addressed for widespread implementation.

2.2.4 BENEFITS AND CHALLENGES

Local Flexibility Markets have proven to be an effective tool for managing the technical needs of distribution networks, facilitating renewable integration and optimizing the use of existing infrastructure. By providing a framework that mobilizes distributed resources, they allow congestion and power quality issues to be resolved in a more dynamic and localized manner.

However, their deployment presents significant challenges. On the regulatory side, it is essential to clearly define the roles of the different stakeholders and establish coordination mechanisms between DSOs and TSOs. At the technical level, advanced digital platforms and real-time monitoring systems are required to identify and activate flexibility when needed. Finally, from an economic perspective, it is crucial to ensure sustainable business models that incentivize the participation of both large aggregators and small prosumers.

2.3 SENSITIVITY COEFFICIENTS IN DISTRIBUTION NETWORKS

The growing complexity of active networks, driven by the massive integration of Distributed Energy Resources (DER), requires analytical tools that allow network operators to understand the local impact of perturbations and make more informed decisions. Among these tools, sensitivity coefficients stand out as key elements for evaluating how variations in active or reactive power at a specific node affect critical network variables, such as nodal voltage or line currents [27].

These parameters provide Distribution System Operators (DSOs) with a quantitative view of the relationship between local actions and global effects, enabling them to identify strategic points in the network where the activation of flexibility resources can be most effective [25]. This capability is essential to address technical challenges such as voltage control, congestion management, and operational planning in an environment characterized by bidirectional power flows and the inherent variability of renewable generation.

2.3.1 TYPES AND APPLICATIONS

There are different types of sensitivity coefficients, each with specific applications in network management:

- **Voltage Sensitivity Coefficients (VSC):** These coefficients relate variations in active or reactive power to voltage changes at the nodes. They are particularly useful for assessing the impact of connecting new distributed energy resources and for designing voltage regulation strategies.
- **Power Transfer Distribution Factors (PTDF):** These determine how power flows are redistributed across network lines when power injection or extraction at a specific node is modified. They are mainly applied in capacity planning and congestion management.

The use of these coefficients enables DSOs and actors in Local Flexibility Markets (LFMs) to make more precise decisions about where and when to activate flexible resources. By quantifying the technical impact of each offer, sensitivity coefficients become an essential element for prioritizing actions that provide the greatest benefit to network stability and efficiency.

2.3.2 TEMPORAL VARIABILITY AND CHALLENGES

Although traditional approaches assume that sensitivity coefficients are constant over time, recent research has shown that these parameters can experience significant variations throughout the day and the year [23]. Factors such as the intermittency of renewable generation, changes in load patterns, and topological modifications of the network directly influence the magnitude and direction of these coefficients.

This temporal variability presents a critical challenge for the operation of active networks. If operational decisions are based on average or outdated values, economic inefficiencies may arise, such as the over-procurement or under-procurement of flexibility, which in turn can leave operational needs unresolved or even create new technical issues in the network.

In this context, the need for methodologies capable of calculating and dynamically updating sensitivity coefficients becomes evident. This work addresses this limitation through a detailed analysis of their temporal and locational variability, aiming to identify critical nodes and design more precise resource activation strategies in local flexibility markets. This approach seeks to provide network operators with more accurate information for real-time decision-making, aligning with the current challenges of the energy transition.

2.4 DATA MINING AND ANALYTICAL TECHNIQUES FOR SENSITIVITY COEFFICIENTS EVALUATION

The increasing complexity of active distribution networks, characterized by bidirectional power flows and the widespread integration of distributed energy resources (DER), requires advanced tools to process and interpret the large volumes of data they generate. In this context, data mining and statistical analysis techniques have become essential for identifying patterns, trends, and relationships that inform operational and planning decisions.

While artificial intelligence (AI) and machine learning methods have gained attention in recent research as promising solutions for predictive modelling in smart grids, the focus of this thesis is on descriptive and exploratory techniques that enable the evaluation of sensitivity coefficients. These coefficients quantify how perturbations in active and reactive power at specific points in the network influence variables such as voltages and line currents. Understanding their locational and temporal variability is critical for developing effective flexibility strategies and supporting the operation of Local Flexibility Markets.

2.4.1 DATA-DRIVEN APPROACHES IN ACTIVE NETWORKS

Data-driven methods offer a way to extract useful information from operational data without requiring full knowledge of network topology or parameters. Recursive Least Squares (RLS) and Kalman Filters, for instance, have been used in active distribution systems for the online estimation and continuous updating of SCs under changing operating conditions. These approaches are particularly valuable in networks with high levels of DER, where frequent reconfiguration and variability challenge traditional model-based analyses [11].

Clustering techniques, correlation matrices, and principal component analysis (PCA) are also widely applied in network studies to detect similarities between nodes, identify critical areas, and reduce the dimensionality of large datasets. These tools form the basis of data mining in the context of electrical networks and have been successfully employed in the literature to support grid monitoring and decision-making.

2.4.2 Challenges and Opportunities

Although advanced data-driven techniques and statistical tools offer significant advantages in processing and interpreting grid data, they also present challenges. The accuracy of the results depends on the quality and resolution of the input data, and the adoption of such methods requires network operators to integrate them into existing management systems. Nevertheless, these approaches open opportunities for developing adaptive operational strategies and supporting the design of LFMs tailored to the dynamic characteristics of active distribution networks [25].

This analytical framework forms the basis of the methodology presented in Chapter 3, where the specific steps for processing and analysing SCs in the case study networks are detailed.

Chapter 3. METHODOLOGY

3.1 GENERAL FRAMEWORK OF THE ANALYSIS

This work starts from the hypothesis that sensitivity coefficients, traditionally used as static parameters in network studies, exhibit significant variability over time. This variability may affect their reliability as a tool for designing control strategies, congestion management, or participation in flexibility markets.

To test this hypothesis, an exhaustive analysis is conducted on the coefficients that relate active and reactive power injections or withdrawals to critical system variables, such as line currents and node voltages. Specifically, the following coefficients are studied:

- **CMdSdP and CMdSdQ**: which express how a variation in active or reactive power affects the current in a line, i.e., indicators of congestion.
- **VMP and VMQ**: which express how a variation in active or reactive power affects the voltage at a node, i.e., indicators of voltage stability.

The coefficients are obtained from hourly load flow simulations over a full year (8,760 hours), which makes it possible to capture seasonality and operational variations. They are then processed using statistical tools and visualizations that allow the evaluation of both their spatial dispersion (by node or line) and their temporal evolution (by hour of the day or cumulatively trends). It should be noted that, in the case of Scenario C, only 7,158 hours of simulation are included due to data availability, compared to the 8,760 hours of Scenarios A and B. This difference has been taken into account when processing the results to ensure the consistency of the analysis.

3.2 ANALYSIS AND DATA PROCESSING TOOLS

To process the simulation results and generate relevant metrics, an analysis architecture based on Python has been developed. The methodological process is structured into four main phases:

3.2.1 Hourly Scenario Simulation

The hourly load flows used in this work were previously calculated from electrical models developed in specific simulation environments and exported for analysis. Each hour considered represents a distinct operating state of the network, incorporating realistic demand and photovoltaic generation profiles to faithfully reproduce the system's temporal variations. These results were subsequently processed using Python tools to generate the sensitivity matrices employed in the study.

The main script used for this task is designed to automate the loading and processing of the hourly data. Starting from an input folder containing the simulation results for each hour, the code builds the sensitivity matrices and prepares the information for subsequent statistical analysis. This procedure accommodates both scenarios with a full year of data (8,760 hours) and cases where the time series is incomplete, adapting the analysis to the actual number of hours available.

3.2.2 Calculation of Sensitivity Coefficients

From the hourly matrices, the code computes the sensitivity coefficients corresponding to each node/line combination. This calculation is performed using internal functions that iterate through the data series and apply, for each hour, an absolute active or reactive power perturbation (positive sign) to both load and generation nodes. This methodological decision allows the network response to be evaluated uniformly, though it implies that in some cases the coefficients associated with generation and load nodes may coincide, as only the physical effect of the perturbation is considered, not its economic or contractual direction.

Within the script, these operations are organized into modules that allow:

- Loading the sensitivity matrices from the hourly files.

- Iterating over each node and line to apply the perturbations.
- Storing the processed results in data structures optimized for later analyses (such as Pandas dataframes).

3.2.3 Statistical Processing and Visualization

The statistical analysis and visualization of results are carried out in a second phase, where the script uses various Python libraries. Among the main tools are Pandas and NumPy, employed for handling data structures, calculating descriptive statistics (means, percentiles), and filtering by network elements.

For generating graphs, the code incorporates Matplotlib and Seaborn, enabling the creation of advanced visual representations such as:

- Boxplots, for locational analysis and identifying nodes or lines with critical behaviour.
- Daily trends, illustrating the average hourly evolution of the coefficients and allowing detection of recurring patterns throughout the day.
- Cumulative duration curves (CDFs), aimed at representing the distribution of sensitivity over the year and evaluating the persistence of certain response levels.
- Heatmaps and correlation matrices, useful for exploring spatial relationships between nodes and potential redundancies in the analysed variables.

The script automatically generates these visualizations and stores them in structured output folders, facilitating their inclusion in the final analysis and the project report.

3.2.4 Node Classification and Prioritization

Finally, based on the statistical analysis performed, nodes are classified according to their relative sensitivity and typology (generation or demand). This classification makes it possible to identify network points with more critical behaviour, thereby establishing objective criteria for prioritizing nodes in bidding strategies, congestion management, and participation in local flexibility markets. This approach facilitates the definition of priority action areas and provides a technical basis for operational decision-making in active distribution networks.

Chapter 4. CASE STUDY

This chapter describes the case study employed to analyse the temporal and locational variability of sensitivity coefficients in low-voltage distribution networks, as well as the defined network scenarios and the tools used for data processing. The aim is to provide a clear technical framework that justifies the approach adopted to assess the potential for nodal flexibility and its application in emerging local markets.

4.1 NETWORK SCENARIOS AND MODELLING

To represent different network configurations and levels of distributed generation penetration, three main scenarios have been defined:

Scenario A: Network with Partial Photovoltaic Penetration

This first scenario represents a low-voltage radial network with 16 nodes. In this case, only 6 nodes have photovoltaic generation, while the others act exclusively as loads. The network consists of 11 residential nodes and 5 commercial ones, differentiated by their consumption profiles and locations. This scenario enables the study of how the coefficients are distributed in a network with localized generation and strong asymmetry between areas.

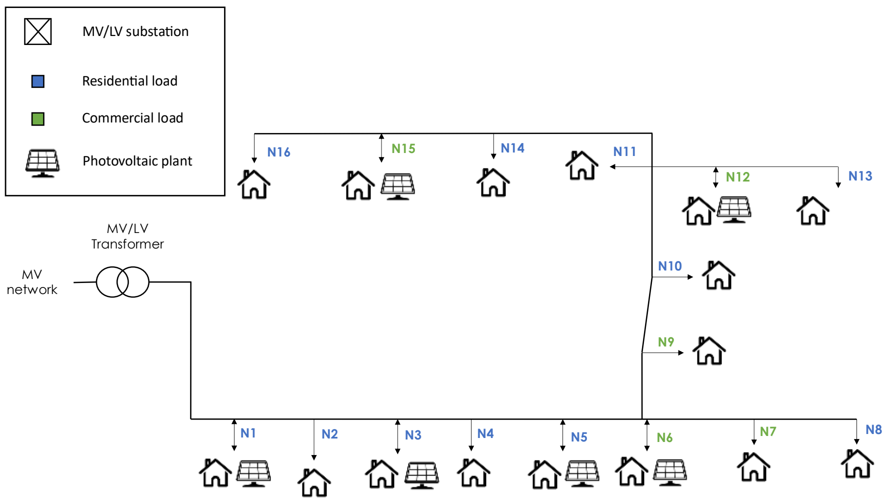

Figure 9. Network topology, Scenario A.

Scenario B: Network with Distributed Generation at All Nodes

In this second case, the same topology as in Scenario A is retained, a meshed configuration with alternative paths between nodes, while photovoltaic generation is integrated at all nodes. This enables the analysis of how sensitivity coefficients are modified when the entire network possesses injection capability, as well as how their behaviour evolves in a significantly more flexible, symmetrical, and potentially bidirectional system.

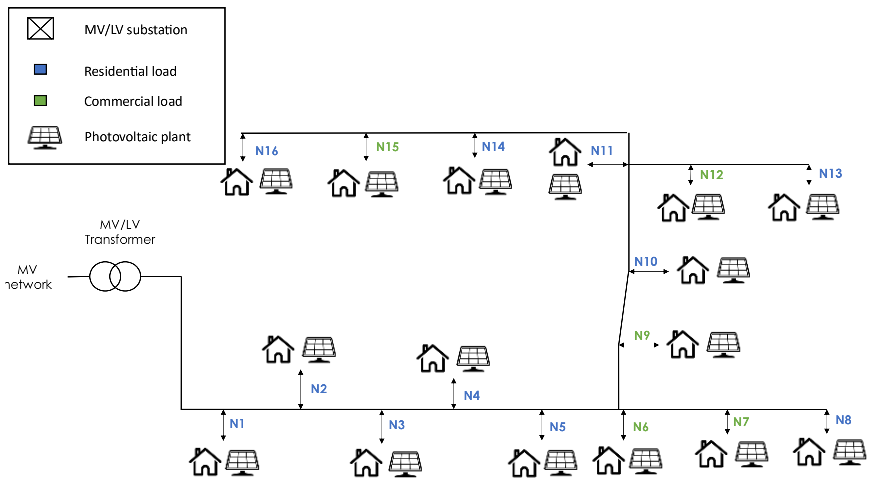

Figure 10. Network topology, Scenario B

Scenario C: network with a branched topology

The third scenario considers a different network topology. It consists of a low-voltage network supplied by a single medium/low-voltage transformer, form which two main branches extend: an upper branch comprising nodes 10 to 16 and a lower branch connecting nodes 1 to 8. All nodes are equipped with photovoltaic generation, facilitating the study of how a radial layout with clearly defined branches influences the distribution of sensitivity coefficients and the propagation of bidirectional power flows.

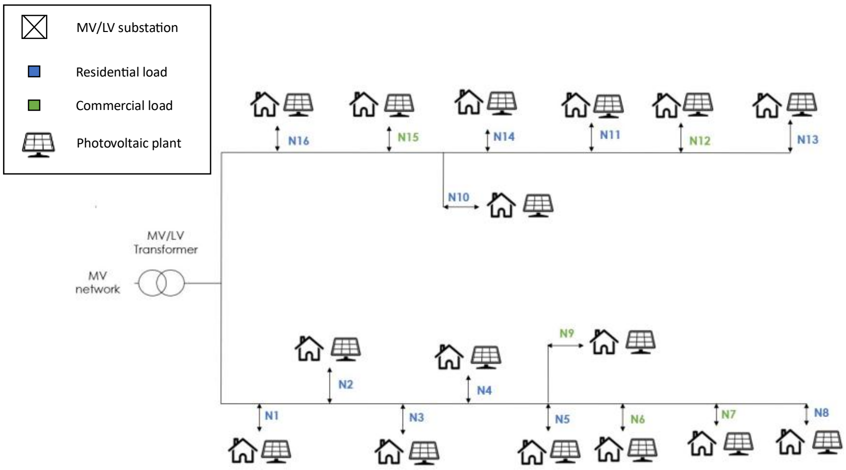

Figure 11. Network topology, Scenario C.

Chapter 5. RESULTS AND ANALYSIS

This chapter presents the results and the sensitivity analysis conducted on three network configurations, focusing on the locational and temporal variability of sensitivity coefficients (SCs). The aim is to characterise how different topologies and levels of distributed photovoltaic (PV) generation influence the propagation of active and reactive power perturbations throughout the system.

