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Small signal stability in low-renewable power systems: A 138 kV Santo Domingo case study

Estabilidad de pequeñas señales en sistemas eléctricos con limitada presencia renovable: Caso Santo Domingo

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KEYWORDS
Renewable energies; small signal; frequency stability; maximum damping; Prony’s method
Energías renovables, pequeña señal, estabilidad de frecuencia, máxima amortiguación, método de Prony

ABSTRACT: Small signal stability in electrical systems refers to the ability of the system to maintain stable operation in the face of low-amplitude disturbances, such as fluctuations in electrical demand or the off and on switching of generators. This type of analysis is essential because it provides insight into how the system responds to minor disturbances, such as variations in generation or unplanned load. Significant disturbances can induce unstable conditions with potentially serious consequences, such as widespread power outages. Advanced mathematical techniques address these issues, such as the Fourier transform and the Prony method. In this study, a method was developed using MATLAB, and flow runs were performed in Digsilent software to analyze the oscillations of small signals in a 138 kV substation with low penetration of renewable energy. This research is relevant because it allows us to assess the impact of small disturbances in the electricity system during the transition toward greater integration of renewable technologies. The goal is to improve the efficiency and safety of electrical infrastructure in the Dominican Republic, ensuring a more reliable and stable energy supply for residents and businesses. The analysis shows that the current system can absorb anomalies of small signals due to the low penetration of renewables. In addition, the tool developed allows the evaluation of scenarios with greater penetration of renewable energy, providing a solid basis for implementing preventive or corrective measures.

RESUMEN: La estabilidad de señal pequeña en sistemas eléctricos se refiere a la capacidad del sistema para mantener un funcionamiento estable frente a perturbaciones de baja amplitud, como fluctuaciones en la demanda eléctrica o la conexión y desconexión de generadores. Este tipo de análisis es esencial porque ofrece información sobre cómo el sistema responde a perturbaciones menores. Las perturbaciones significativas pueden inducir condiciones inestables con potenciales consecuencias graves. Para abordar estas cuestiones, se emplean técnicas matemáticas avanzadas, como la transformada de Fourier y el método de Prony. En este estudio, se ha desarrollado un método utilizando MATLAB y realizando corridas de flujo en software Digsilent para analizar las oscilaciones de pequeñas señales en una subestación de 138 kV con baja penetración de energía renovable. Esta investigación es relevante porque permite evaluar el impacto de las pequeñas perturbaciones en el sistema eléctrico durante el proceso de transición hacia una mayor integración de tecnologías renovables. El objetivo es mejorar la eficiencia y seguridad de la infraestructura eléctrica en la República Dominicana, asegurando un suministro de energía más confiable y estable para residentes y empresas. El análisis demuestra que el sistema actual es capaz de absorber anomalías de pequeñas señales debido a la baja penetración de renovables. Además, la herramienta desarrollada permite la evaluación de escenarios con mayor penetración de energía renovable, proporcionando una base sólida para la implementación de medidas preventivas o correctivas.

1. Introduction

Renewable energy sources notably impact the transmission grid's small-signal characteristics. There is a growing concern that fluctuations in supply could jeopardize the stability of the transmission grid [1].

Stability has become a critical factor in an ever-evolving environment where technical advancements and the complexity of electrical and electronic systems have become more significant. To maintain system’s optimal and dependable performance, it is now essential to anticipate and comprehend how they will react to small amplitude disruptions [2]. For example, changing weather conditions such as cloud cover or variation in sunlight intensity can affect solar energy production. The abovementioned factors can result in fluctuations in electrical power generation and, therefore, small disturbances in the electrical system [3].

Small-signal stability, a cornerstone of electrical, electronic, and control systems engineering, describes a system's ability to maintain synchronization despite minor disturbances. It assesses how a system responds dynamically around its stable operating point and investigates the impact of disturbances and low-magnitude fluctuations. This evaluation is necessary to ascertain the system's resilience and capacity to continue providing steady performance across various operating circumstances [4].

The increasing use of solar and wind energy has made it difficult to maintain grid stability [5]. Due to their limited ability to regulate frequency, these generation systems respond with delay to disturbances, such as load variations or transmission line failures. This slow response can cause electrical generators to lose synchronization, which in turn can lead to blackouts and equipment damage. It is therefore essential to analyze low-frequency disturbances to ensure system stability and avoid more serious consequences [6] [7].

Renewable power sources and dynamic loads will increase volatility and complexity in future power systems, changing how power systems operate [8].

In power systems with low renewable energy penetration, small-signal stability is crucial. This refers to the ability of the system to maintain its operational equilibrium in the face of disturbances. Although it may initially seem less susceptible to instabilities, the transition to renewable sources requires adaptation.

Understanding how disturbances affect a conventional generation from fossil fuels with a high mechanical inertia system is critical to a stable transition to a future with high renewable energy penetration [9].

In conclusion, small signal analysis is a fundamental tool to ensure the stability of the Dominican electricity system, especially because the power system of the Dominican Republic is dominated by coal and natural gas plants. However, in long-term planning, scenarios with high penetration of renewable energy and little generation with fossil fuels are proposed, which is a challenge for the stability of the Dominican electric power system.

Considering the aforementioned, this study aims to provide a tool for evaluating the behavior of the electrical system where intermittent renewable energies are incorporated. A model was developed to assess the stability of small signals in electrical power systems (EPS), enabling the assessment to be carried out. The main contributions of this paper are as follows:

- Analysis of the impact of small signal oscillations in the electrical system with low penetration of renewable energy.
- Development of a mathematical program that allows analyzing and interpreting small signal disturbances in power systems.
- To compare the identification of different oscillation modes in a system with low renewable energy penetration in the Dominican Republic and another system with moderate renewable energy penetration in Peru to evaluate the impact of small disturbances in an electrical system.

This paper is organized as follows: Section 2 presents the methodology used to develop the proposed model. Section 3 analyses the low oscillations found in a power system. Additionally, the proposed method for analyzing small signals is presented. Section 4 displays the simulation results for each of the scenarios. Section 5 provides a summary and recommendations for future directions.

2. Methodology

To carry out this study, small-signal oscillations in power systems were analyzed using the phases presented in this section.

The initial phase of the study focused on identifying and evaluating different types of oscillations that can occur within electrical power systems. Various small signal analysis techniques were also explored to understand the behavior of these oscillations. In the second phase, popular software tools such as MATLAB Simulink, Octave, and Digsilent were compared to determine their effectiveness in analyzing small signal models and simulating the behavior of power systems under different conditions.

For the third phase, a specific section of the Dominican Republic's electrical power grid was selected for in-depth analysis. This section included a diverse mix of generators making it a representative example of the country's power system. Additionally, this area had a history of experiencing oscillations or disturbances, providing valuable data for studying these phenomena. The 138 kV bus in Santo Domingo was chosen as the focal point of this analysis.

In the fourth phase, different scenarios were simulated to assess the system's response to various conditions. These simulations were divided into morning and evening blocks to capture potential variations in load and generation patterns throughout the day. Furthermore, a comparative analysis was conducted between the oscillation modes observed in the Dominican Republic's power system and those found in the Peruvian power system. This comparison aimed to identify similarities, differences, and potential contributing factors to the observed oscillations in both countries.

3. Analysis of Power System Low Oscillations

The effectiveness of power system stability is evaluated in terms of how the system behaves when disturbed. It is considered stable if, after a disturbance, no generator or load protection trips occur, except for isolation trips to protect the system. The study of the stability of power systems is divided into three study groups dedicated to a specific area depending on the magnitude that causes system instability. These groups are angle, voltage, and frequency stability [10].

Angle stability is the ability of electrical generators to maintain synchronism with the electrical grid after a disturbance. This stability is directly linked to the ability of synchronous machines to maintain the balance between mechanical and electromagnetic torque [11]. Voltage stability is the ability of the power system to maintain its voltage on the substation bars within the permitted parameters of normal and post-disturbance operation of the system [12]. Frequency stability is the ability of power systems to maintain frequency values at a constant operating value or values close to this after a significant disturbance has occurred in the network. The IEEE PES introduces resonance stability (HVDC systems, FACTS devices, and DFIG controls can introduce torsional and electrical oscillations in power grids, affecting resonance stability by interacting with rotating machinery, voltage control mechanisms, and grid dynamics) and converter-driven stability (interactions between converters, grid faults) in the new classification of power system stability, included in technical report TR77 [13].