The analysis is divided into two main sections. First, the locational variability of SCs is examined to identify spatial patterns and critical nodes where flexibility interventions could have the greatest impact. Second, the temporal variability of SCs is analysed to understand how sensitivity evolves over the daily cycle and to highlight time windows where the network is most vulnerable to congestion and voltage issues. Each section explores the three scenarios, radial topology with partial PV generation (Scenario A), radial topology with distributed PV generation (Scenario B), and branched topology with distributed PV generation (Scenario C), before synthesising the findings and discussing their implications.

This dual perspective provides a comprehensive understanding of sensitivity dynamics in active distribution networks and lays the foundation for defining flexibility strategies tailored to the physical and operational characteristics of the system.

5.1 LOCATIONAL VARIABILITY OF SENSITIVITY COEFFICIENTS

Scenario A: Radial topology with partial PV generation

In Scenario A, the network exhibits a radial topology where a single medium-to-low voltage transformer supplies power to sixteen nodes arranged along multiple feeders. Photovoltaic (PV) generation is installed at only six of these nodes, with the remaining ten acting exclusively as loads. This limited penetration of generation determines the operational characteristics of the system and strongly influences the spatial distribution of sensitivity coefficients.

Under these conditions, power flows are predominantly unidirectional, originating at the transformer and propagating downstream to supply the demand at each node. The installed PV capacity, while significant in some nodes, is insufficient to reverse the direction of currents in the feeder lines for most of the year. Even during periods of high solar irradiation, surplus PV generation tends to be absorbed locally or by neighbouring loads situated closer to the periphery of the network. As a result, the transformer remains the primary source of power injection, and the sensitivity patterns reflect the predictable behaviour of a passive radial system.

The analysis of the congestion sensitivity coefficient (CMdSdP) reveals these characteristics clearly. The boxplots of CMdSdP for load nodes (Figure 12) provide a detailed visualisation of this behaviour. In these plots, the X-axis represents the network lines (*Line_x_y*), and the Y-axis shows the sensitivity coefficients, which quantify how perturbations in active power at load nodes affect the current flowing through each line. The colours distinguish the different load nodes, allowing a clear comparison of their relative influence across the network.

The boxplots display a high degree of uniformity, with consistent median values and narrow interquartile ranges in most lines. This homogeneity indicates that active power perturbations propagate similarly throughout the system, producing predictable effects in line currents and congestion levels. The absence of extreme outliers reinforces the notion that the network is robust against typical daily and seasonal fluctuations in demand and PV output.

However, some deviations from this global pattern can be observed in nodes with PV generation, particularly N6, N7, N11, N12, and N13, and in the lines connecting them. Nodes such as N6 and N12, for example, exhibit slightly wider interquartile ranges and occasional outliers in their boxplots. These behaviours are associated with periods in which local PV generation approaches or slightly exceeds the demand at these nodes, temporarily reducing the net power drawn from the transformer. While these situations do not result in sustained power flow reversals, they do create localised increases in sensitivity in lines such as Line_6_7 and Line_11_12.

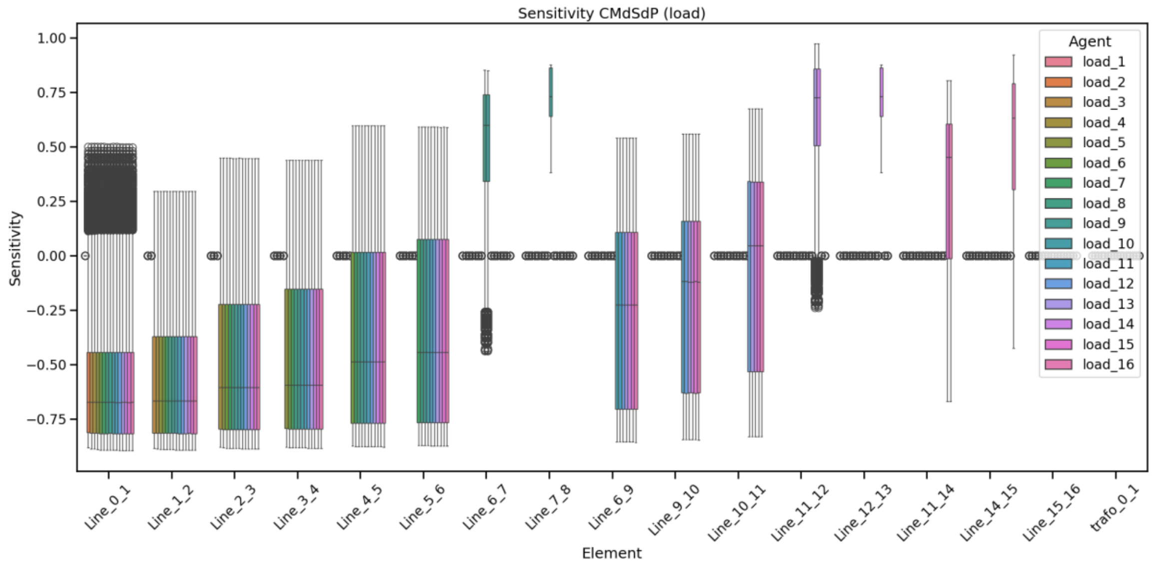

Figure 12. Boxplots of CMdSdP for load nodes, Scenario A. Source: Own elaboration

The heatmap of CMdSdP (Figure 13) corroborates this interpretation. It shows a gradual gradient of sensitivity values radiating outward from the transformer, with higher sensitivity concentrated in the outer branches, such as those supplying N14 and N15, which are electrically distant from the source and lack local generation. Lines such as Line_12_13 and Line_11_12 exhibit slightly elevated sensitivity levels relative to their position in the network, reflecting the influence of PV injections at nodes N12 and N13. These effects, although spatially limited, demonstrate how even partial distributed generation can alter the local propagation of perturbations in a radial system.

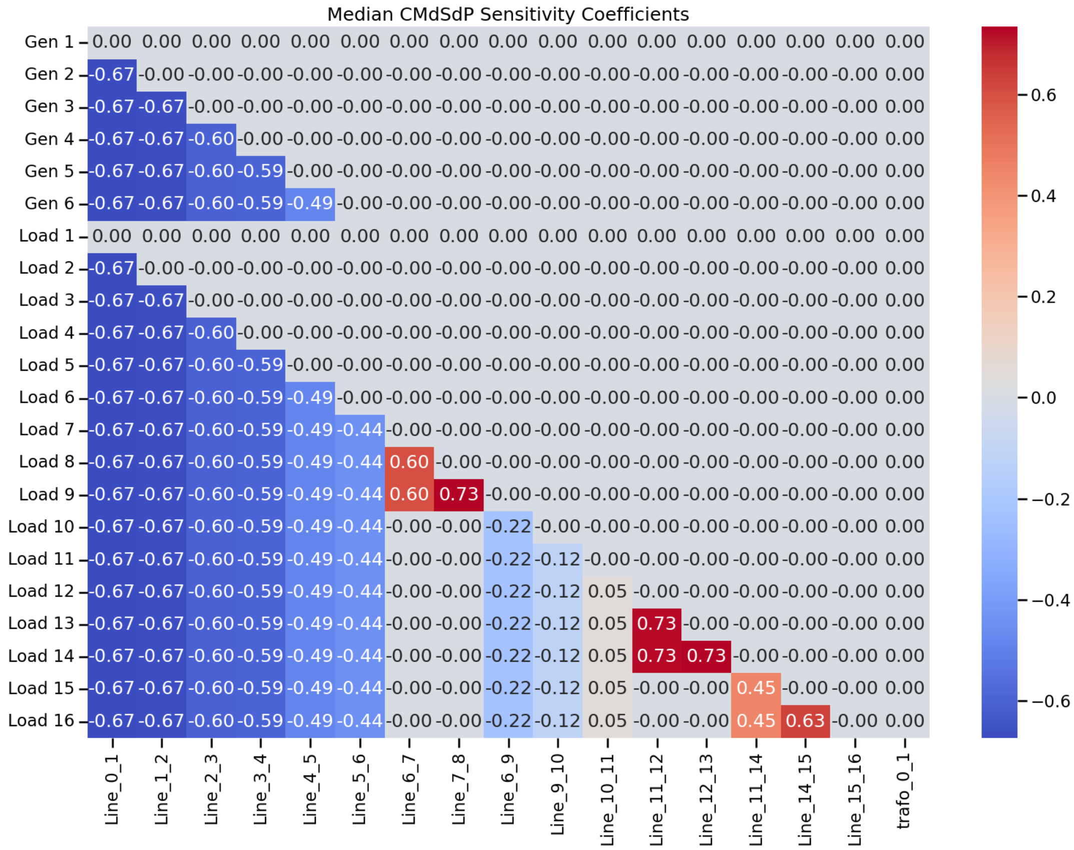

Figure 13. Heatmap of CMdSdP coefficients, Scenario A. Source: Own elaboration.

Despite these localised phenomena, the overall behaviour of Scenario A remains characteristic of a passive radial network. The limited PV penetration ensures that the transformer continues to dominate power injection, and perturbations introduced at the periphery propagate back through the feeders without alternative flow paths to redistribute them. This explains why N14 and N15 emerge as the most critical nodes in terms of congestion sensitivity: their distance from the transformer and the absence of PV generation makes them particularly susceptible to voltage drops and congestion under stressed operating conditions.

From an operational perspective, these findings suggest that flexibility measures in radial networks with partial PV penetration should prioritise nodes located at the network's extremities. Deploying local voltage support or demand response at N14 and N15 would mitigate the accumulation of stress along feeder lines, while monitoring nodes such as N6, N12, and N13 may also prove beneficial to address occasional localised sensitivity increases associated with PV generation.

Although the reactive power sensitivity coefficient (CMdSdQ) was also computed for this scenario, its variation across the network is relatively modest and follows similar spatial patterns to CMdSdP. As such, it provides limited additional insight into the locational variability of sensitivity and is not the focus of this analysis. Similarly, the correlation between nodes is low in Scenario A due to the uniformity of flows and limited generation variability, and thus the correlation analysis will be addressed in more depth in subsequent scenarios where its relevance is greater.

In summary, Scenario A demonstrates the typical behaviour of radial distribution networks with limited distributed generation. Power flows are stable and unidirectional, and locational sensitivity is concentrated at nodes that are electrically distant from the supply point. Nevertheless, the presence of PV generation at certain nodes introduces occasional localised sensitivity effects, highlighting the need for careful monitoring even in largely passive systems.

Scenario B: Radial topology with distributed PV generation

Scenario B retains the radial topology of Scenario A but introduces photovoltaic (PV) generation at all sixteen nodes. This modification fundamentally alters the operation of the network, transforming it from a passive distribution system into an active one where nodes can alternate between consuming and injecting power. The presence of distributed generation throughout the network increases the complexity of power flows and introduces phenomena such as bidirectionality and dynamic congestion, which are reflected in the spatial distribution of sensitivity coefficients.

Unlike Scenario A, where power flows are predominantly unidirectional from the transformer to the loads, Scenario B exhibits bidirectional power flows under certain operating conditions. This behaviour arises because during periods of high solar irradiation, local PV generation at some nodes exceeds the instantaneous demand, resulting in surplus power being injected back into the network. Consequently, current reversals can occur in feeder lines, especially in areas where the cumulative generation of adjacent nodes significantly surpasses their aggregated load.

The boxplots of CMdSdP for load nodes (Figure 14) provide clear evidence of this dynamic behaviour. Compared to Scenario A, the distributions in Scenario B display significantly greater dispersion, with wider interquartile ranges and frequent outliers. Nodes such as N6, N12, and N15 emerge as particularly relevant, exhibiting periods where their sensitivity to active power perturbations fluctuates markedly throughout the year. These fluctuations reflect the dual role of these nodes as both consumers and generators, depending on the balance between PV output and local demand. The presence of numerous outliers suggests that specific operating conditions, such as sharp transitions in PV production during cloud movements or evening hours, can lead to transient but substantial changes in congestion sensitivity.

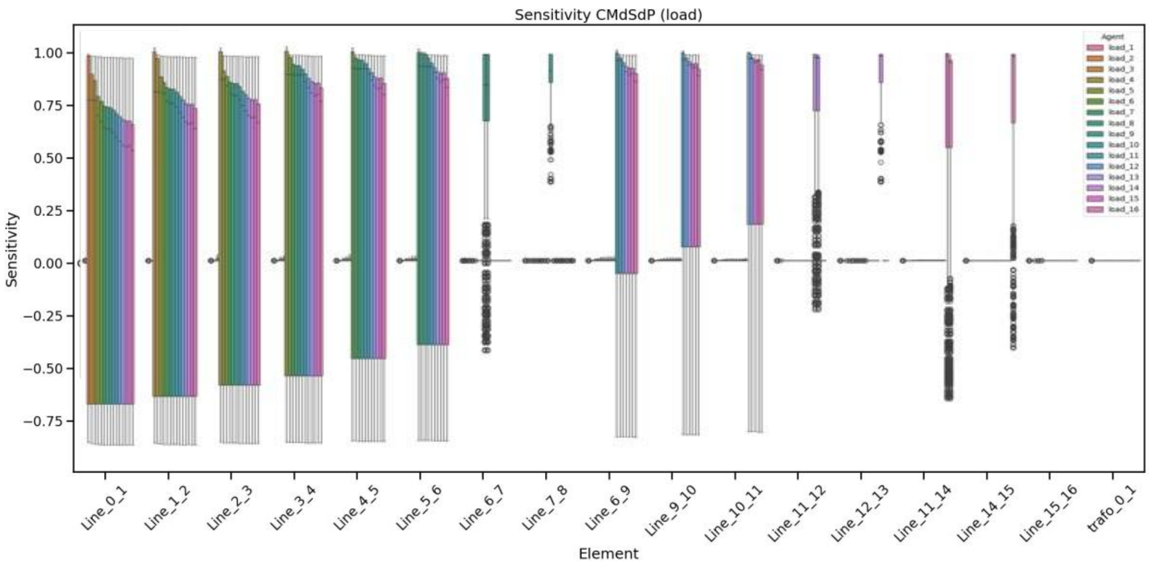

Figure 14. Boxplots of CMdSdP for load nodes, Scenario B. Source: Own elaboration

The heatmap of CMdSdP (Figure 15) further illustrates the heterogeneous nature of the spatial sensitivity distribution in this scenario. Unlike the gradual gradient observed in Scenario A, the sensitivity values in Scenario B are distributed irregularly across the network. Lines such as Line_6_7, Line_11_12, and Line_12_13 show heightened sensitivity at various times, reflecting the influence of distributed generation on local power flows. This pattern underscores how the radial structure, combined with pervasive PV injection, creates multiple localised zones of potential congestion rather than concentrating sensitivity at the periphery.

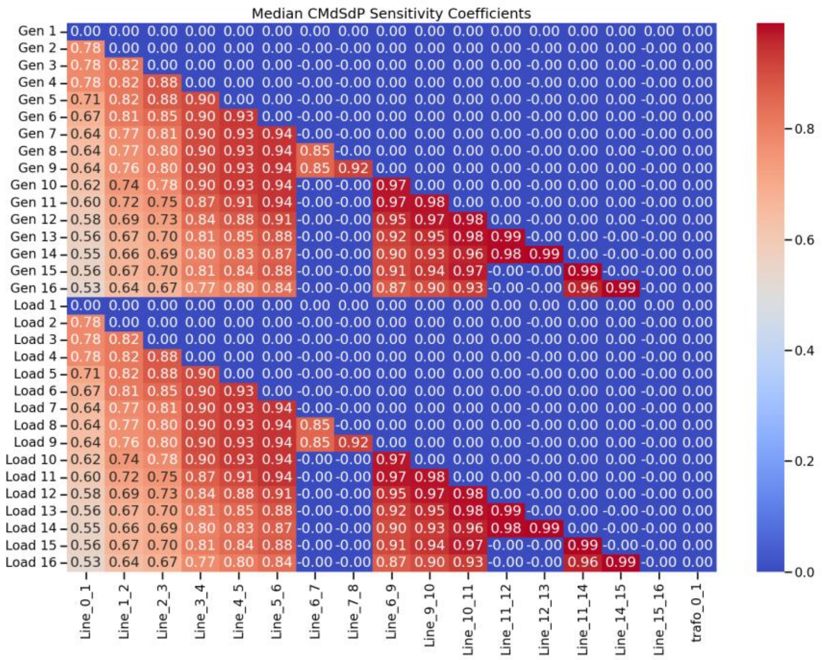

Figure 15. Heatmap of CMdSdP coefficients, Scenario B. Source: Own elaboration.

The analysis of the reactive power sensitivity coefficient (CMdSdQ) offers additional insights into the locational variability. In Scenario B, CMdSdQ exhibits similar spatial heterogeneity to CMdSdP but with distinct characteristics. Nodes with substantial PV capacity, such as N6, N12, and N13, show higher CMdSdQ values, particularly during midday periods when PV inverters are more active in regulating reactive power. These variations highlight the role of distributed generation not only in affecting active power flows but also in influencing the voltage stability of the network.

The correlation analysis adds a further layer of understanding to these dynamics. In Scenario B, the sensitivity coefficients of certain nodes and lines are highly correlated, suggesting the presence of clusters of nodes that tend to behave similarly in response to perturbations. For instance, nodes in the upper feeder, including N11, N12, and N13, exhibit strong correlations in both CMdSdP and CMdSdQ values. This indicates that operational changes at one of these nodes can have a synchronized effect on the others. In contrast, nodes closer to the transformer show weaker correlations, reflecting their more stable and predictable behaviour. This clustering effect points to the potential for defining operational flexibility zones, where coordinated control actions could be implemented to manage sensitivity effectively.

These findings collectively illustrate the transformation of the network's spatial sensitivity profile under full PV penetration. While the radial topology remains unchanged, the introduction of distributed generation renders the system far more dynamic, with multiple nodes alternately acting as sources and sinks of power. From an operational perspective, this complexity necessitates flexibility strategies that are both granular and adaptive, capable of responding to rapidly shifting sensitivity patterns.

In summary, Scenario B demonstrates how full PV penetration fundamentally alters the locational variability of sensitivity coefficients in a radial network. The combination of bidirectional power flows, spatially distributed sensitivity hotspots, and node clustering highlights the need for sophisticated monitoring and control mechanisms. These insights lay the groundwork for designing flexibility products that can adapt to the complex and evolving conditions of active distribution systems.

Scenario C: Branched topology with distributed PV generation

Scenario C introduces a structural change in the low-voltage network by adopting a branched topology, in which two main feeders extend from the central transformer to supply all sixteen nodes. As in Scenario B, photovoltaic (PV) generation is present at every node, allowing the entire network to operate as a fully distributed and active system. This new configuration, combining widespread PV penetration with a non-radial topology, significantly influences the spatial distribution of sensitivity coefficients and the localisation of congestion risks.

The branched structure of the network alters the way in which power flows propagate and disturbances are absorbed. Unlike in radial systems, where perturbations travel along fixed paths, the presence of two feeders in Scenario C allows for partial redistribution of flows across branches. However, the system remains largely tree-like and unmeshed, which means that localised bottlenecks can still arise, particularly at branching points and near the transformer.

The boxplots of CMdSdP for load nodes (Figure 16) reveal a more heterogeneous distribution of sensitivity values compared to Scenario A but less extreme than those observed in Scenario B. Certain nodes, particularly N6 and N9 in the lower branch, exhibit larger interquartile ranges and frequent outliers, indicating more pronounced fluctuations in congestion sensitivity. These nodes are located in areas where multiple downstream PV generators inject power simultaneously, causing variations in line loading and altering the network's ability to absorb local perturbations. In contrast, nodes in the upper branch, such as N12 and N15, show narrower boxplots and more stable median values, suggesting more predictable behaviour throughout the year.

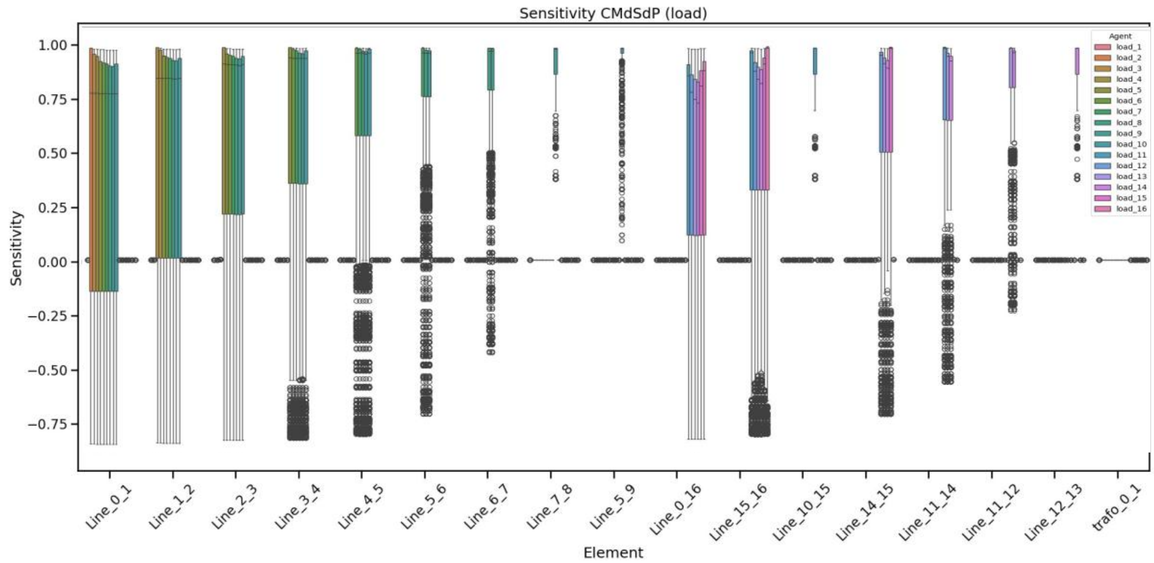

Figure 16. Boxplots of CMdSdP for load nodes, Scenario C. Source: Own elaboration

This asymmetry in sensitivity is closely related to the branch-specific configuration of loads and generation. The lower branch, being longer and more heavily loaded, accumulates more generation-related variability, especially in lines such as Line_6_7, where the combined effect of downstream injections makes the local sensitivity more volatile. Meanwhile, the upper branch benefits from a shorter feeder and fewer interacting generators, which stabilises its response to local changes.

The heatmap of CMdSdP (Figure 17) visually reinforces this interpretation. It highlights concentration of sensitivity in specific sections of the network, particularly in lines near the transformer (e.g., Line_0_1) and at key branching points (Line_5_6, Line_10_15). These lines serve as critical transit routes for power flows from both branches, and as such, are more exposed to congestion when generation in multiple areas coincides. Unlike Scenario A, where sensitivity followed a clear radial gradient, and Scenario B, where hotspots were scattered irregularly, Scenario C presents a structured pattern of locational variability, strongly shaped by the underlying topology.

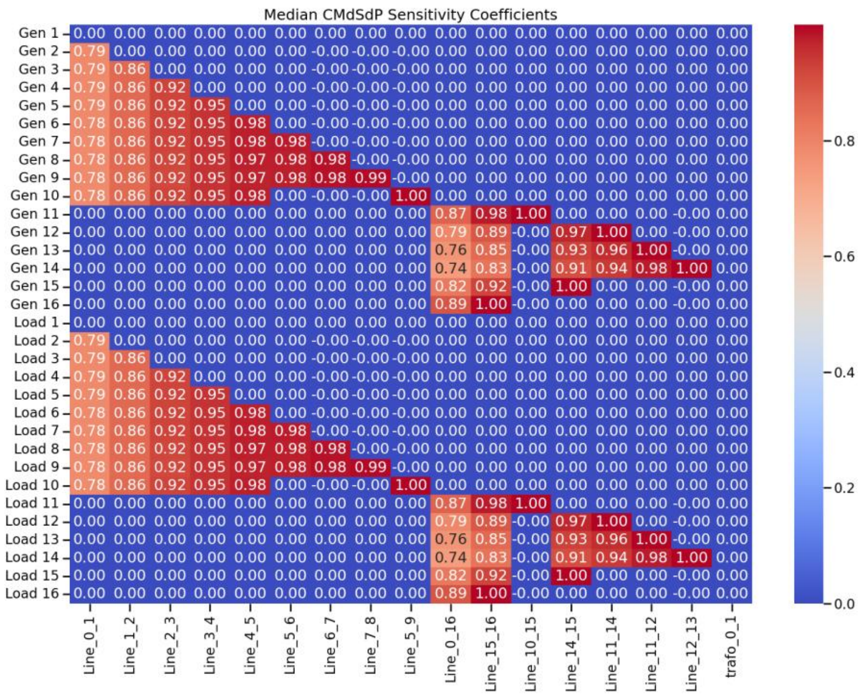

Figure 17. Heatmap of CMdSdP coefficients, Scenario C. Source: Own elaboration

Despite the full PV penetration, the system does not exhibit the same level of bidirectional complexity as Scenario B. While local flow reversals do occur, especially during solar peak hours, the branch separation tends to contain these effects, reducing the likelihood of widespread sensitivity fluctuation. This relative confinement of power dynamics suggests that operational strategies can benefit from a branch-based approach, targeting flexibility interventions to specific feeder segments rather than individual nodes.

Although reactive power sensitivity coefficients (CMdSdQ) were also computed, their contribution to the locational analysis in this scenario is marginal. The branch structure and the uniform PV distribution lead to reactive flows that, while present, do not exhibit significant spatial differentiation under typical operating conditions. As such, CMdSdP remains the most informative coefficient for understanding congestion-related behaviour in this case.

In conclusion, Scenario C illustrates how network topology, specifically a branched configuration, modulates the spatial variability of sensitivity coefficients, even under conditions of full PV penetration. The emergence of branch-dependent critical zones and the relative stability within each feeder suggest that flexibility strategies should be structured around topological segmentation, prioritising lines and nodes that act as local bottlenecks or inter-branch gateways. These findings highlight the importance of aligning flexibility product design with the physical structure of the network to ensure targeted and effective congestion management.

5.1.1 SYNTHESIS OF LOCATIONAL SENSITIVITY ANALYSIS

The comparative analysis of the three network scenarios highlights how the spatial distribution of sensitivity coefficients (SCs) evolves as a function of network topology and the level of distributed generation (DG) penetration. Each configuration presents distinct patterns of locational variability, which in turn have critical implications for operational planning and flexibility product design.

In Scenario A, the combination of a radial network structure and limited PV generation produces a spatial sensitivity profile that is highly stable and predictable. Power flows remain consistently unidirectional throughout the year, with variability concentrated in the outer sections of the system. These electrically remote areas, lacking local generation capacity, display heightened congestion sensitivity. This behaviour, as reflected in the CMdSdP boxplots, indicates that targeted flexibility interventions in such regions could be effective in mitigating voltage drops and alleviating line overloads.

In Scenario B, the introduction of PV generation at all nodes transforms the radial network into a fully active system, where nodes can act as both consumers and generators. This results in the emergence of bidirectional power flows during periods of high solar production and a more complex, heterogeneous sensitivity profile. Boxplots of CMdSdP display wider dispersion and frequent outliers, especially at nodes like N6, N12, and N15, reflecting dynamic congestion risks. Heatmaps reveal distributed sensitivity hotspots throughout the network. This scenario highlights the need for granular, node-specific flexibility strategies capable of adapting to rapidly changing network conditions.

In Scenario C, the introduction of a branched topology coupled with full PV penetration results in a sensitivity profile that is both structured and asymmetric. Certain areas, such as the lower branch (nodes N6 and N9), exhibit higher congestion sensitivity due to the cumulative effect of downstream generation, while other areas, such as the upper branch (nodes N12 and N15), display more stable patterns. The heatmap of CMdSdP highlights critical lines near the transformer and at branching points (e.g., Line_0_1 and Line_5_6), which serve as bottlenecks for inter-branch power flows. These results underscore the importance of branch-based operational strategies to manage localized congestion effectively.

Overall, the analysis demonstrates that locational variability in SCs becomes increasingly complex as networks transition from passive to active systems. Boxplots and heatmaps have proven to be effective tools for identifying critical nodes and lines where flexibility measures would be most impactful.

The insights gained from the locational analysis highlight the critical role of SC variability in active distribution networks. They demonstrate that flexibility measures must be spatially targeted and aligned with the physical structure of the network to ensure technical effectiveness and economic efficiency. Moreover, the identification of sensitivity clusters in Scenario B points to the potential for flexibility zones, where coordinated interventions could optimize grid operation.

Finally, this locational analysis provides the foundation for understanding temporal sensitivity dynamics. As will be explored in the following section, the interplay between spatial and temporal variability further influences the design of adaptive flexibility solutions in networks with high DG penetration.

5.2 TEMPORAL VARIABILITY OF SENSITIVITY COEFFICIENTS

To clarify the methodology behind the temporal analysis, it is important to note that the two lines shown in the graphs (generation and load) do not represent different technologies connected to the same node. Instead, they correspond to two distinct perturbations applied during the calculation of sensitivity coefficients: an absolute active or reactive power increase at load nodes and a similar perturbation at generation nodes. This approach was chosen to evaluate the network's response uniformly for both types of nodes, without considering the economic or contractual direction of the power exchange.

While sensitivity coefficients are inherently technology-agnostic, presenting separate curves for load and generation allows the identification of any asymmetries in the network's response to active and reactive power injections or withdrawals. In many cases, especially in scenarios with homogeneous distributed generation, the curves coincide, reflecting the physical equivalence of perturbations applied at nodes classified as load or generation.

Scenario A: Radial topology with partial PV generation

The temporal analysis of Scenario A examines how sensitivity coefficients (SCs) evolve over a daily cycle in a radial network with limited photovoltaic (PV) generation. This configuration, with only six of sixteen nodes equipped with PV, results in a passive system with unidirectional power flows, but the daily trends of the SCs reveal notable differences between the behaviour of load and generation nodes.

The CMdSdP coefficients for loads show a clearly defined hourly pattern (Figure 18). During the early hours of the day (00:00–06:00), values remain relatively stable at approximately –0.08, indicating moderate sensitivity to demand perturbations. As the day progresses, the magnitude of these negative coefficients steadily increases, peaking at about –0.3 between 19:00 and 20:00. This trend reflects the combined effect of declining PV generation and rising net demand during the evening, which amplifies the system's vulnerability to load increases and raises the risk of congestion in the feeder lines.

In contrast, the CMdSdP coefficients for generation exhibit a more stable profile throughout the day. Values fluctuate only slightly, ranging from –0.05 to –0.08, with a minor dip to approximately –0.12 in the evening hours. This suggests that the contribution of distributed generation to alleviating congestion diminishes slightly as solar output declines, though its overall impact remains limited due to the low number of PV nodes.