This study focuses on the stability of the frequency after a failure or sudden imbalance occurs in the system's generation and load relationship [14]. Figure 1 shows the distribution of the different stability studies and the attributions corresponding to each system.

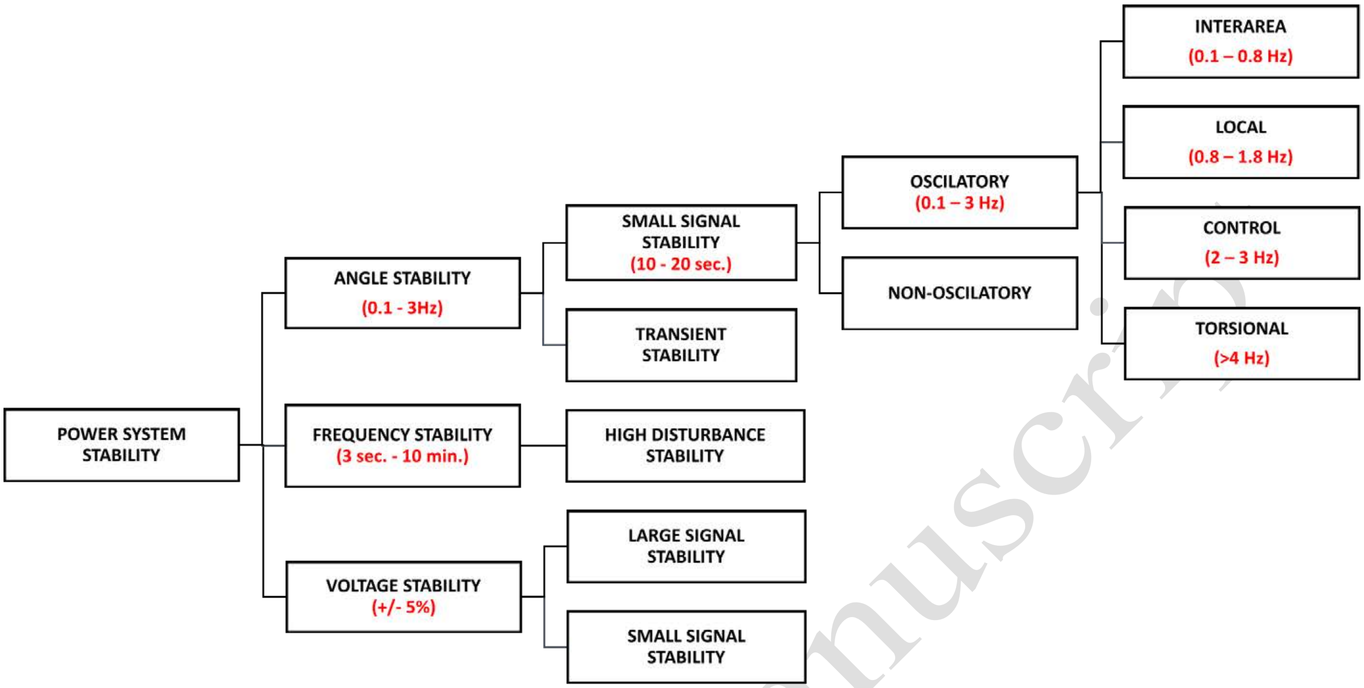


Figure 1. Stability classification of electrical systems

The small signal stability study is an analytical tool for assessing an EPS's behavior in the face of potential small-magnitude occurrences. Transmission line openings, load block or generator connections and disconnections, and EPS control can all result in small signal oscillations. Signal oscillation modes are typically used to categorize small signal oscillations. These modes can be classified into control, torsional, interarea, and local [15].

- In control mode, these oscillation patterns result from flaws in power plant management systems. They are connected to power system control circuits that include excitation devices, voltage regulators, frequency regulators, and other management parts that keep the electrical system stable in the face of disruptions. Since they typically happen when one plant oscillates concerning another, they are also known as internal plant modes [16].
- The oscillations produced by the generating plants' mechanical systems are known as torsional modes. In the electrical system, they manifest as mechanical oscillations, particularly in the rotating rotor and shaft of generators. They have to do with the generator's electrical network and the turbine's inclination for its component elements to oscillate [17].
- The oscillation mode, known as the interarea mode, appears in large-scale or interconnected EPSs when transmission lines connect two or more sizable regions. Weak linkages cause these oscillations, interfering with the grid's ability to run all its generators [18].
- The local mode is the oscillation mode produced by a generator or power plant connected to a sizable EPS. In this mode, the network's behavior is influenced by the generator's oscillations interacting with it. Some grid-connected producing units may produce these oscillations or occur between generators in the same plant or adjacent plants [19], [20].

These modes function as a signal of the criticality of the oscillations and the kind of oscillation and behavior that occur in the system [21]. **Table 1** displays the classification of EPS oscillation modes, their frequency ranges, the location of typical oscillations, and some of their most important consequences.

Table 1. An overview of the modes of oscillation

Ref.	Mode	Minimum Frequency (Hz)	Maximum Frequency (Hz)	Occurrence Place	Effects
[16]	Control	2	3	Control equipment	Insertion of poles in the stability diagram
[17]	Torsional	4	> 4	Mechanical systems	Vibrations in the axes of the machines
[18]	Interarea	0.1	0.8	Between areas	Active and reactive power oscillations
[19]	Local	0.8	1.8	Power plant	Frequency oscillation

Based on the system's data and the arrangement of analysis techniques, one can approach the stability of a small signal in a topic from various angles. **Table 2** summarizes the different methods of small signal analysis.

Table 2. Small-signal analysis methods overview

Method of Analysis	**Reference**	**Description**	**Advantages**	**Disadvantages**
Analysis by synchro phasor measurement	[22]	Phasor-based real-time stability measurement	Real-time stability monitoring essential	Advanced tech raises complexity
Modal analysis		Analyze natural frequencies, oscillations	Identifies modes, detects resonance	Increased size complicates implementation
Analysis of eigenvalues	[23]	Eigenvalues represent oscillation frequencies	Accurate stability and oscillations representation.	Complex results in nonlinear systems
Prony's Method	[24]	Fourier analysis with modal information	Assesses transient stability, disturbances	Intensive data processing challenges
Lyapunov method	[24]	Stability index from asymptotic stability	Flexible across various systems	System-dependent, not universally applicable
State Spaces Method	[25]	Represents the system via state variables	Detailed stability via pole locations	In-depth knowledge of control theory. Difficult to

Method of Analysis	**Reference**	**Description**	**Advantages**	**Disadvantages**
				implement in large systems
AESOPS algorithm	[26]	Analyze spontaneous oscillations: frequency, amplitude, duration	Mitigates unexplained spontaneous oscillations	Complex cause identification requires analysis.
Jacobian	[27]	Linearize the system, calculate Jacobian equations	Quick approximation for linear systems	Not valid for large perturbations
Fourier transform	[28]	Decomposes signal for stability analysis	Analyzes periodic and non-periodic signals	Inadequate for complex nonlinear dynamics
Stockwell Transform (S-Transform)	[29]	Combines Fourier and wavelet transforms	Detailed time-frequency representation for transients	Requires complex computational processing.

The system's frequency, an extract from the EPS that models the required machinery, and other techniques that enable the study of this topic can all be used to investigate the EPS. Regarding assessment techniques, EPS can be assessed by mathematical models, including modal analysis, eigenvalue decomposition, the Prony method, and the Fourier transform [30]. The Prony method and the Fourier transform were used for the proposed model. The Prony method was chosen for this study because the Coordinating Organism of the Interconnected Electrical System (OC-SENI) of the Dominican Republic had successfully used it in the past to analyze transient stability and disturbances.

The Prony method analyzes modal information such as relative phase, damping, and frequency. This method is an extension of Fourier analysis with the option of taking modal information from the different simulation programs used for power system analysis. This method can acquire modal information, including transient stability or specific large-scale disturbances. In conclusion, this tool is widely used in studies conducted on a transmission system power [31]. The mathematical description is as follows (see **Equation 1**):

$$\hat{\boldsymbol{y}}(\boldsymbol{t}) = \sum_{\boldsymbol{i}=\mathbf{1}}^{\boldsymbol{n}} \boldsymbol{A}_{\boldsymbol{i}}\, \boldsymbol{e}^{\boldsymbol{\sigma i\, t}} \boldsymbol{cos}\, (\boldsymbol{\omega}_{\boldsymbol{i}} \boldsymbol{t} + \emptyset_{\boldsymbol{i}}) \tag{1}$$

Where A_i are the amplitude components of the series, σi are the damping components, ω_i are the angular-frequency components, $\emptyset_{and\ i}$ are the phase components.