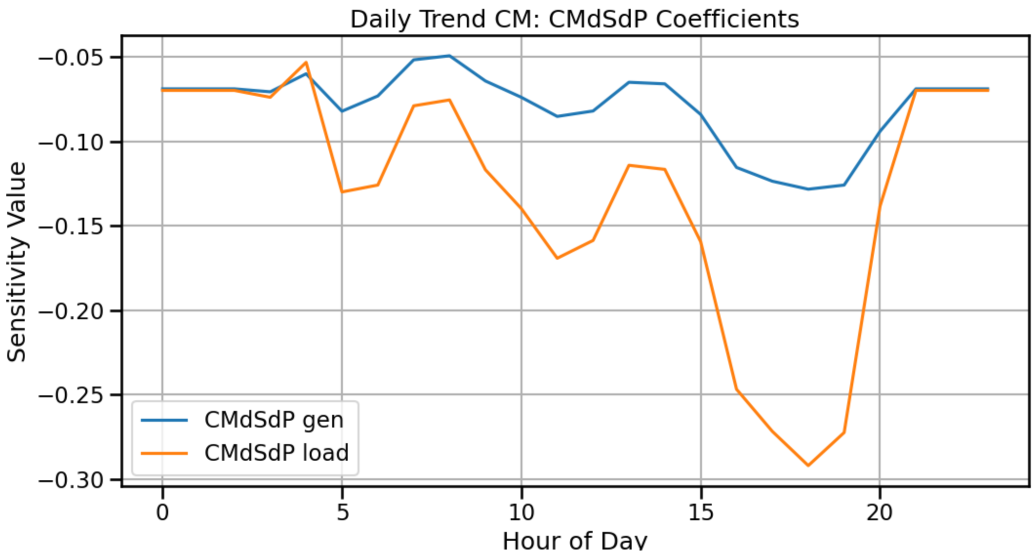

Figure 18. Daily trend of CMdSdP coefficients, Scenario A. Source: Own elaboration

The CMdSdQ coefficients reveal a distinct temporal behaviour compared to active power sensitivity. For loads (Figure 19), coefficients are positive during nighttime hours (around +0.1), then decrease progressively from early morning, crossing into negative values (reaching approximately –0.1) between 05:00 and 20:00. This sign change indicates that, during periods of high solar irradiation, net loads at certain nodes behave like generators due to PV injection, which reduces power flows in specific lines and alters the system's response to reactive power perturbations. By contrast, the generation curve remains predominantly negative throughout the day, with less variability and a flatter profile. This difference arises because perturbations in generation directly affect nodes with reactive power export capacity, whereas load perturbations interact with PV output only in some parts of the network.

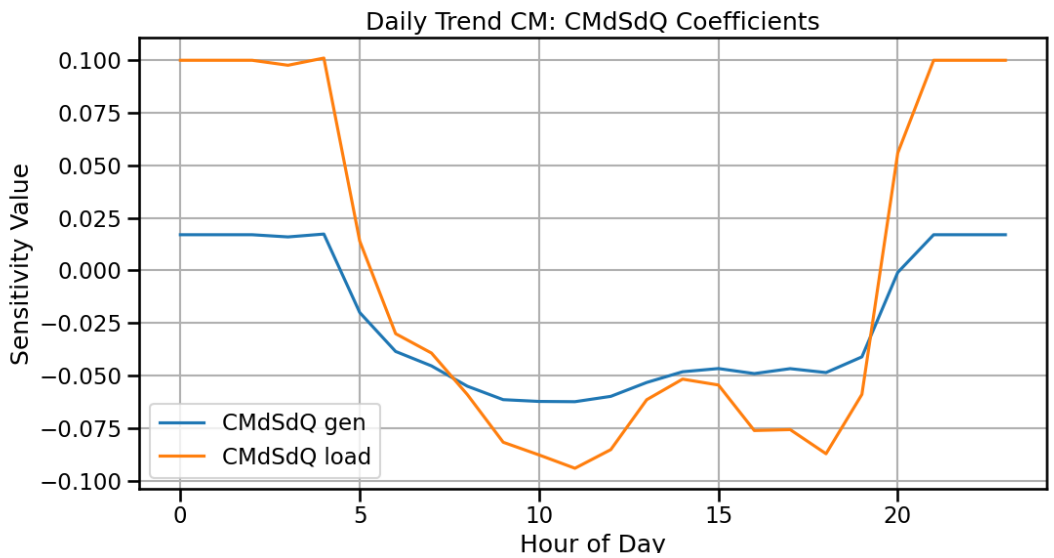

Figure 19. Daily trend of CMdSdQ coefficients, Scenario A. Source: Own elaboration

The voltage management factors (VMP and VMQ) remain practically constant throughout the day. For both loads and generation, the curves are nearly flat, showing minimal temporal variability. VMP (Figure 20) values are slightly higher for load nodes compared to generation nodes, indicating a marginally greater sensitivity to voltage changes when perturbations are applied at consumption points. However, this difference is small and consistent across the 24-hour period. The stability of these coefficients reflects the limited capacity of PV generation in this scenario to induce significant fluctuations in power flows that could affect nodal voltages.

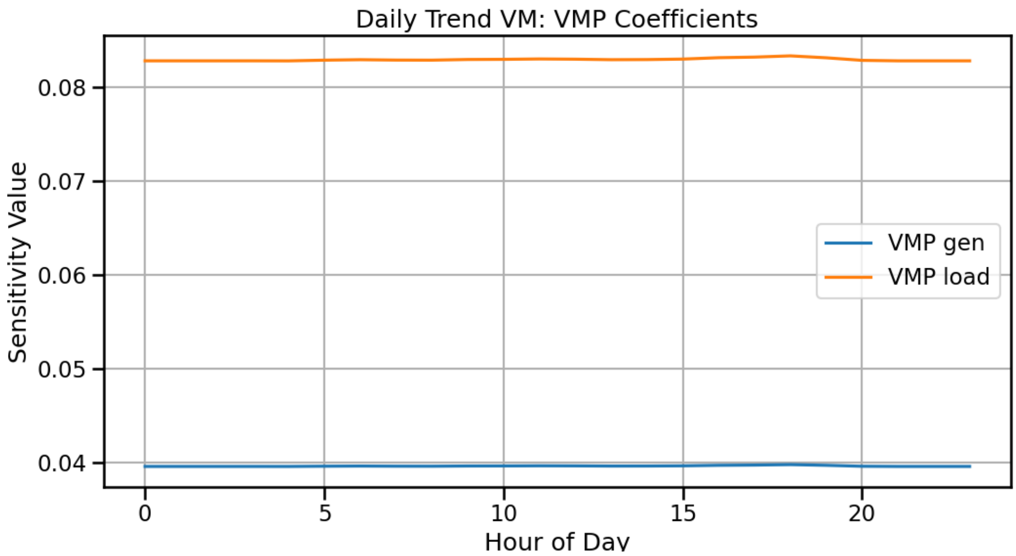

Figure 20. Daily trend of VMP coefficients, Scenario A. Source: Own elaboration

Overall, Scenario A demonstrates a system with predictable daily dynamics. While voltage sensitivity remains effectively time-invariant, congestion sensitivity exhibits a clear evening peak associated with the reduction in PV generation and increased net demand. These results suggest that in radial networks with limited DG, flexibility measures should focus on active power management during evening hours to mitigate congestion risks, whereas voltage-focused interventions may play a secondary role due to the inherent stability of VMP and VMQ.

Scenario B: Radial topology with distributed PV generation

In Scenario B, the radial network is equipped with photovoltaic (PV) generation at all sixteen nodes, transforming it into a fully active system where power flows and sensitivity profiles are strongly influenced by the balance between local demand and distributed generation. Due to the calculation methodology used, the perturbations applied to load and generation nodes are absolute and positive, resulting in practically symmetrical profiles for both. This approach allows for a uniform evaluation of the network's response but means that the coefficients associated with loads and generators coincide in magnitude and behaviour.

The CMdSdP coefficients exhibit a highly dynamic hourly pattern that reflects the interplay between demand, PV production, and bidirectional power flows (Figure 21). During the early morning hours (00:00–05:00), sensitivity values are negative and of low magnitude (~ –0.08), indicating moderate network response to incremental active power. Between 06:00 and 15:00, a progressive change of sign is observed, with coefficients becoming positive and exceeding +0.3 at midday. This reversal highlights periods where PV injection surpasses local demand, causing the direction of power flows to invert and substantially modifying how the network responds to perturbations. In these hours, incremental active power injections reduce current flows in the main lines instead of increasing them, alleviating congestion. After 18:00, CMdSdP values drop sharply and return to negative values, reflecting the system's transition back to a demand-dominated state with unidirectional flows.

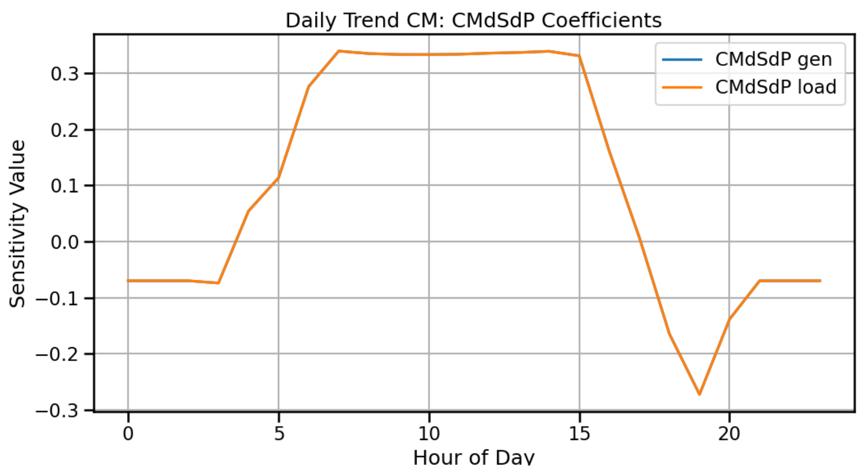

Figure 21. Daily trend of CMdSdP coefficients, Scenario B. Source: Own elaboration

The CMdSdQ coefficients (Figure 22) display a similarly distinct daily behaviour. During nighttime hours (00:00–05:00 and 20:00–24:00), coefficients are positive (~ +0.1), meaning that increases in reactive power at those times contribute to raising current flows and potentially heightening network stress. Between 06:00 and 19:00, however, the coefficients turn negative, reaching a minimum (~ –0.075) around midday. This inversion reflects how distributed generation reverses the net reactive power flows in the network, so that incremental reactive power at certain nodes can actually reduce congestion in the main lines during high PV output periods.

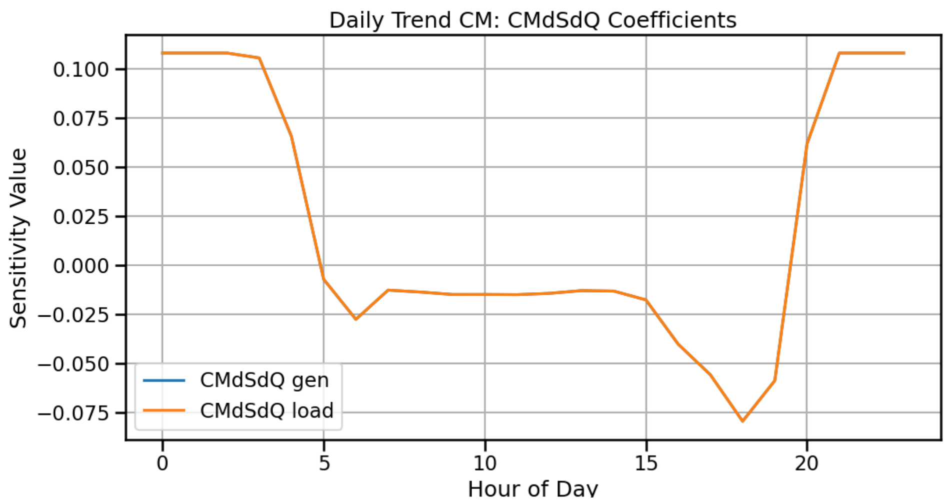

Figure 22. Daily trend of CMdSdQ coefficients, Scenario B. Source: Own elaboration

The voltage management factors (VMP and VMQ) in Scenario B also exhibit greater temporal variation compared to Scenario A, highlighting the influence of distributed generation on voltage sensitivity throughout the day. In the VMP curve (Figure 23), a downward trend is observed from early morning (00:00–05:00), reaching a minimum between 10:00 and 15:00, coinciding with the hours of maximum PV production. This dynamic suggests that during periods of high local generation, the network benefits from reduced sensitivity to active power perturbations, thanks to the voltage support provided by PV inverters.

In contrast, the VMQ coefficients (Figure 24) follow an opposite pattern. The curve rises progressively during the early hours, peaking around midday, and then decreases during the afternoon and evening. This behaviour reflects how reactive power compensation needs and variations in load influence the network's voltage sensitivity.

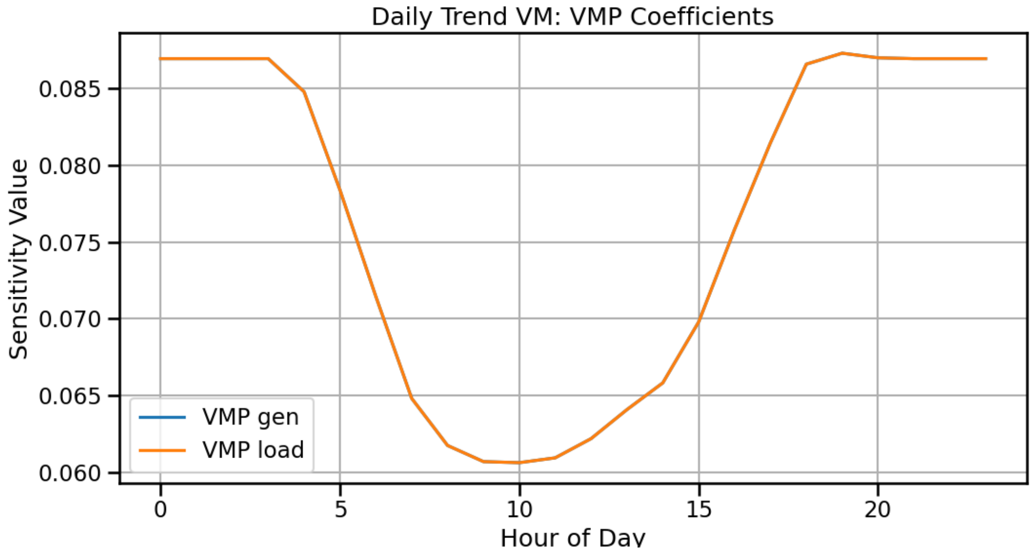

Figure 23. Daily trend of VMP coefficients, Scenario B. Source: Own elaboration

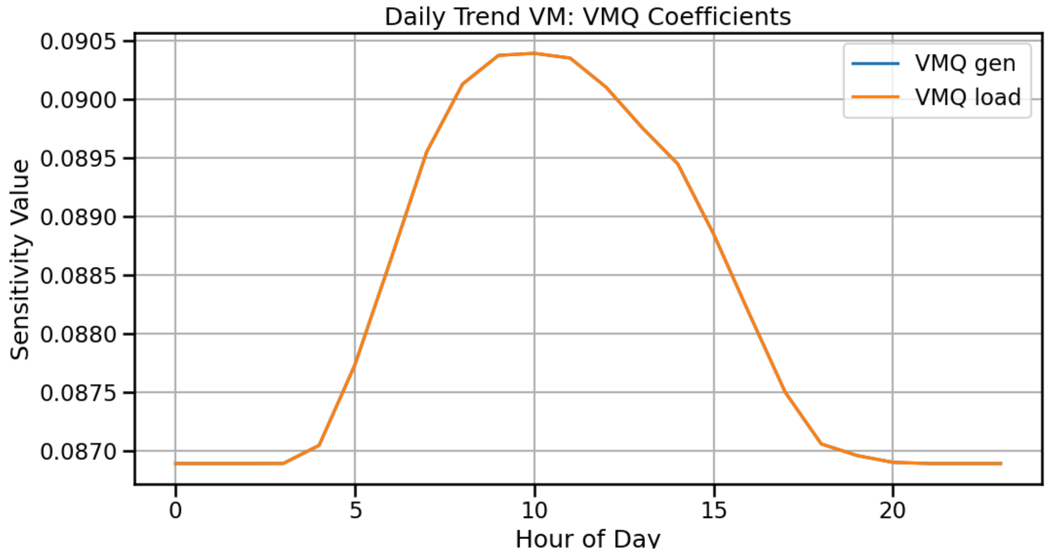

Figure 24. Daily trend of VMQ coefficients, Scenario B. Source: Own elaboration

Although these dynamics highlight the increased complexity of Scenario B, it is important to note that the absolute variations in VMP and VMQ remain small: for VMP, values fluctuate between 0.06 and 0.085, while VMQ remains within the narrow range of 0.087 to 0.0905.

In summary, Scenario B illustrates how distributed PV generation creates time-dependent sensitivity patterns in active networks. The reversal of power flows during midday hours, combined with the dynamic behaviour of reactive power, underscores the need for flexibility strategies that adapt to these daily transitions. Active power management is critical during the evening demand peaks, while reactive power compensation plays a key role in maintaining voltage stability during periods of high PV output.

Scenario C: Branched topology with distributed PV generation

Scenario C introduces a branched topology in the low-voltage network while maintaining photovoltaic (PV) generation at all sixteen nodes. This configuration, combined with the presence of distributed generation, creates an active system where power flows are more evenly distributed across the network. The temporal behaviour of the sensitivity coefficients (SCs) in Scenario C exhibits patterns closely resembling those observed in Scenario B, with minor but relevant differences in magnitude and variability due to the branched structure.

The CMdSdP coefficients present a well-defined daily trend that mirrors the behaviour described in Scenario B (see Figure 21). During nighttime hours, values remain positive and stable at approximately +0.07, reflecting moderate network sensitivity to active power perturbations. As solar generation ramps up in the morning, the coefficients rise, leading to a sustained period of higher sensitivity around +0.25 during midday hours. This increase reflects how distributed PV generation reduces the overall burden on feeder lines by supplying local demand, thereby modifying the network's response to active power increments.

In the late afternoon, a sharp decline occurs, with CMdSdP values turning negative and reaching a minimum of approximately –0.1 around 18:00, before stabilizing again during the night. While these dynamics are qualitatively similar to Scenario B, the range of variation is more moderate in Scenario C. In Scenario B, the coefficients reached higher peaks (+0.3) and deeper minima (–0.3). This attenuation in Scenario C is attributed to the branched topology, which facilitates a more distributed flow of active power and mitigates the magnitude of sensitivity variations across the network.

The CMdSdQ coefficients also exhibit a daily pattern that broadly aligns with those in Scenarios A and B. However, a key difference in Scenario C is that the coefficients remain positive throughout the entire day (see Figure 22). Even during periods of maximum PV generation, there is no reversal of reactive power flows, as observed in the other scenarios. This behaviour reflects how the branched network structure promotes a more homogeneous distribution of reactive power exchanges, preventing the concentration of flows that might otherwise lead to negative coefficients.

The voltage sensitivity coefficients (VMP and VMQ) show very limited daily variability, confirming the robustness of the branched topology against hourly disturbances. The VMP curve exhibits a subtle V-shaped trend, with values close to 0.028 during nighttime hours and a slight dip to ~0.025 during midday (see Figure 23). In contrast, the VMQ coefficients display an inverted pattern, with a minimal increase during midday that remains within a few thousandths (see Figure 24). Compared to Scenario B, these results confirm that although both networks operate as fully active systems, Scenario C's branched topology effectively dampens the network's sensitivity to perturbations.

This similarity in the overall temporal dynamics between Scenarios B and C suggests that flexibility strategies developed for fully active radial systems may be largely applicable to branched networks as well. However, the attenuated variability in Scenario C indicates that operational interventions could adopt a slightly less granular approach, focusing on key branching points and transformer connections where temporal sensitivity fluctuations are more likely to concentrate.

5.2.1 SYNTHESIS OF TEMPORAL SENSITIVITY ANALYSIS

The temporal analysis of sensitivity coefficients (SCs) across the three network scenarios reveals how daily cycles in demand and photovoltaic (PV) generation shape the network's response to perturbations. These patterns highlight the dynamic nature of active distribution systems and their implications for operational planning and flexibility provision.

In Scenario A, the radial topology combined with limited PV generation results in a passive system with unidirectional power flows. The CMdSdP coefficients for loads display a clear evening peak as net demand rises and PV output declines, indicating increased congestion sensitivity during these hours. Conversely, the CMdSdQ coefficients exhibit a sign reversal during daylight hours, reflecting localized PV injection at certain nodes. However, voltage sensitivity (VMP and VMQ) remains nearly constant throughout the day, underscoring the system's stability against active and reactive power perturbations.

In Scenario B, the introduction of PV generation at all nodes transforms the system into a fully active network, producing highly dynamic temporal patterns. The CMdSdP coefficients exhibit a marked reversal in sign around midday, as PV generation surpasses local demand and power flows invert. This behaviour highlights the bidirectional nature of active power flows in high-DG networks. Similarly, the CMdSdQ coefficients show negative values during solar hours, indicating the role of distributed generation in modulating reactive power flows. Voltage sensitivity (VMP and VMQ) also displays greater variability, though absolute fluctuations remain moderate. These findings point to the need for flexibility strategies that adapt to rapidly changing conditions, particularly around midday and evening transitions.

In Scenario C, the branched topology introduces a damping effect on temporal sensitivity variations. The CMdSdP and CMdSdQ coefficients follow patterns similar to those in Scenario B but with a narrower range of fluctuations. In particular, CMdSdQ remains positive throughout the day, reflecting the branched network's ability to distribute reactive power flows more evenly and avoid localized reversals. Voltage sensitivity (VMP and VMQ) shows very limited variability, highlighting the robustness of this configuration against hourly perturbations.

Across all scenarios, the interplay between PV generation and demand cycles emerges as a key driver of temporal variability in SCs. The presence of distributed generation introduces bidirectional flows and dynamic transitions in sensitivity, particularly in radial networks. By contrast, branched topologies tend to stabilize these effects, creating more homogeneous profiles over time.

These insights are particularly relevant for Local Flexibility Markets (LFMs), where temporal variability in SCs must be considered when designing flexibility products. Adaptive strategies that align with daily patterns, such as congestion management during evening peaks or voltage support during midday PV surpluses, are essential to ensure the technical and economic efficiency of flexibility interventions in active distribution systems

5.3 *GENERAL DISCUSSION: INTEGRATION OF LOCATIONAL AND TEMPORAL SENSITIVITY*

The combined analysis of locational and temporal variability in sensitivity coefficients (SCs) provides a comprehensive understanding of how distribution networks respond to perturbations under different topologies and levels of distributed generation (DG). This dual perspective highlights the dynamic nature of active networks and underscores the importance of adaptive operational strategies.

Across all scenarios, a clear relationship emerges between spatial and temporal variability. Nodes identified as critical in the locational analysis, such as N14 and N15 in Scenario A or N6 and N12 in Scenario B, also exhibit periods of heightened temporal sensitivity, particularly during evening demand peaks or midday solar surpluses. This overlap amplifies their operational significance, suggesting that flexibility interventions targeted at these nodes could yield maximal impact in mitigating congestion and supporting voltage stability.

Network topology plays a decisive role in shaping these patterns. Radial configurations (Scenarios A and B) concentrate sensitivity at peripheral nodes and show more pronounced temporal fluctuations, including bidirectional power flows in high-DG contexts. In contrast, the branched topology of Scenario C distributes flows more evenly, attenuating both locational hotspots and hourly variability. This structural difference implies that radial networks may require more granular, node-specific flexibility strategies, while branched systems could benefit from zone-based approaches focused on key feeders and branching points.

From an operational perspective, the findings highlight two critical time windows:

- Evening demand peaks, where reduced PV output leads to increased sensitivity and congestion risks.
- Midday solar hours, where distributed generation reverses flow and alters both active and reactive power dynamics.

Flexibility measures must be designed to address these transitions, ensuring that resources are deployed when and where they are most effective.

This integrated understanding of sensitivity variability forms the technical foundation for Local Flexibility Markets (LFMs). By identifying nodes and periods of criticality, network operators can define targeted flexibility products that align with the physical realities of the grid, enhancing both economic efficiency and system reliability.

Chapter 6. FUTURE WORK: FLEXIBILITY STRATEGIES AND MARKET APPLICATIONS.

The detailed analysis of the locational and temporal variability of sensitivity coefficients (SCs) presented in Chapter 4 highlights their potential role in supporting adaptive operational strategies and the design of Local Flexibility Markets (LFMs). By quantifying how active or reactive power perturbations propagate through distribution networks, SCs provide a technical foundation for identifying critical areas, prioritising flexibility resources, and enhancing both the technical and economic efficiency of grid operations.

However, it is important to emphasise that this thesis does not directly implement flexibility mechanisms or market designs. Instead, the insights gained suggest promising directions for future research and practical applications in active distribution networks.

6.1 IMPLICATIONS OF SENSITIVITY VARIABILITY FOR NETWORK OPERATION

The findings of this study reveal that SCs are neither spatially uniform nor temporally constant, which has direct implications for network management.

In radial networks with limited PV penetration (Scenario A), sensitivity tends to concentrate at peripheral nodes and peaks during evening demand hours, suggesting that flexibility interventions targeted at specific nodes and times can effectively mitigate congestion and support voltage stability.

In fully active radial networks (Scenario B), the presence of PV generation at all nodes introduces midday flow reversals and wider temporal variability, creating distributed hotspots of sensitivity. These dynamics require granular control schemes capable of adapting to rapidly changing conditions.

The branched network (Scenario C) exhibits a more balanced distribution of power flows, with attenuated sensitivity fluctuations. This topology allows for aggregated, zone-based flexibility approaches, as sensitivity patterns are more homogeneous across the network.

Across all scenarios, the findings reinforce the need to integrate sensitivity analysis into operational decision-making processes and to update SCs regularly. Outdated coefficients risk undermining network management strategies and compromising the efficiency of flexibility mechanisms.

6.2 PROSPECTIVE FLEXIBILITY STRATEGIES AND MARKET DESIGN

The variability of sensitivity coefficients also opens opportunities for designing flexibility strategies and bidding mechanisms that respond to the dynamic needs of active distribution networks.

One potential approach involves node prioritisation, where areas identified as critical through SC analysis guide the activation of distributed resources to alleviate congestion and improve voltage profiles. In Scenario B, for example, nodes such as N6, N12, and N15 exhibited high SC values and played a disproportionate role in grid performance. In Scenario C, nodes like N6 and N9 emerged as critical during periods of high PV activity. Targeting these areas in flexibility offers could maximise technical impact and reduce operational costs.

The temporal analysis further highlights the importance of aligning flexibility deployment with critical time windows. In networks with high PV penetration, nodes may even reverse their role (acting as net consumers or net generators) depending on the hour of the day. Incorporating these temporal dynamics into bidding strategies would allow resources to be concentrated where and when they are most effective.

Another prospective strategy involves defining flexibility clusters based on the spatial correlations observed in SC patterns. Rather than managing nodes individually, grouping them into technical zones could simplify operations and enable coordinated offers that respond to the network's overall needs. This aligns with proposals in recent literature advocating for the creation of flexibility areas managed jointly by distribution system operators, aggregators, and prosumers [17].

Finally, the dynamic nature of sensitivity coefficients underscores the need for periodic recalibration. Future research could explore the integration of real-time estimation platforms or artificial intelligence tools to ensure that bidding strategies are based on accurate and up-to-date information.

6.3 CONNECTING TECHNICAL ANALYSIS WITH LOCAL FLEXIBILITY MARKETS

The findings of this study highlight the potential of sensitivity coefficient analysis to bridge the gap between the technical evaluation of distribution networks and the practical implementation of Local Flexibility Markets. By providing insights into how active and reactive power perturbations propagate through the grid, SCs can support network operators in managing congestion and voltage more efficiently and offer aggregators robust technical criteria for defining competitive offers. Prosumers could also benefit from these approaches, participating in local markets and receiving incentives for delivering flexibility services that support system stability.

The comparative analysis of scenarios suggests promising directions for future work. In networks with partial distributed generation (Scenario A), hybrid strategies that combine centralised mechanisms in stable areas with dynamic flexibility offers at critical nodes could be explored. In fully active networks (Scenario B), a granular, real-time approach may be necessary to address the greater variability observed.

In summary, these insights provide a foundation for future research into adaptive bidding strategies and the development of LFMs tailored to the dynamic characteristics of active distribution networks. Such work could contribute to the design of smart and resilient markets that align flexibility activation with real-time system needs.

Chapter 7. CONCLUSION

This study has conducted an in-depth analysis of the locational and temporal variability of sensitivity coefficients in active distribution networks, evaluating their impact on network operation and exploring their potential applications in flexibility management. Through a methodological approach that combines statistical analysis, graphical representation, and operational reflection, relevant patterns have been identified that influence both congestion management and voltage regulation across different network configurations.

One of the most notable findings is that network sensitivity is not constant; it varies significantly depending on the location of nodes, the time of day, and the distribution of renewable generation. In Scenario A, characterized by a radial structure and photovoltaic (PV) generation limited to six nodes, the coefficients exhibit stable and predictable behaviour, with predominantly unidirectional power flows and sensitivity concentrated in peripheral areas. This pattern suggests that flexibility strategies in such networks should focus on centralized mechanisms and on mitigating congestion in lines distant from the main supply point.

In contrast, Scenario B, with PV generation distributed across all nodes, exhibits more complex behaviour. The network operates in a fully active state, and bidirectional flows introduce greater dispersion and temporal variability in the SCs. Critical areas emerge dynamically, reflecting the need for granular and adaptive strategies capable of responding to dynamic operating conditions in real time.

Scenario C, defined by a branched topology, further emphasizes the influence of network structure on sensitivity patterns. The main bifurcation generates divergent behaviours in the two branches: while one shows a progressive decrease in sensitivity as distance from the transformer increases, the other maintains more homogeneous coefficients but with localized outliers. These findings underscore the importance of considering topology when designing control mechanisms and flexibility strategies.

The temporal analysis revealed that sensitivity is not uniform throughout the day. In networks with high PV penetration, nodes alternate between acting as net loads or net generators depending on the time window. This diurnal variability indicates that flexibility offers should target critical time windows to maximize their technical and economic effectiveness.

Additionally, the spatial correlation analysis revealed the potential for defining flexibility clusters in active networks. In scenarios with distributed generation, the high degree of coupling between nodes suggests that coordinated offers at the level of technical areas could simplify operations and improve overall system efficiency.

A key conclusion of this study is that static or outdated SCs are insufficient for the management of modern networks. Without periodic recalibration, operational decisions may become inefficient or even counterproductive, leading to over-procurement or under-procurement of flexibility resources and leaving critical needs unresolved.

Beyond the technical analysis, this work highlights the potential of SC-based approaches to support the design of adaptive bidding strategies and Local Flexibility Markets (LFMs). While these aspects were not directly implemented in this thesis, they represent promising avenues for future research.

As future directions, the development of artificial intelligence tools for the automatic detection of critical areas, the implementation of real-time bidding algorithms, and the validation of these strategies in advanced simulation environments or pilot projects are suggested. These developments would consolidate the role of SC analysis as an essential element in the dynamic and efficient operation of future power networks.

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ANEXO I

The Python code developed as part of this work performs the statistical and graphical analysis of sensitivity coefficients in active distribution networks. It automates the processing of hourly load flow results, calculates locational and temporal metrics (CMdSdP, CMdSdQ, VMP, and VMQ), and generates the visualizations used throughout the study, including boxplots, heatmaps, daily trends, and correlation matrices. The source code is available in the following GitHub repository:
https://github.com/ClaudiaCantalapiedra/TFG/blob/main/analisisdatos.ipynb
Its inclusion in this annex serves to document the computational methodology applied and facilitates the reproducibility of the analysis for future research.