The Fourier transform allows us to decompose a signal into its frequency components, defined as follows: If f(t) is a signal in the time domain, then its Fourier transform F(ω) in the frequency domain is given by [32]. The mathematical description is as follows (see **Equation 2**):

$$F(\omega) \ = \ \int \ f(t)\ e\hat{}(-i\omega t)\ dt \tag{2}$$

Where i is the imaginary unit, ω is the angular frequency, and the integral is taken over the entire time domain.

During operation, power systems can produce instability in some system parameters, such as voltage, current, power, and frequency oscillations. Because of this, methods and systems have been designed over time to compensate for these oscillations. These systems are known as shock absorbers [33].

Dampers in power systems are the equipment responsible for damping or attenuating system oscillations that produce instability in the network. Among the dampers used today, we can find the Automatic Voltage Regulator (AVR), which regulates the voltage of the generators. The Power System Stabilizer (PSS), which operates in conjunction with the AVR, is also used to increase the damping of the oscillation modes that may be generated in the system [34].

Damping plays a vital role in a power system's oscillations. Damping torque analysis is a study in which the low-frequency oscillations found in a power system are analyzed. It also indicates that this damping torque can affect the main characteristics of the attenuation of the oscillation mode of the power system [35].

3.1 Methods Delimitation

In post-event stability studies, the Prony method of signal analysis is employed to ascertain the oscillations of the signal, their damping, and the oscillation frequencies' constituent parts. The Fourier transform is a mathematical tool for breaking down a function or signal into its frequency components. By converting a function or signal from the time domain to the frequency domain, the Fourier transform enables analysis and comprehension of the many frequency components present in the signal. A frequency spectrum that displays the amplitude and phase of each frequency component present in the original signal can be created by applying the Fourier transform to a signal [36], [37].

Several engineering applications apply a mathematical formula called the wavelet transform to signal analysis. It works by breaking a signal into several elements known as wavelets, which are functions that fall into the time and frequency domains. This transform can represent both high-frequency and low-frequency information. [38], [39].

To assess the study scenario, a comparative analysis of various techniques available for evaluating small perturbations was conducted. The frequency spectrum, a graphical representation of a signal's components, was utilized to differentiate between the different analysis methods. The amplitudes and phases of the various frequency components that make up the original signal are revealed when a frequency analysis uses methods like the Fourier transform. The frequency spectrum represents this information [40], [41].

Poles and zeros are techniques used to analyze a system's stability [42]. In the complex plane, poles, and zeros are both significant locations that reveal details about the system's stability. The position of the poles in the complex plane impacts a system's stability. The system is deemed stable if the actual parts of the poles are negative. On the other hand, a graph tends to become unstable and show divergent or oscillatory tendencies if a pole appears in the imaginary region [43].

The eigenvalue equation, often known as the characteristic equation of a linear system, has solutions that are its values. The components required to determine a system's inherent frequency and the SEP's modes of reaction to external disturbances are known as eigenvalues. Each eigenvalue's natural and imaginary components represent the corresponding response mode's frequency and damping. The real part of the eigenvalue determines the mode's natural frequency, and the imaginary component indicates its damping rate [44], [45], [46], [47].

3.2 Method Development

A technique was introduced to stabilize a small signal in an EPS when renewable energy sources are present in the network. This technique was accomplished using a MATLAB-developed mathematical analysis application, which used the tools available for power system analysis and intricate mathematical computations. The broad range of available mathematical models and their simple implementation led to the choice of this program. The program was developed using a flowchart (see Figure 2) that illustrates how the program assesses the frequency data to ascertain the presence of a small signal.

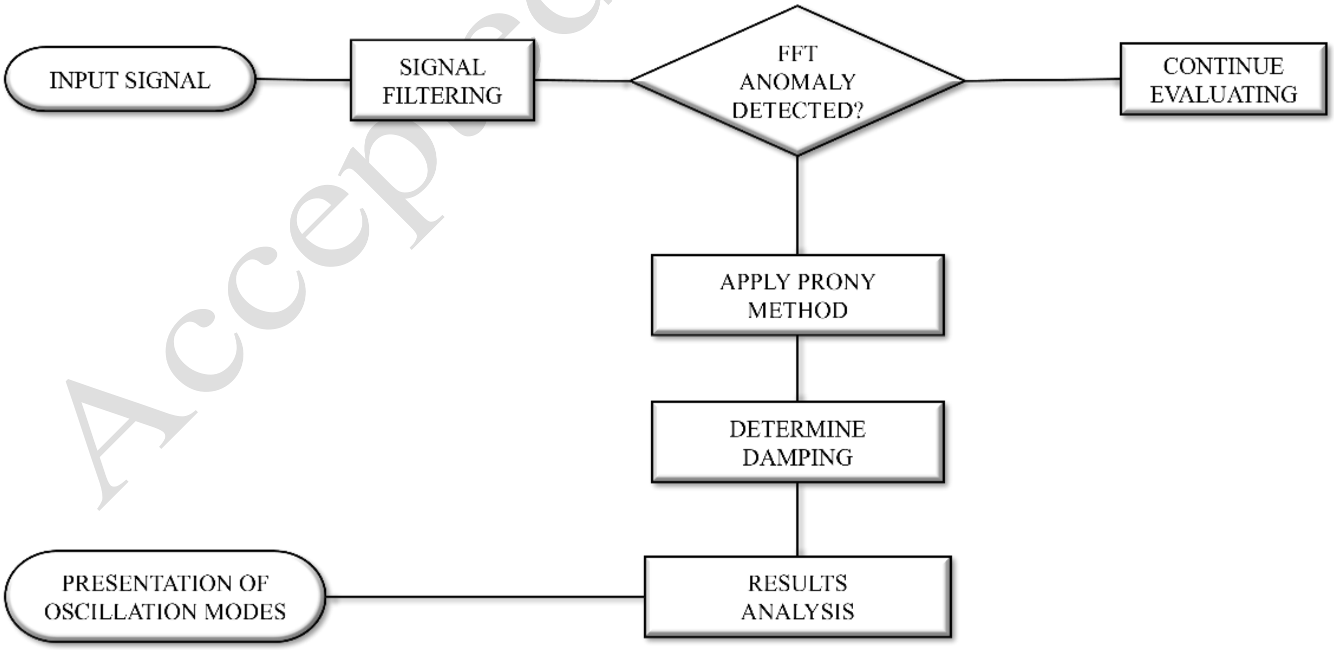
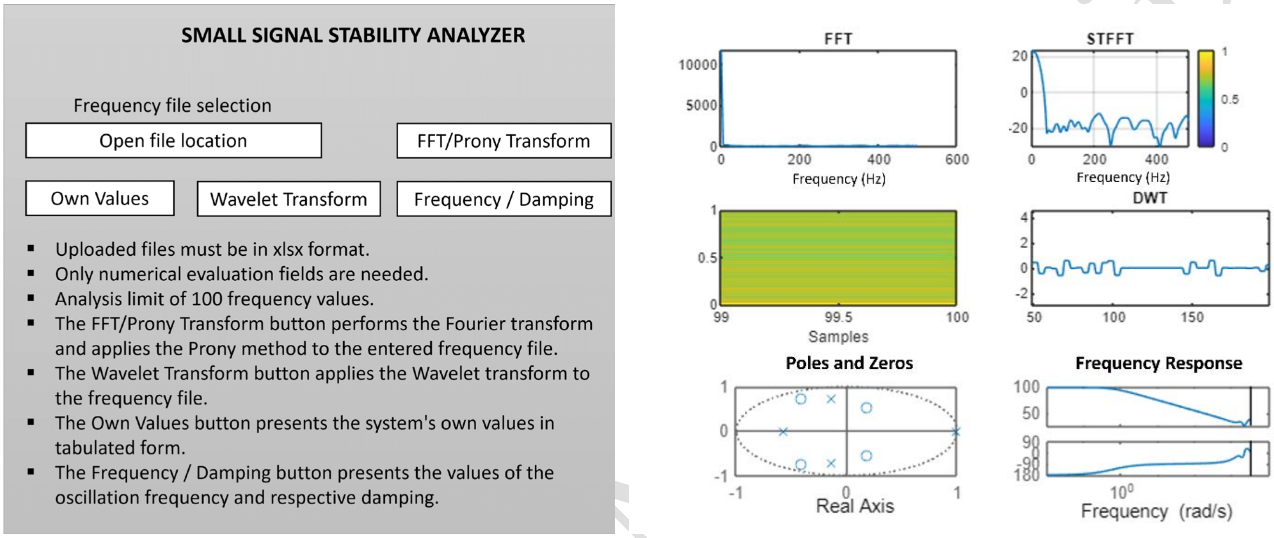


Figure 2 Methodology for small signal stability analysis

Figure 3 shows the user interface, and six auxiliary program analyses created to analyze small signal stability. It represents the plot of the studied frequency, the Fourier transform, and the sampled signal's power spectrum. Likewise, the oscillation modes that appear in the sampled signal, the eigenvalues of these modes, and the damping related to each oscillation mode are presented. The sampled system's pole and zero stability graph are added as an additional visual verification method.



- Uploaded files must be in xlsx format.
- Only numerical evaluation fields are needed.
- Analysis limit of 100 frequency values.
- The FFT/Prony Transform button performs the Fourier transform and applies the Prony method to the entered frequency file.
- The Wavelet Transform button applies the Wavelet transform to the frequency file.
- The Own Values button presents the system's own values in tabulated form.
- The Frequency / Damping button presents the values of the oscillation frequency and respective damping.

(a) (b)

Figure 3. (a) Graphic interface of the program. (b) Supplementary results window.

It assessed the suggested program to determine the reliability of the outcomes it produced. Analyses were conducted by contrasting the outcomes with the methods used by other sources of advice to achieve this. It assessed the program's validity by subjecting it to a battery of tests in various scenarios, where the conditions of the frequency signal produced different outcomes for variability. It gathered sufficient samples to evaluate the program's overall reliability.

3.3 Case Study

The Dominican Republic's electrical infrastructure, especially its Hainamosa substation, will be used as a reference point for this study. This system operates at 138 kV voltage, and frequency fluctuations can be measured here thanks to the frequency meter equipment installed in the substation. Due to its 12 connection fields within the substation and its ability to create oscillations across multiple substations, it is the best substation for this investigation. The connections between the several substations in the vicinity of Hainamosa can be seen in **Figure 4**. The System National Electric Interconnected (SENI) database, publicly available from the Dominican Republic's Coordinating Body (OC), can be found here: The SENI Database.

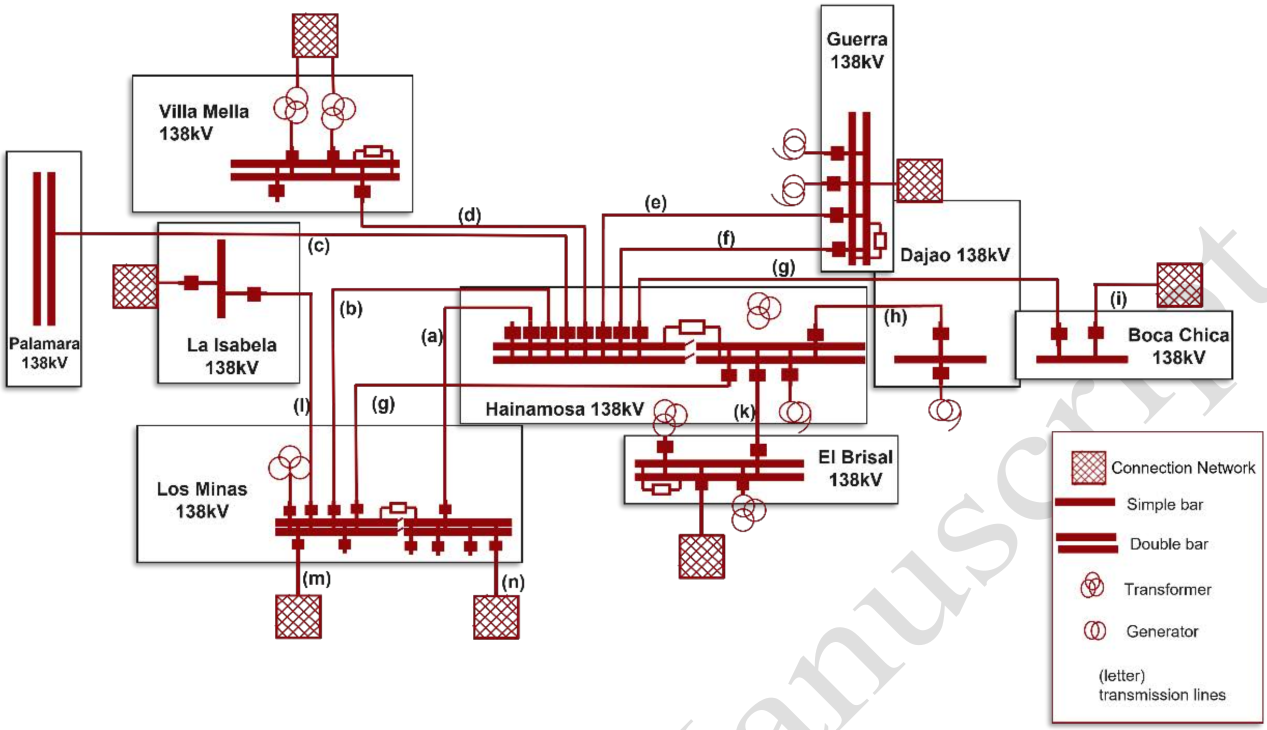


Figure 4. Connections diagram between the national electrical system's 138kV substations

Using the previously described 138 kV Hainamosa substation as a reference point, it assessed the behavior of the frequency oscillations of the Dominican electrical system to examine the influence of renewable energy sources on the oscillations of the network's small signals. Multiple frequency databases are available for the intended investigation, organized by period into two-hour informational blocks. The abovementioned information allowed us to run many test simulations and see whether there was any instability in the little signals. The scenarios will occur between 11:00 and 16:00 because these are the hours when renewable energy sources participate more in the Dominican Republic's energy grid. As explained below, it included the assessment of three distinct scenarios, each involving varying frequency values depending on the day and hour.

- **Scenario One**
  Hours are from 09:00 to 11:00 A.M. Location: 138 kV Hainamosa Substation.
  Date: September 5, 2023
  The electrical system's frequency spectrum was recorded while operational at the previously indicated time and place. At this time, a 150-second sample was taken for the first case.
- **Scenario Two**
  Hours are from 2:00 P.M. to 4:00 P.M. Location: 138 kV Hainamosa Substation.
  Date: September 5, 2023
- **Scenario Three**
  Hours are from 2:00 P.M. to 4:00 P.M. Location: 138 kV Hainamosa Substation.
  Date: April 9, 2023

- **Scenario Four**
  It then simulated a situation in which the network experienced slight signal oscillations. To do this, random values that can cause slight signal oscillations were generated using the Excel calculating tool.
- **Scenario Five and Six**
  It assessed the Peruvian electric system for this scenario and analyzed its daily operation.

4. Results and Discussion

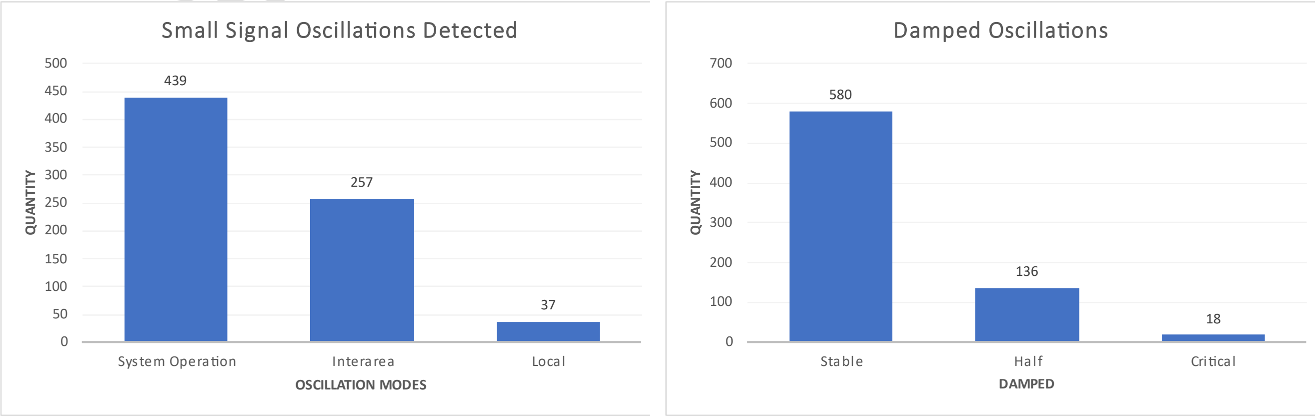
When damping is applied to stable oscillation modes in the system, the results are expressed positively; however, when damping is applied to an unstable mode, the results are expressed negatively. It is done to make these outcomes easier to understand. Eight possibilities of minor signal oscillations correspond to hourly frequency periods at various system operating times. The electrical systems of Peru and the Dominican Republic were the ones that were assessed. An overview of these systems' energy matrices based on conventional and renewable energy sources is shown in **Table 3**.