The appendices also contain all supplementary figures and results that were not included in the main body of the document. These images provide detailed analyses by scenario and coefficient, enabling the reader to explore the specific characteristics of each node and the temporal evolution of the metrics. This comprehensive set of results supports a deeper understanding of the locational and temporal variability identified in the study.

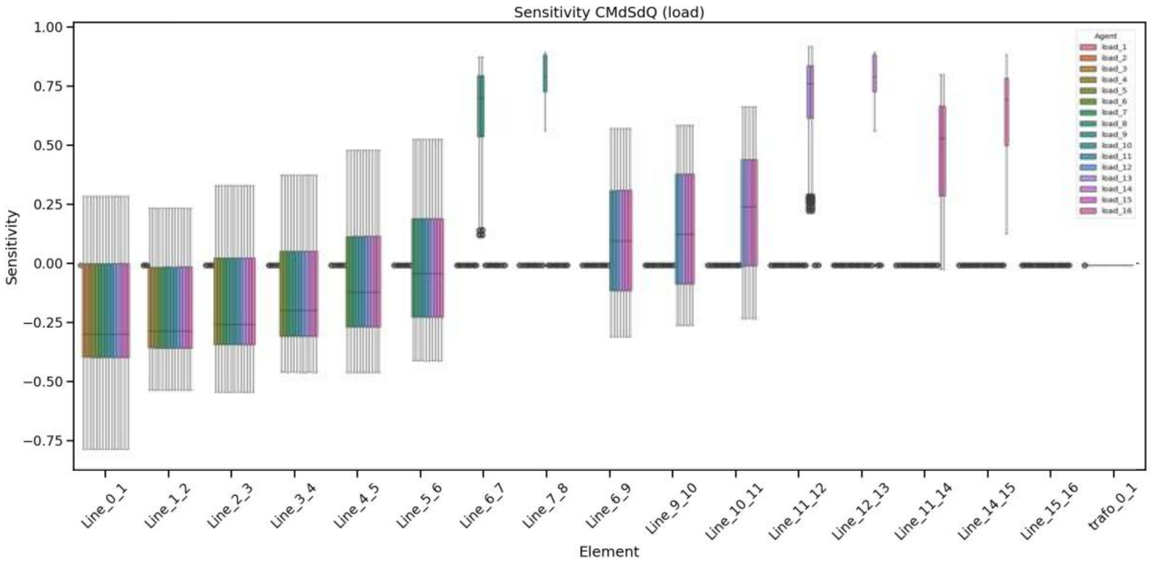

Figure 25. Boxplots of CMdSdQ for load nodes, Scenario A. Source: Own elaboration

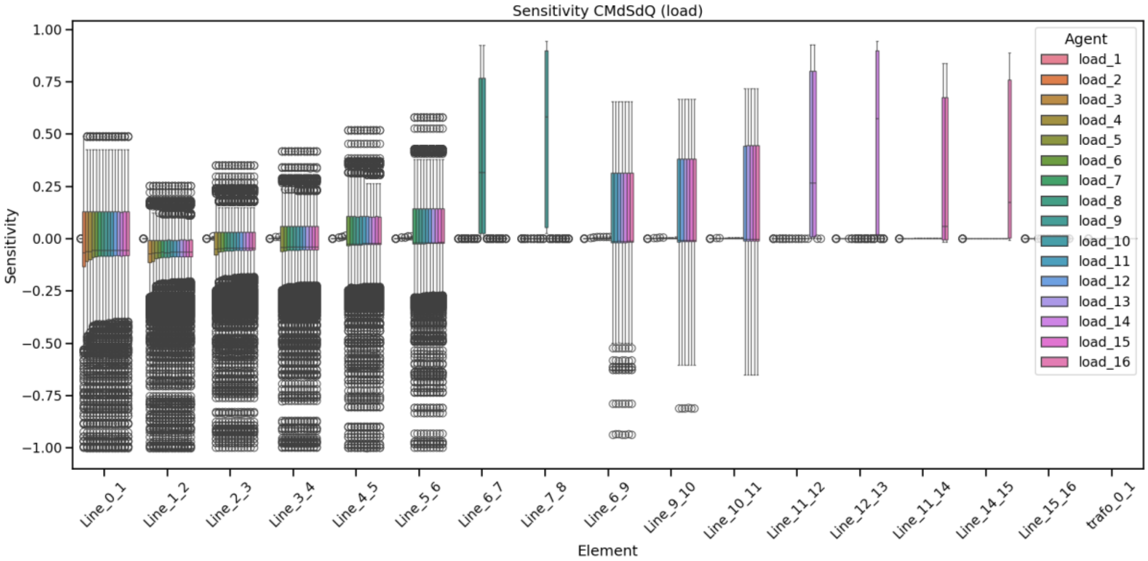

Figure 26. Boxplots of CMdSdQ for load nodes, Scenario B. Source: Own elaboration

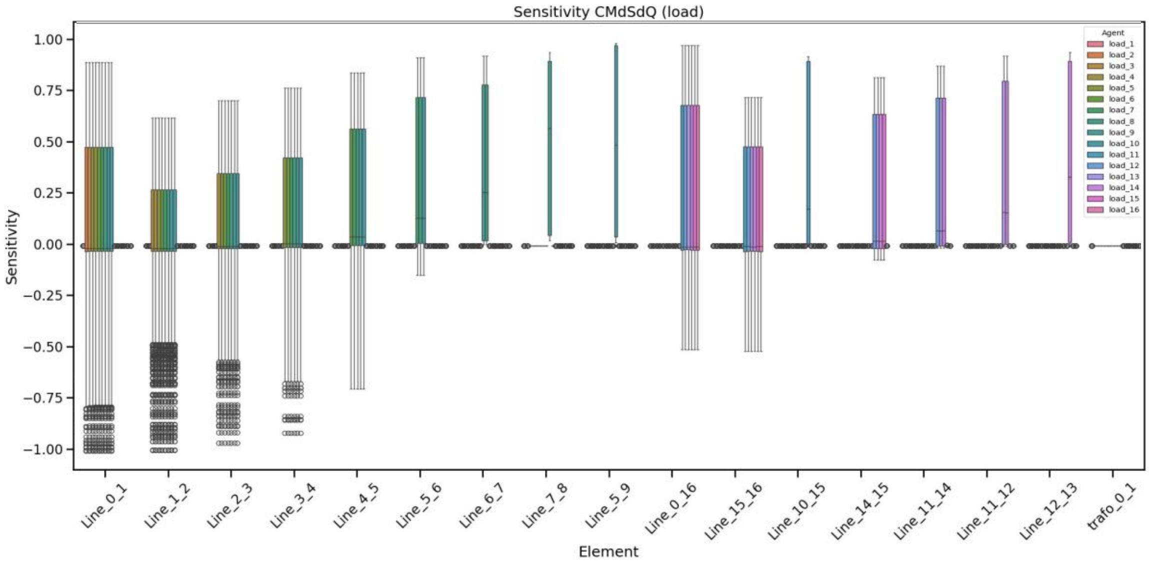

Figure 27. Boxplots of CMdSdQ for load nodes, Scenario C. Source: Own elaboration