Table 3. General attributes of each nation's energy matrix

Installed Capacity	Dominican Republic (MW)	Peru (MW)
Renewable Energy Sources	1,445.98	6,280
Conventional Energy Sources	3,629.40	9,062
Total	5,075.38	15,342

Scenario One

The outcomes of this initial scenario are shown in **Figure 5**, where we can observe that oscillation modes at frequencies lower than 0.08 Hz are predominant owing to the electrical system's operation. The simulation displayed 37 local oscillation modes and 257 interarea oscillation patterns. The system rapidly dampened the network's stable oscillation modes, representing the final modes category. The maximum oscillation frequency was 1.1333 Hz, the maximum damping was 99%, the minimum was 2.765%, and the minimum oscillation frequency was 0.0044 HZ. Regarding the system's damping, it presented 580 stable damping, 136 medium damping, and 18 critical grid damping.

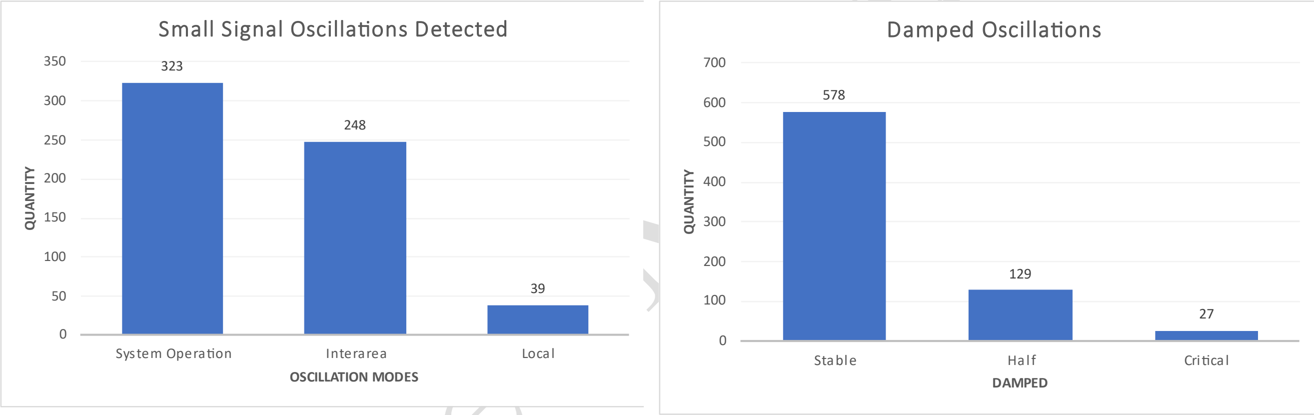


(a) (b)

Figure 5. (a) The number of small signal oscillations detected for Scenario One. (b) Number of damped oscillations detected for Scenario One.

Scenario Two

In this case, as **Figure 6** shows, the system provided 248 interarea oscillation patterns but only 39 local oscillation modes. This test obtained oscillations with a maximum frequency of 1.12 Hz. The maximum frequency of small signal oscillation was 1.12 Hz, while the minimum was 0.0046 Hz. The analysis of damping of the oscillations showed favorable results for the stability of the system since the most significant number of oscillation modes that were presented in the system were stably damped with a total of 578 damped modes, 129 modes had medium damping, and only 27 modes presented critical damping. However, these did not generate instability in the network because they dampened modes of power system operation.

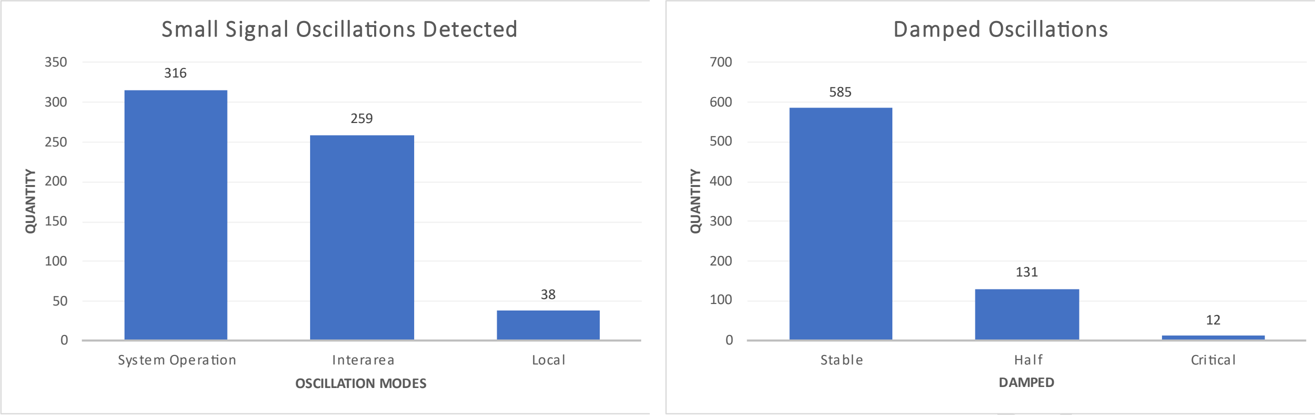


(a) (b)

Figure 6. (a) Number of small signal oscillations detected for Scenario Two. (b) Number of damped oscillations detected for Scenario Two.

Scenario Three

The results obtained by applying the small signal assessment system are presented in Figure 7. The predominance of oscillation modes of operation of the system is visualized with a total of 316; then, in second place, we have the inter-area oscillation modes with a total of 259 modes found, and finally, the local modes with 38 oscillation modes found. Most of the oscillation modes in the system were stably damped in most cases, with 585 of these values. Only 12 modes with critical damping were presented in this scenario. The maximum oscillation frequency was 1.12 Hz, and the oscillation damping range was between 100% and 3.67%.

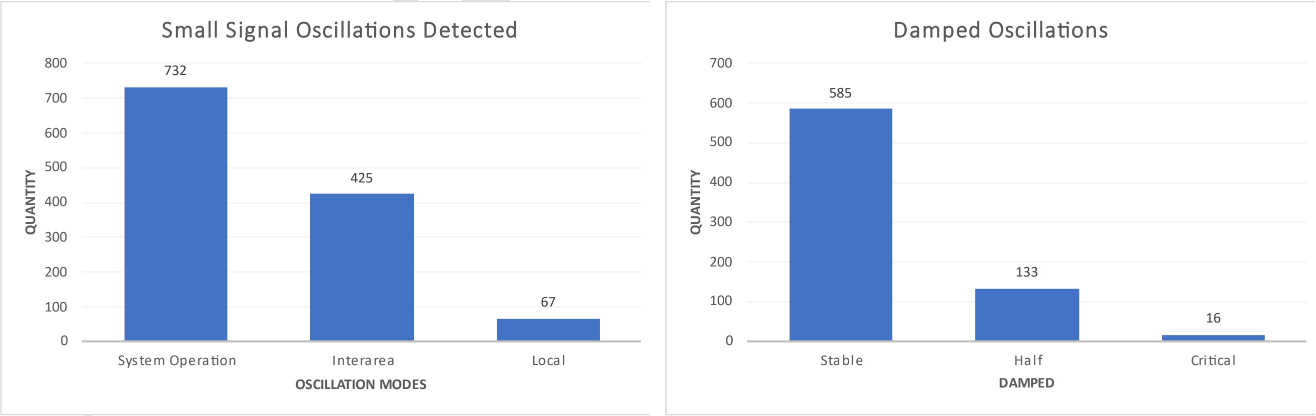


(a) (b)

Figure 7. (a) Number of small signal oscillations detected for Scenario Three. (b) Number of damped oscillations detected for Scenario Three.

Scenario Four

Figure 8 shows the results obtained when evaluating the proposed scenario four. It is shown that most of the present modes corresponded to oscillations due to the operation of the power system itself. Moreover, the grid detected 425 interarea oscillation modes and 67 local oscillation modes. The maximum oscillation frequency in this scenario was 1.11 Hz, while the minimum reached approximately 0.01 Hz. The system evaluated in this fourth scenario was able to stably damp 585 modes, indicating that the system is capable of maintaining system stability most of the scenario time. Only 16 oscillation modes had critical damping; however, they did not present an instability event in the system.

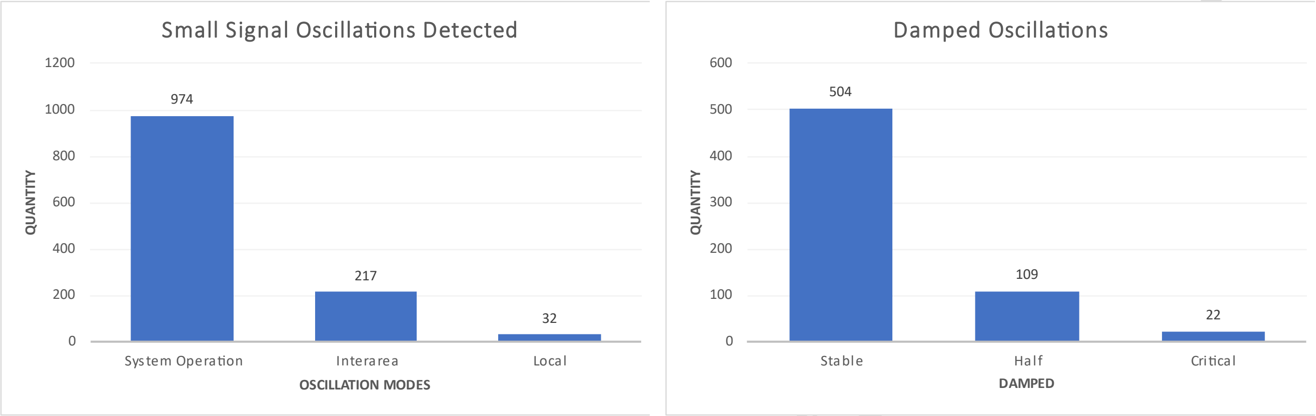


(a) (b)

Figure 8. (a) Number of small signal oscillations detected for Scenario Four. (b) Number of damped oscillations detected for Scenario Four.

Scenario Five

Figure 9 presents the results obtained when evaluating scenario five. This scenario shows that the presence of local and interarea modes in the system represent only 20% of the oscillation modes present in the system. These results show that this disturbance is not due to a small signal oscillation in the power system but to another type of disturbance analyzed under another stability branch.



(a) (b)

Figure 9. (a) Number of small signal oscillations detected for Scenario Five. (b) Number of damped oscillations detected for Scenario Five.

Scenario Six

Frequent oscillation scenarios were created in an electrical system. This scenario was created to assess the detection of unstable oscillations in the electrical system using the tool designed to evaluate small signal oscillations. It was created based on a period of 10 seconds, for which intervals of 0.1 seconds were created between samples to better represent the data obtained by the frequency meter used in the other simulations.

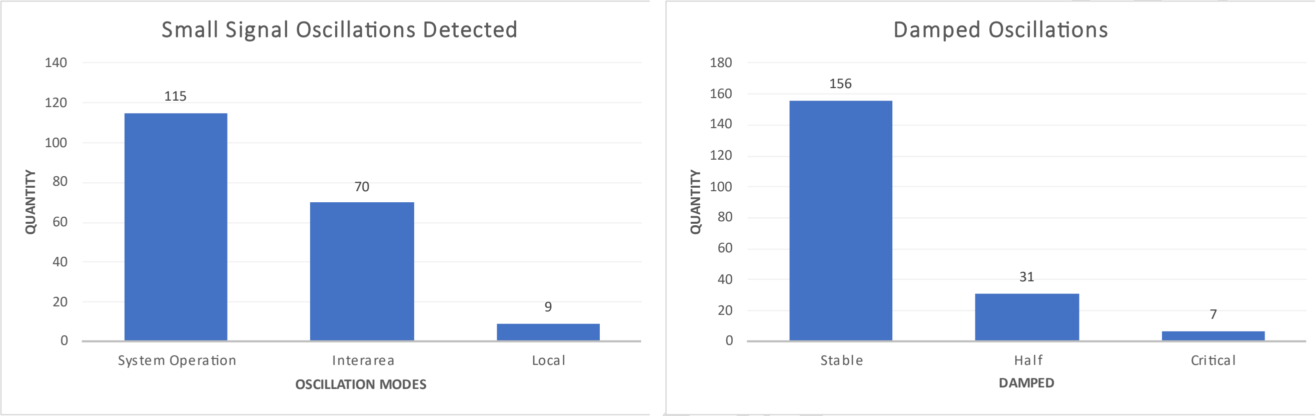
Table 4 summarizes the oscillation modes detected in scenario six, for which a small signal oscillation has been detected in the system, as mentioned above. It is shown that the generated oscillation occurred at a frequency of 0.0022 Hz and had negative damping, which, following our analysis methodology, determined that this oscillation is unstable. Likewise, inter-area mode oscillations can be observed in mode 3, and oscillations due to the system's operation can be observed in modes 1 and 4.

Table 4. Outcomes of Scenario Six

Mode	Damping (%)	Deadening	Frequency (Hz)
Mode 1	12.1553	0.121553	0.0321
Mode 2	12.1553	0.121553	0.0321
Mode 3	40.7751	0.407751	0.1333
Mode 4	6.9258	0.069258	0.0114
Mode 5	-100	-1	0.0022

Scenario Seven

For this scenario, frequency data was extracted from the National Electrical System of Peru to evaluate other electrical systems that are not composed of conventional energy sources within their energy matrix. A sample of frequencies from Peru's electrical system was analyzed, which yielded the values presented in **Figure 10**. The system detected 115 oscillation modes, 70 inter-area oscillation modes, and nine local oscillation modes. Most modes in this system were damped above 15%, indicating a relatively high damping.

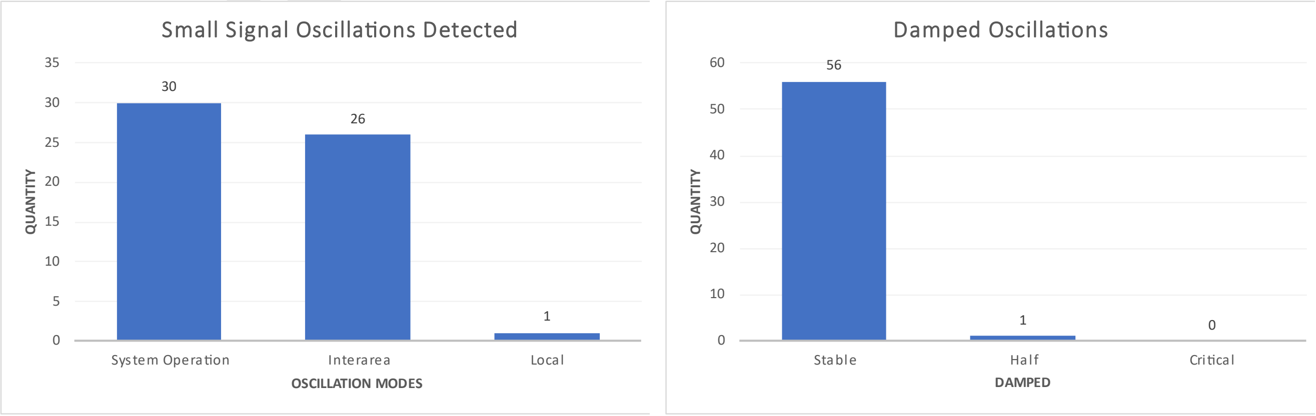


(a) (b)

Figure 10. (a) The number of small signal oscillations detected for Scenario Seven. (b) Number of damped oscillations detected for Scenario Seven.

Scenario Eight

Figure 11 presents a summary of the oscillation modes that occurred in this system. It shows that the maximum oscillation frequency was 1.49 Hz, while the minimum was approximately 0.02 Hz due to system operation. The damping in this electrical system is relatively stable, as seen in this figure. It evaluated some of the oscillation modes of the electrical system in one of the scenarios. The instability event that occurred in this scenario was detected at a shallow oscillation frequency of 0.0055 Hz.



(a) (b)

Figure 11. (a) The number of small signal oscillations detected for Scenario Eight. (b) Number of damped oscillations detected for Scenario Eight.