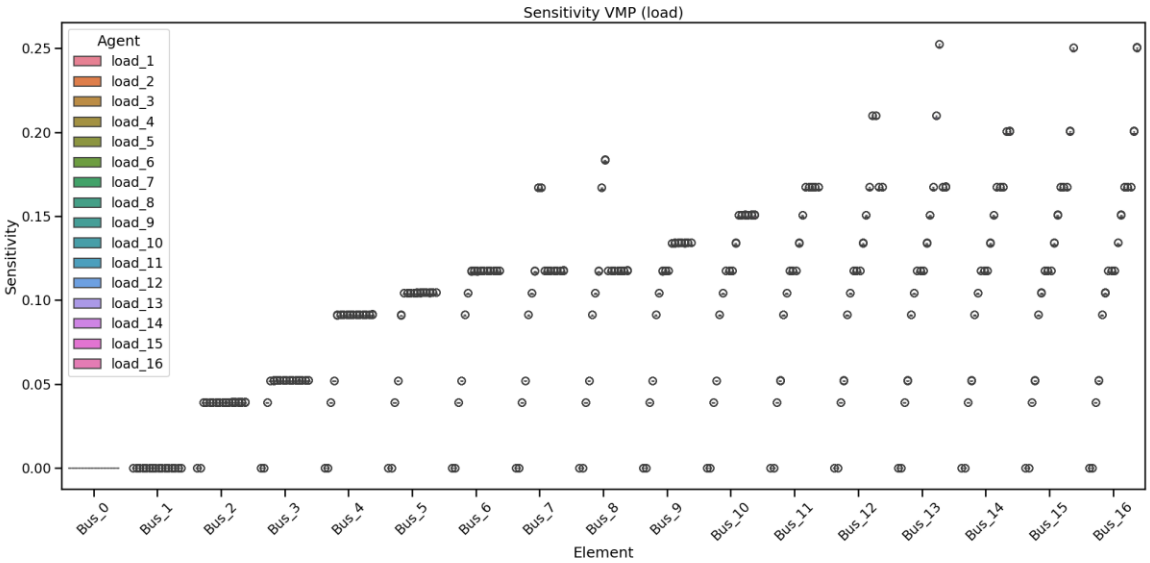

Figure 28. Boxplots of VMP for load nodes, Scenario A. Source: Own elaboration

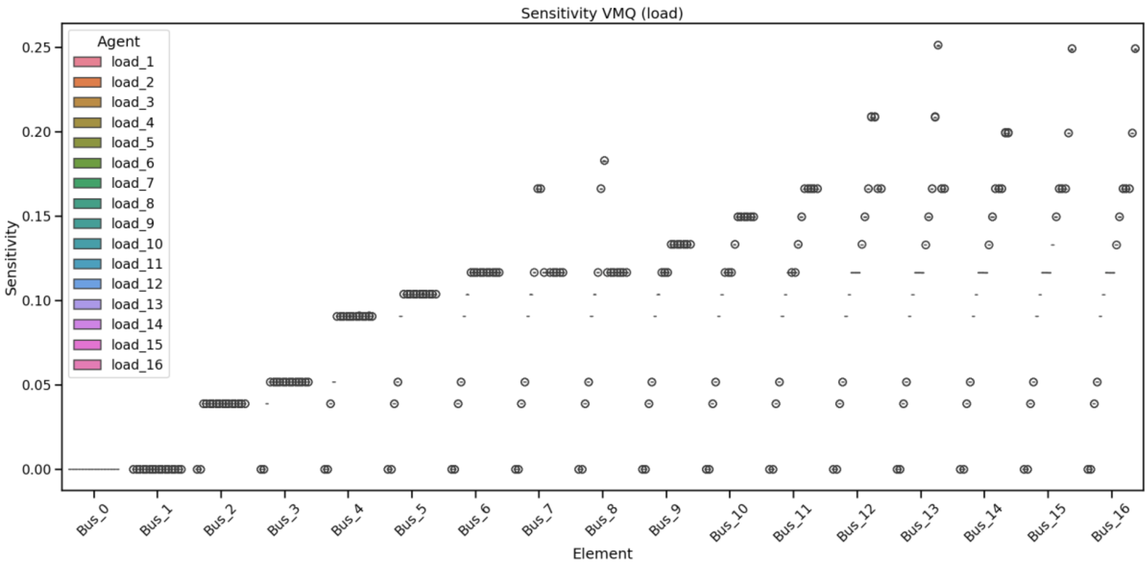

Figure 29. Boxplots of VMQ for load nodes, Scenario A. Source: Own elaboration

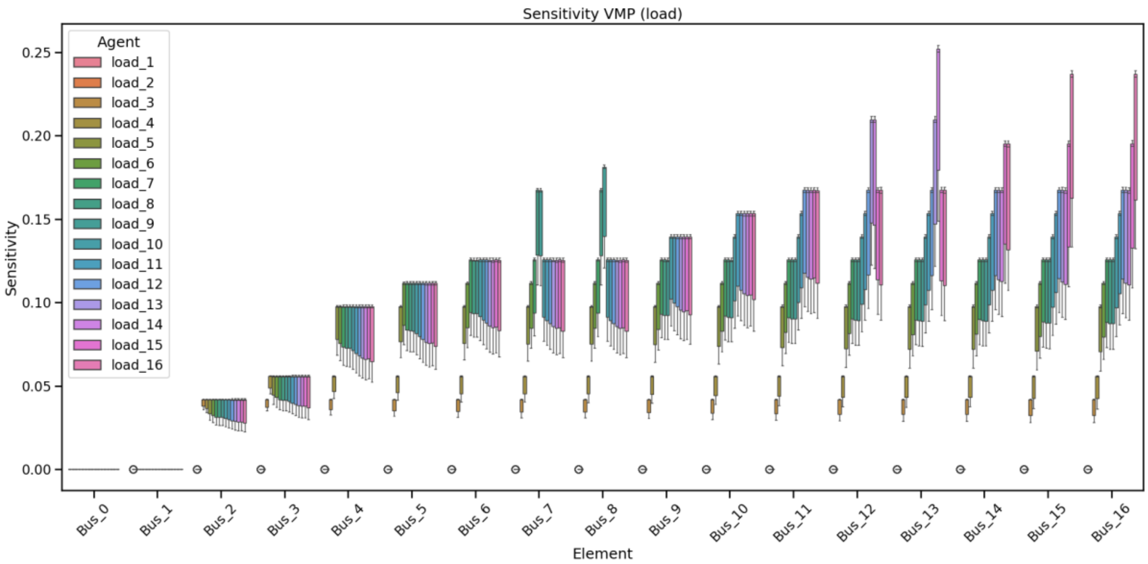

Figure 30. Boxplots of VMP for load nodes, Scenario B. Source: Own elaboration

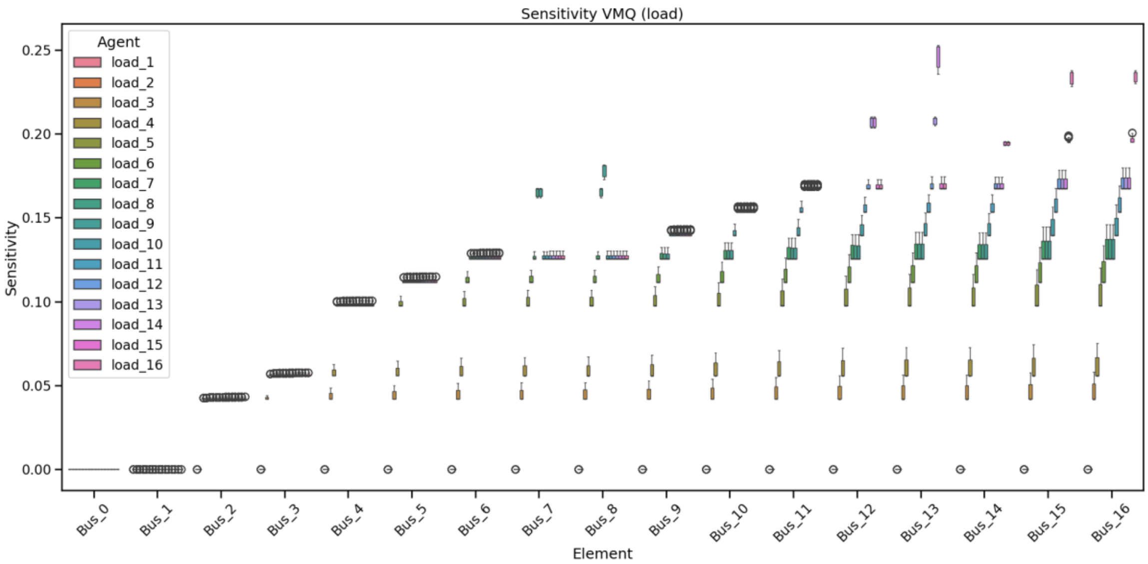

Figure 31. Boxplots of VMQ for load nodes, Scenario B. Source: Own elaboration

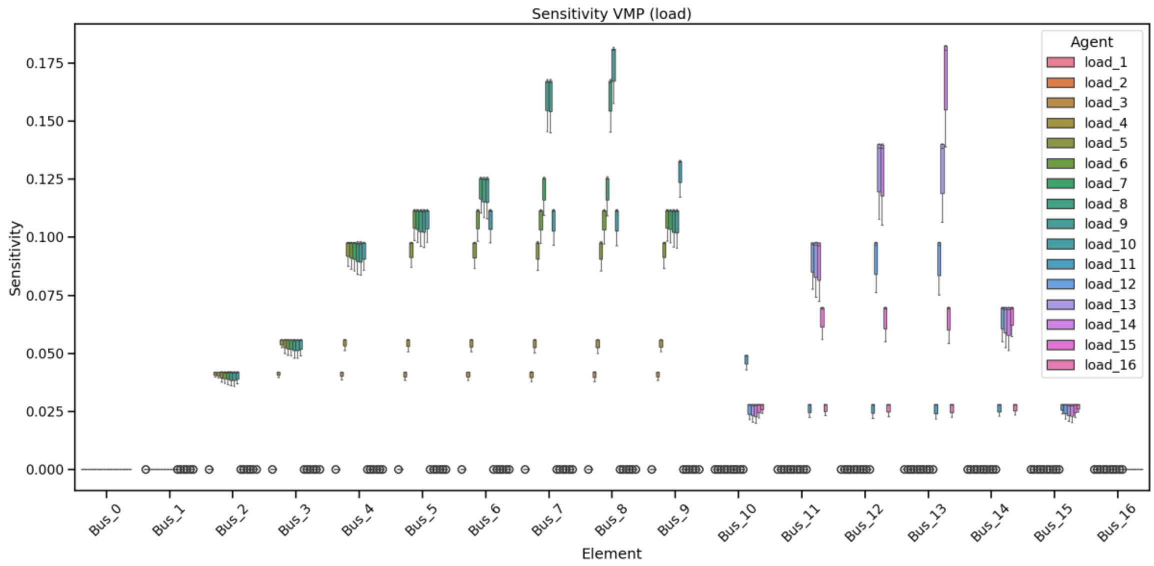

Figure 32. Boxplots of VMP for load nodes, Scenario C. Source: Own elaboration

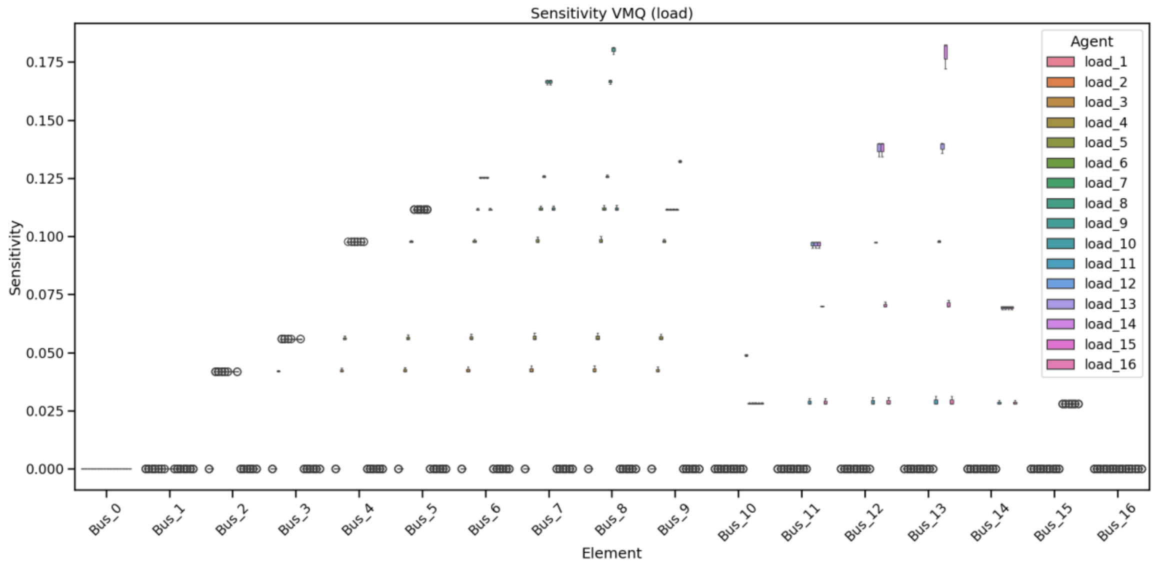

Figure 33. Boxplots of VMQ for load nodes, Scenario C. Source: Own elaboration

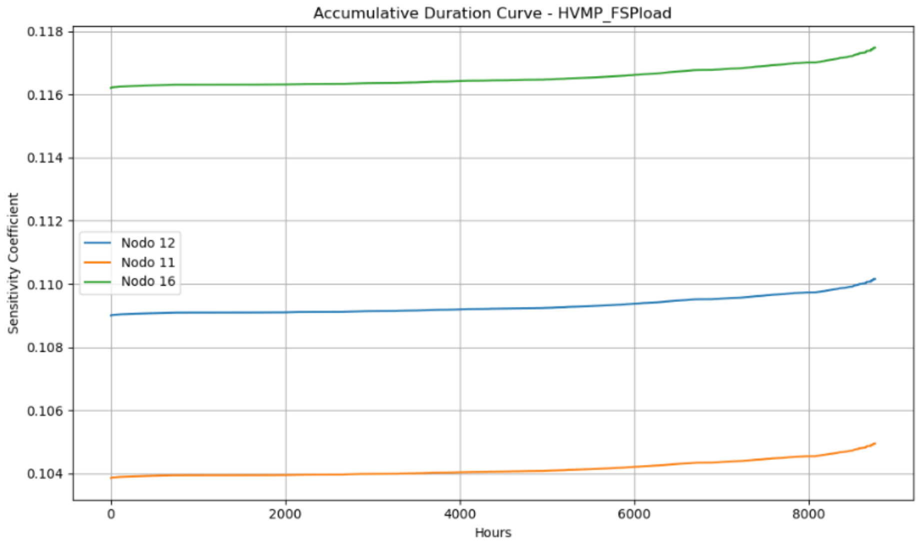

Figure 34.Cumulative duration curve for loads in Scenario A. Source: Own elaboration

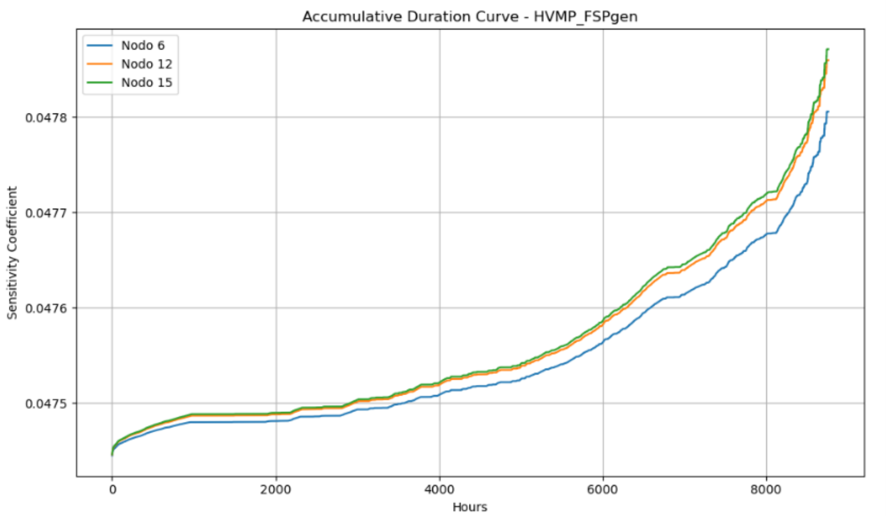

Figure 35.Cumulative duration curve for generation in Scenario A. Source: Own elaboration

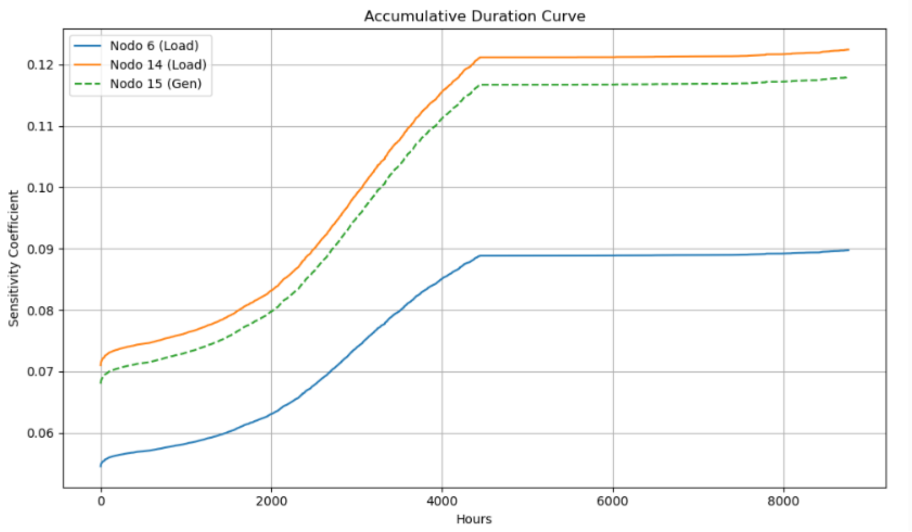

Figure 36.Combined cumulative duration curve for load and generation in Scenario B. Source: Own elaboration

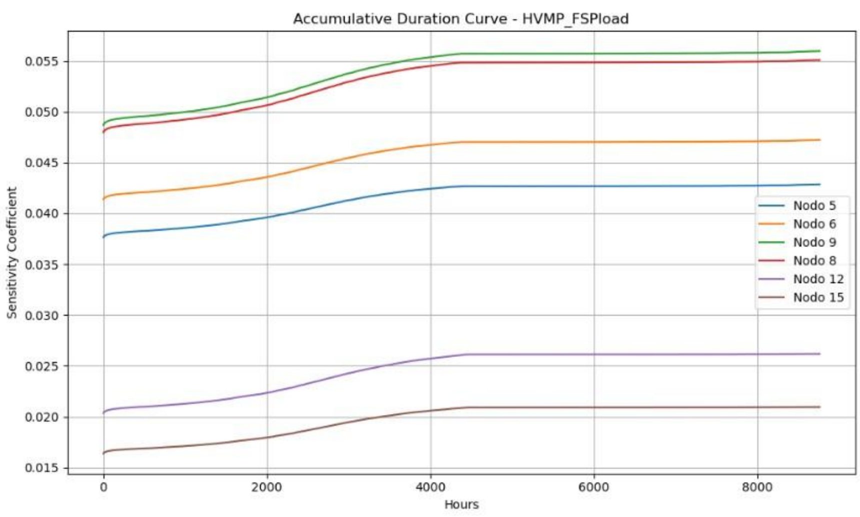

Figure 37. Cumulative duration curve for loads in Scenario C. Source: Own elaboration

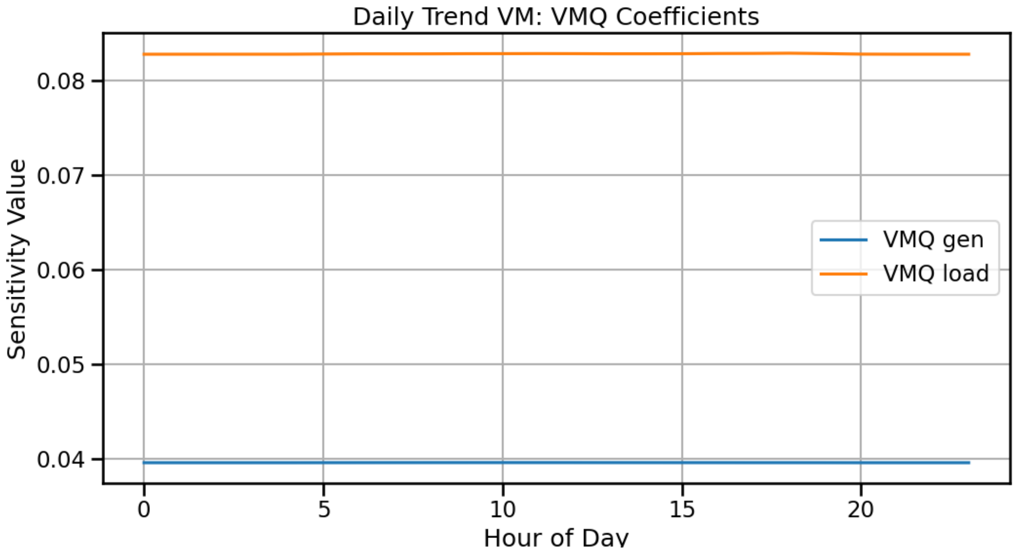

Figure 38. Daily trend of VMQ coefficients, Scenario A. Source: Own elaboration

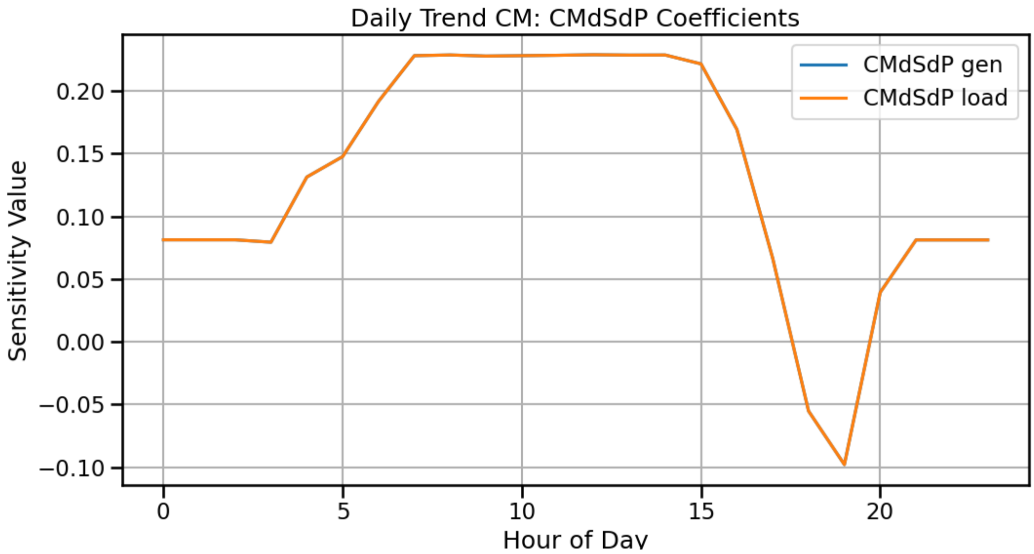

Figure 39. Daily trend of CMdSdP coefficients, Scenario C. Source: Own elaboration

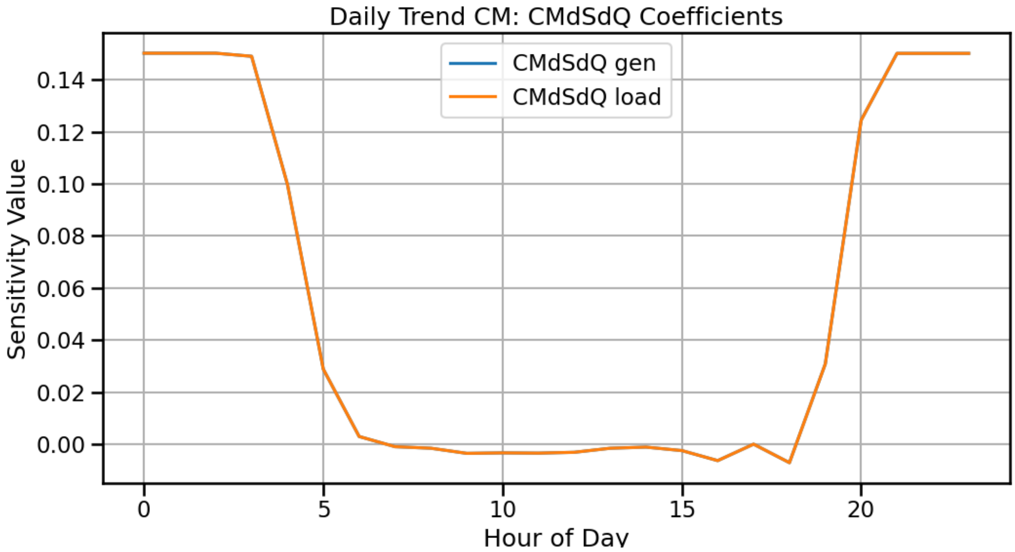

Figure 40. Daily trend of CMdSdQ coefficients, Scenario C. Source: Own elaboration

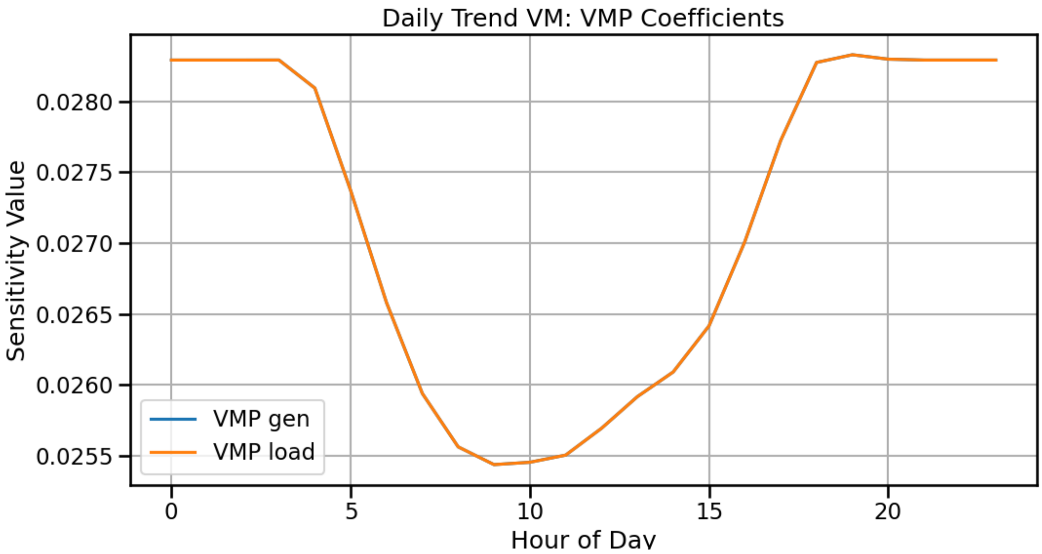

Figure 41. Daily trend of VMP coefficients, Scenario C. Source: Own elaboration

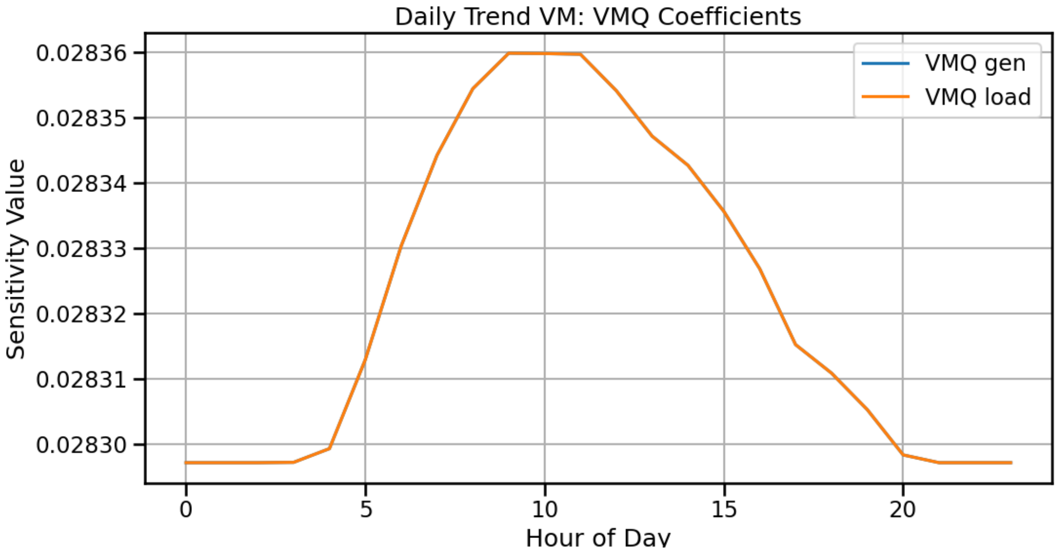

Figure 42. Daily trend of VMQ coefficients, Scenario C. Source: Own elaboration

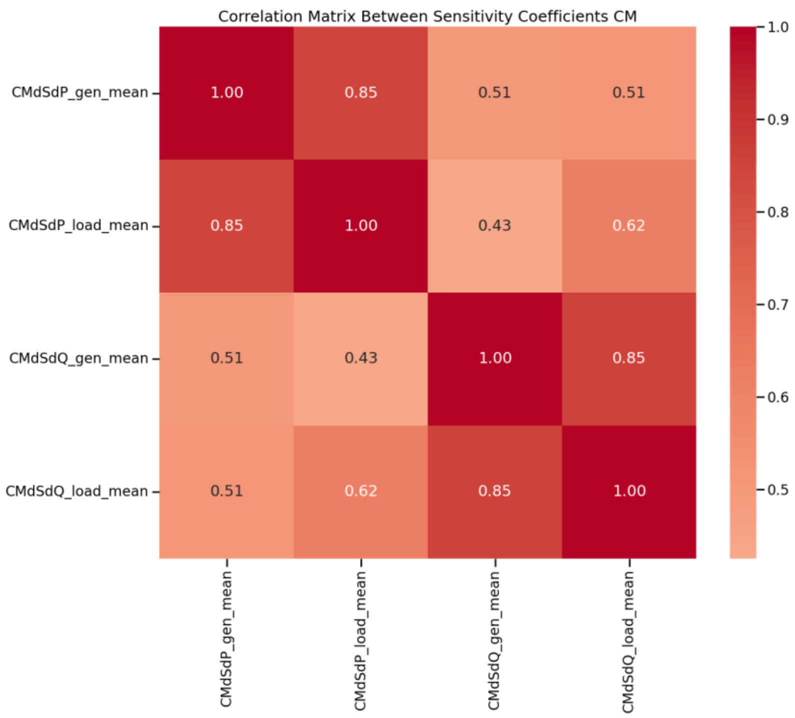

Figure 43. Correlation matrix of CMdSdP and CMdSdQ, Scenario A. Source: Own elaboration

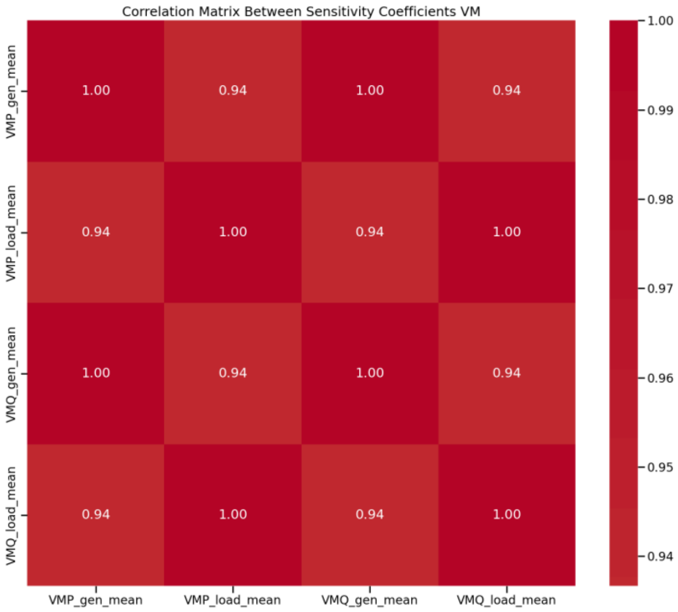

Figure 44. Correlation matrix of voltage sensitivity coefficients (VMP and VMQ), Scenario A. Source: Own elaboration

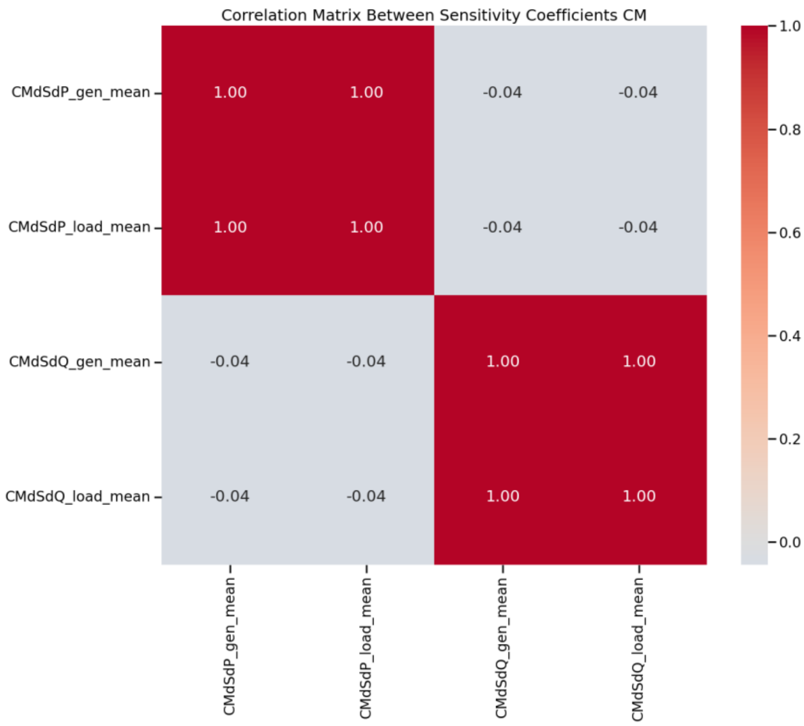

Figure 45. Correlation matrix of CMdSdP and CMdSdQ, Scenario B. Source: Own elaboration.

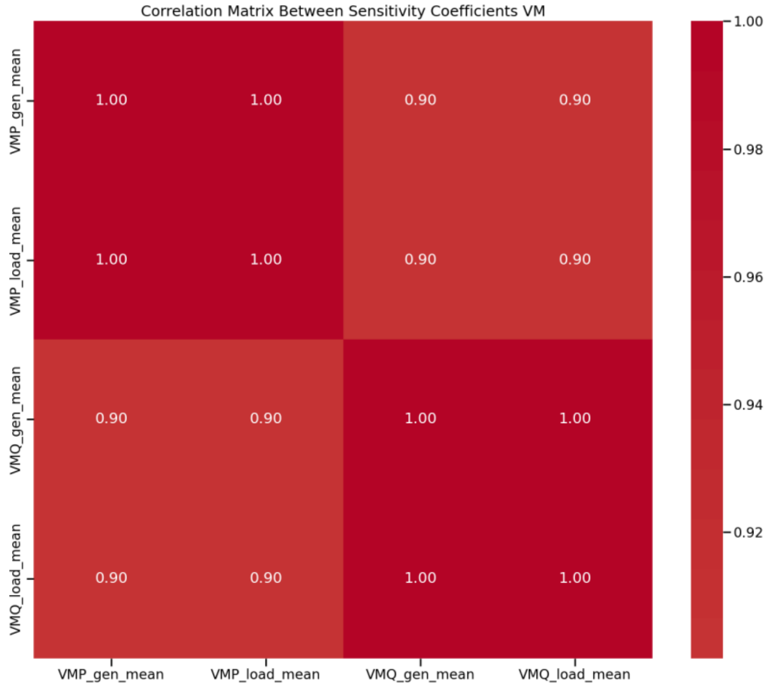

Figure 46. Correlation matrix of voltage sensitivity coefficients (VMP and VMQ), Scenario B. Source: Own elaboration.

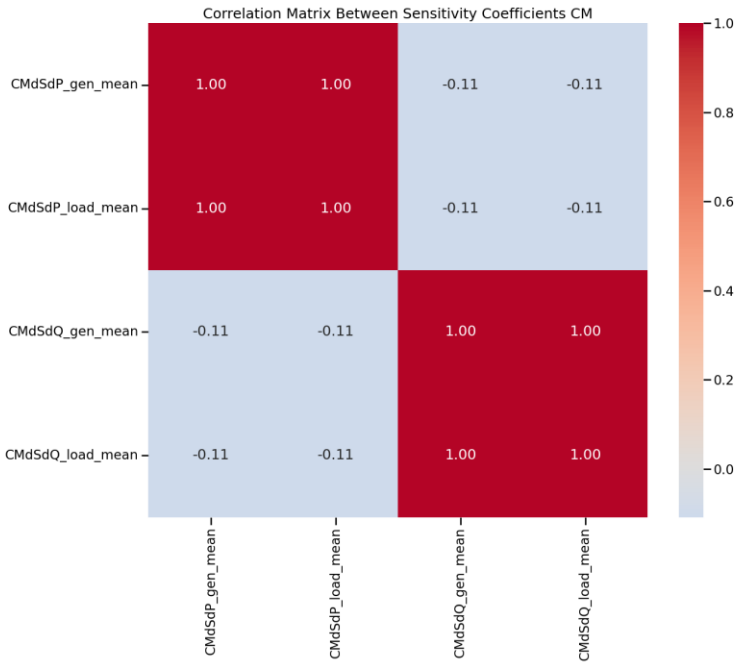

Figure 47. Correlation matrix of CMdSdP and CMdSdQ, Scenario C. Source: Own elaboration

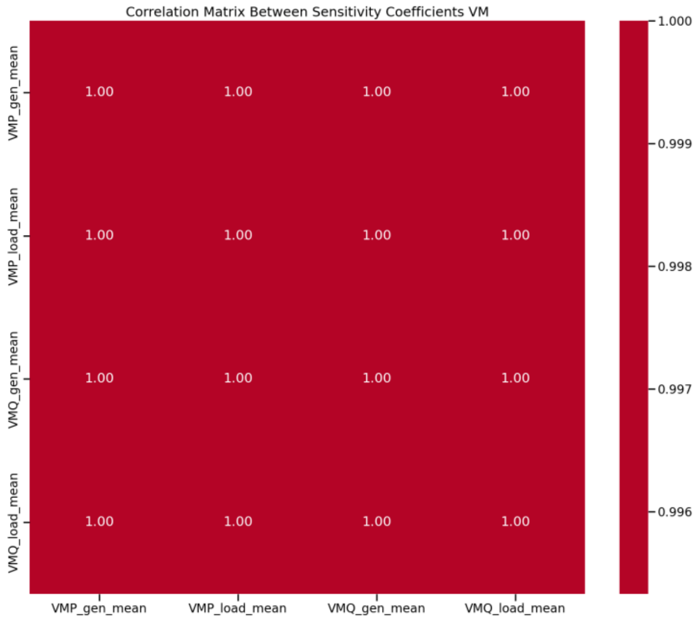

Figure 48. Correlation matrix of voltage sensitivity coefficients (VMP and VMQ), Scenario C. Source: Own elaboration.