5. Conclusions

The objective of this project was to confirm the tight connection between the integration of renewable energy sources and the stability of small signals in a power system where the matrix's share of these generation technologies is low. However, the results showed a different outcome than anticipated. It was feasible to show one practical way to investigate the system's behavior. At the same time, these unconventional sources operate to analyze the stability of small signals in a power system with lower penetration of renewable sources. Several tests were run using the available historical frequency data, and the findings were encouraging for the research. It was determined that while the power system naturally and effectively dampens the oscillation modes, the low penetration of renewable sources in an electrical system does not produce small signal oscillations.

It was demonstrated that while renewable energy sources contribute little to the energy matrix, the electrical system dampens small signal oscillations. Conventional generators can safely absorb such oscillations and maintain system stability during a small signal disturbance. According to frequency analysis, the case study's renewable energy sources' intermittency or variability does not significantly alter system frequency, which could result in either undamped or inadequately damped oscillation. Thus, it is unlikely that the oscillations observed in this study will result in system failures or blackouts in the grid. In contrast, only one blackout in a transmission line has been verified in the Dominican Republic's electrical system in recent years, indicating the system's ability to absorb small signal abnormalities.

Conversely, the Peruvian electrical system had small signal instability. Nonetheless, the analyzed scenarios showed that Peru's electrical system could considerably dampen these small signal oscillations, with most of the oscillations being damped stably. The study presented that if the system's installed capacity is substantial and the changes are significantly severe, an electrical system may generate oscillations due to modest signal instability caused by renewable sources.

Declaration of competing interest

We declare that we have no significant competing interests, including financial or non-financial, professional, or personal interests interfering with the complete and objective presentation of the work described in this manuscript.

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Data availability statement

The authors confirm that the data supporting the findings of this study are available within the article.

References

[1] M. Yao, S. Roy, and J. L. Mathieu, "Using demand response to improve power system small-signal stability," *Sustain. Energy, Grids Networks*, vol. 36, p. 101214, 2023, doi: https://doi.org/10.1016/j.segan.2023.101214.

[2] C. Yan, L. Zhou, W. Yao, J. Wen, and S. Cheng, "Probabilistic small signal stability analysis of power system with wind power and photovoltaic power based on probability collocation method," *Glob. Energy Interconnect.*, vol. 2, no. 1, pp. 19–28, 2019, doi: https://doi.org/10.1016/j.gloei.2019.06.003.

[3] C. G. Tapia Abugoch, "Estudio de estabilidad de pequeña perturbación del sistema eléctrico chileno considerando la política energética 2050," Universidad de Chile, 2020. [Online]. Available: https://repositorio.uchile.cl/handle/2250/176983

[4] A. Sajadi, S. Zhao, K. Clark, and K. A. Loparo, "Small-Signal Stability Analysis of Large-Scale Power Systems in Response to Variability of Offshore Wind Power Plants," *IEEE Syst. J.*, vol. 13, no. 3, pp. 3070–3079, Sep. 2019, doi: 10.1109/JSYST.2018.2885302.

[5] M. B. Dastas and H. Song, "Renewable Energy Generation Assessment in Terms of Small-Signal Stability," *Sustainability*, vol. 11, no. 24, p. 7079, Dec. 2019, doi: 10.3390/su11247079.

[6] C. Canizares *et al.*, "Benchmark Models for the Analysis and Control of Small-Signal Oscillatory Dynamics in Power Systems," *IEEE Trans. Power Syst.*, vol. 32, no. 1, pp. 715–722, Jan. 2017, doi: 10.1109/TPWRS.2016.2561263.

[7] A. Musengimana, H. Li, X. Zheng, and Y. Yu, "Small-Signal Model and Stability Control for Grid-Connected PV Inverter to a Weak Grid," *Energies*, vol. 14, no. 13, p. 3907, Jun. 2021, doi: 10.3390/en14133907.

[8] A. Sajadi, S. Zhao, K. Clark, and K. A. Loparo, "Small-Signal Stability Analysis of Large-Scale Power Systems in Response to Variability of Offshore Wind Power Plants," vol. 13, 2018, doi: 10.1109/JSYST.2018.2885302.

[9] L. Ding, X. Lu, and J. Tan, "Small-Signal Stability Analysis of Low-Inertia Power Grids with

Inverter-Based Resources and Synchronous Condensers," in *2022 IEEE Power & Energy Society Innovative Smart Grid Technologies Conference (ISGT)*, 2022, pp. 1–5. doi: 10.1109/ISGT50606.2022.9817556.

[10] A. Herrero Sabat, "Aportaciones a la estabilidad de plantas marinas de generación eléctrica, con volantes de inercia," Universitat Politècnica de Catalunya, 2023. doi: 10.5821/dissertation-2117-389982.

[11] D. E. Echeverría and J. C. Cepeda, "Evaluación de Estabilidad Transitoria de Sistemas de Potencia utilizando el concepto de Centro de Inercia," *Rev. Técnica "Energía,"* vol. 14, no. 1, Jan. 2018, doi: 10.37116/revistaenergia.v14.n1.2018.157.

[12] A. Estrada Cruz, "Evaluación de un esquema de acción remedial basado en un disparo automático de generación para mitigar problemas de estabilidad angular en el sistema eléctrico nacional," 2018. [Online]. Available: https://repositorioinstitucional.buap.mx/items/ed8e8b0d-24ed-464a-876b-1e76ec2d15e5

[13] J. V. Hatziargyriou, N., Milanović *et al.*, "Stability definitions and characterization of dynamic behavior in systems with high penetration of power electronic interfaced technologies," 2020. doi: https://doi.org/10.17023/zwwp-vv02.

[14] G. E. Román Beltrán, "Análisis de estabilidad transitoria de ángulo y frecuencia del sistema híbrido de las íslas Galápagos Baltra-Santa Cruz," 2022. [Online]. Available: https://bibdigital.epn.edu.ec/handle/15000/23204

[15] Y. Li, L. Fu, Q. Li, W. Wang, Y. Jia, and Z. Y. Dong, "Small-signal modelling and stability analysis of grid-following and grid-forming inverters dominated power system," *Glob. Energy Interconnect.*, vol. 6, no. 3, pp. 363–374, Jun. 2023, doi: 10.1016/j.gloei.2023.06.010.

[16] D. S. Granados, "Diseño y ajuste en linea de un estabilizador de sistemas de potencia/Design and online tuning of a power system stabilizer," *Ingenieria*, vol. 31, p. 141+, Dec. 2020, [Online]. Available: https://link.gale.com/apps/doc/A678018700/IFME?u=anon~ed15504a&sid=googleScholar&xid=d6e60a6a

[17] E. F. Guanochanga Collaguazo and M. G. Ocaña Frutos, "Ubicación de un control de modos deslizantes y PSS's con el objetivo de amortiguar oscilaciones electromecánicas utilizando el método del residuo y fuzzy," 2018.

[18] M. A. Carreño Galeano, "Estabilidad de pequeña señal de un sistema de potencia con VSCs de tipos grid-following y grid-forming considerando los algoritmos VSM, droop control y VOC," Universidad de los Andes, 2022. [Online]. Available: http://hdl.handle.net/1992/58724

[19] M. P. Martínez, Y. R. Domínguez, and E. G. Hidalgo, "Estabilidad transitoria de pequeñas oscilaciones en los sistemas eléctricos de potencia. Dispositivos usados para mejorarla," Universidad Tecnologica de La Habana Jose Antonio Echavarria, 2018. [Online]. Available: https://www.researchgate.net/publication/331357789_Estabilidad_transitoria_de_pequenas_oscilaciones_en_los_sistemas_electricos_de_potencia_Dispositivos_usados_para_mejorarla

[20] R. E. Cubillo, "Determinación de Modos Oscilatorios Presentes en el Sistema Eléctrico

Ecuatoriano Mediante Técnicas Estadísticas," *Rev. Técnica "Energía,"* vol. 13, no. 1, Jan. 2017, doi: 10.37116/revistaenergia.v13.n1.2017.16.

[21] R. I. Zúñiga Gajardo, "Análisis técnico de interconexiones regionales desde una perspectiva de estabilidad," Universidad de Chile, 2021. [Online]. Available: https://repositorio.uchile.cl/handle/2250/182465

[22] M. Hojabri, U. Dersch, A. Papaemmanouil, and P. Bosshart, "A Comprehensive Survey on Phasor Measurement Unit Applications in Distribution Systems," *Energies*, vol. 12, no. 23, p. 4552, Nov. 2019, doi: 10.3390/en12234552.

[23] M. Amin and M. Molinas, "Small-Signal Stability Assessment of Power Electronics Based Power Systems: A Discussion of Impedance- and Eigenvalue-Based Methods," *IEEE Trans. Ind. Appl.*, vol. 53, no. 5, pp. 5014–5030, 2017, doi: 10.1109/TIA.2017.2712692.

[24] M. Khodadadi Arpanahi, M. Kordi, R. Torkzadeh, H. Haes Alhelou, and P. Siano, "An Augmented Prony Method for Power System Oscillation Analysis Using Synchrophasor Data," 2019. doi: 10.3390/en12071267.

[25] J. Li, J. Zhou, and B. Chen, "Review of wind power scenario generation methods for optimal operation of renewable energy systems," *Appl. Energy*, vol. 280, p. 115992, 2020, doi: https://doi.org/10.1016/j.apenergy.2020.115992.

[26] D. L. Dinesha, "Application of Semi Analytical Methods for Large Power System Simulations," Indian Institute of Science, 2018. [Online]. Available: https://www.researchgate.net/profile/Disha-Dinesha/publication/360256610_Application_of_Semi_Analytical_Methods_for_Large_Power_System_Simulations/links/626ba2e66a39cb1180e3c418/Application-of-Semi-Analytical-Methods-for-Large-Power-System-Simulations.pdf

[27] R. Idema and D. J. P. Lahaye, *Computational Methods in Power System Analysis*. Atlantis Press Paris, 2014. [Online]. Available: https://link.springer.com/book/10.2991/978-94-6239-064-5#about-this-book

[28] P. Khetarpal and M. M. Tripathi, "A critical and comprehensive review on power quality disturbance detection and classification," *Sustain. Comput. Informatics Syst.*, vol. 28, p. 100417, 2020, doi: https://doi.org/10.1016/j.suscom.2020.100417.

[29] C. Beuter and M. Oleskovicz, "S-transform: from main concepts to some power quality applications," *IET Signal Process.*, vol. 14, no. 3, pp. 115–123, May 2020, doi: https://doi.org/10.1049/iet-spr.2019.0042.

[30] D. Córdova Jimmy and D. S. Zambrano Chicaiza, "Estudio de estabilidad y confiabilidad ante la integración de generación distribuida en la red de distribución UN Milagro," 2022. [Online]. Available: https://www.dspace.espol.edu.ec/handle/123456789/57026

[31] R. F. Carvajal Uribe, "Identificación de modelos de oscilaciones inter_áreas de sistemas de potencia mediante algoritmos generalizados de Prony," Tecnologico Nacional de Mexico, 2019. [Online]. Available: https://rinacional.tecnm.mx/bitstream/TecNM/1647/1/%2806%29-TMCIE-2019-Rafal Fernando Uribe Carvajal.pdf

[32] Y. Guan, Z. Q. Zhu, I. A. A. Afinowi, J. C. Mipo, and P. Farah, "Difference in maximum torque-speed characteristics of induction machine between motor and generator operation modes for electric vehicle application," *Electr. Power Syst. Res.*, vol. 136, pp. 406–414, Jul. 2016, doi: 10.1016/j.epsr.2016.03.027.

[33] G. A. Rodríguez Proaño, "Implementación de herramientas de análisis modal para evaluar el impacto en la estabilidad de pequeña señal del sistema eléctrico debido a la generación eólica: evaluar el nivel de amortiguamiento y determinación de los modos críticos para múltiples escen," 2022. [Online]. Available: http://bibdigital.epn.edu.ec/handle/15000/22422

[34] D. J. Guaman Apolo and J. E. Villacís Rodríguez, "Modelado de compensadores automáticos de potencia reactiva en lenguaje de programación dpl y dsl para la interconexión Ecuador-Perú 500 kv," 2022. [Online]. Available: http://repositorio.utc.edu.ec/handle/27000/9783

[35] J. Bi, H. Sun, S. Xu, R. Song, B. Zhao, and Q. Guo, "Mode-based Damping Torque Analysis in Power System Low-frequency Oscillations," *CSEE J. Power Energy Syst.*, vol. 9, no. 4, pp. 1337–1347, 2023, doi: 10.17775/CSEEJPES.2020.00990.

[36] C. A. Juarez and D. G. Colome, "Estimación en línea de modos interárea utilizando la Transformada Wavelet Discreta y el Análisis Prony," in *2018 IEEE 38th Central America and Panama Convention (CONCAPAN XXXVIII)*, IEEE, Nov. 2018, pp. 1–8. doi: 10.1109/CONCAPAN.2018.8596557.

[37] F. J. Villalobos-Piña and R. Alvarez-Salas, "Algoritmo robusto para el diagnóstico de fallas eléctricas en el motor de inducción trifásico basado en herramientas espectrales y ondeletas.," *Rev. Iberoam. Automática e Informática Ind. RIAI*, vol. 12, no. 3, pp. 292–303, Jul. 2015, doi: 10.1016/j.riai.2015.04.003.

[38] J. López Espejel, M. S. Yahaya Alassan, E. M. Chouham, W. Dahhane, and E. H. Ettifouri, "A comprehensive review of State-of-The-Art methods for Java code generation from Natural Language Text," *Nat. Lang. Process. J.*, vol. 3, p. 100013, Jun. 2023, doi: 10.1016/j.nlp.2023.100013.

[39] I. Abdulrahman, "MATLAB-Based Programs for Power System Dynamic Analysis," *IEEE Open Access J. Power Energy*, vol. 7, pp. 59–69, 2020, doi: 10.1109/OAJPE.2019.2954205.

[40] F. Zonzini, M. Mohammadgholiha, and L. De Marchi, "A Combination of Chirp Spread Spectrum and Frequency Hopping for Guided Waves-based Digital Data Communication with Frequency Steerable Acoustic Transducers," in *2022 IEEE International Ultrasonics Symposium (IUS)*, IEEE, Oct. 2022, pp. 1–4. doi: 10.1109/IUS54386.2022.9958662.

[41] J. Lin, L. Ma, and Y. Yao, "A Fourier Domain Training Framework for Convolutional Neural Networks Based on the Fourier Domain Pyramid Pooling Method and Fourier Domain Exponential Linear Unit," *IEEE Access*, vol. 7, pp. 116612–116631, 2019, doi: 10.1109/ACCESS.2019.2936591.

[42] O. V. Prokhorova and S. P. Orlov, "Parametric optimization of control systems by the Etalon Control System assign using the root locus method or the poles and zeros location," in *2017 IEEE II International Conference on Control in Technical Systems (CTS)*, IEEE, Oct. 2017, pp. 16–19. doi: 10.1109/CTSYS.2017.8109476.

[43] Y. Su, C. Zeng, D. Kang, X. Wang, and H. Wang, “Analytic study on the poles and zeros for mechanical plants,” in *2017 3rd IEEE International Conference on Computer and Communications (ICCC)*, IEEE, Dec. 2017, pp. 2940–2944. doi: 10.1109/CompComm.2017.8323070.

[44] W. Zi-li, S. Xiao-ou, and W. Xiao-rong, “Spectrum Sensing Detection Algorithm Based on Eigenvalue Variance,” in *2019 IEEE 8th Joint International Information Technology and Artificial Intelligence Conference (ITAIC)*, IEEE, May 2019, pp. 1656–1659. doi: 10.1109/ITAIC.2019.8785807.

[45] P. Jorkowski and R. Schuhmann, “Mode tracking for parametrized eigenvalue problems in computational electromagnetics,” in *2018 International Applied Computational Electromagnetics Society Symposium (ACES)*, IEEE, Mar. 2018, pp. 1–2. doi: 10.23919/ROPACES.2018.8364147.

[46] C. Li, G. Li, C. Wang, and Z. Du, “Eigenvalue Sensitivity and Eigenvalue Tracing of Power Systems With Inclusion of Time Delays,” *IEEE Trans. Power Syst.*, vol. 33, no. 4, pp. 3711–3719, Jul. 2018, doi: 10.1109/TPWRS.2017.2787713.

[47] X. Cun, X. Chen, G. Geng, and Q. Jiang, “Online Tracking of Small-Signal Stability Rightmost Eigenvalue Based on Reference Point,” *IEEE Access*, vol. 11, pp. 40469–40478, 2023, doi: 10.1109/ACCESS.2023.3267802.