Bibliographic Review on Power Oscillation Detection Methods

Marta Bernal-Sancho[1]*, Maria Paz Comech[2], and Noemí Galán-Hernández[1]
[1]Electrical Systems Department, CIRCE Technology Centre, Zaragoza, 50018 Spain
[2]CIRCE Mixed Research Institute (CIRCE Technology Centre and University of Zaragoza), Zaragoza, 50018 Spain
*mbernal@fcirce.es

Abstract

The detection and damping of oscillations have become one of the key aspects to consider for preventing system instability. The importance lies in the fact that oscillations in a system can cause instability and lead to malfunctions, damage, or even catastrophic failures. Detecting and damping oscillations at an early stage can prevent them from amplifying and ultimately stabilize the system. Furthermore, detecting and damping oscillations can improve system performance and increase the lifetime of the components involved, as well as improve overall system reliability and safety. Therefore, it is crucial to prioritize the detection and damping of oscillations as part of system design and maintenance. This paper analyses different methods for power oscillation detection in the electric grid. The scope of the paper is to compare and identify the most suitable power oscillation detection method for field applications, with the main objective of detecting interarea oscillations. The comparison concerns the Matrix Pencil Method, Prony Analysis, and the Fast Fourier Transform (FFT). The performance of the three methods is tested when detecting interarea oscillations in a simulated signal in an electric system to evaluate their sensitivity, time response and accuracy against this phenomenon by comparing the results with the DIgSILENT PowerFactory (DSPF) eigenvalue tool. The expected outcomes of the study include identifying the most suitable method for practical power system applications and providing recommendations for implementing power oscillation detection techniques in the field.

Keywords – Interarea oscillation, stability, electric grid, Matrix Pencil Method, Prony Analysis, Fast Fourier Transform

1 Introduction

Renewable power generation, mainly solar and wind energy, has significantly increased over the last years, as data from the International Renewable Energy Agency (IRENA) [1] shows. This increase leads to a reduction in traditional generation based on synchronous machines, which are responsible for different aspects related to the stability of the electrical system.

Thus, concern about decreased network inertia and damping properties has increased nowadays [2] [3]. The consequences of electrical system instability problems are often severe and can range from permanent damage to equipment and process downtime to causing an area-wide blackout [4].

A central problem of the power system stability is related to the electromechanical oscillations, which can be classified into two main groups [5]: local mode oscillations and interarea mode oscillations. Local mode oscillations are in the frequency range from 0.7 to 2.0 Hz and occur when a generator oscillates against the rest of the system. The characteristics of these oscillations are well comprehended, and solutions to their stability problems are available. Nonetheless, the features of interarea mode oscillation are far more complicated to analyse and control. Interarea oscillations are in the frequency range from 0.1 to 0.7 Hz and take place between groups of generators. The leading causes are heavy power transfer across weak tie-lines or high-gain exciters [5] [6]. The controls used for damp interarea oscillations are the Power System Stabilizer (PSS) of generators and Power Oscillation Damping (POD) in FACTS.

Recent studies show that interarea oscillations have been responsible for several large-scale power system failures in different parts of the world, such as the 1996 Western System Coordinated Council (WSCC) blackout [7] and the 2003 Northeast blackout in North America [8]. A more recent and closer example is the unexpected opening of a line in the French system (in the western 400 kV interconnection corridor with the Spanish system) that triggered an oscillatory incident in the Continental Europe electricity system (CE) in December 2016 [9]. These examples illustrate the significance of the problem of interarea oscillations.

Therefore, for secure and stable power system operation, detection and damping oscillations between interconnected generators constitute a significant concern [10]. If not detected and damped quickly, these oscillations can lead to line tripping, network splitting, generator outages, and even blackouts [6] [11].

Throughout the article, three methods for power oscillation detection are analysed. The methods are Fast Fourier Transform (FFT), Prony Analysis and Matrix Pencil Method (MPM).

- The FFT can be used to analyse the frequency content of power system signals and to identify the presence of power oscillations and their frequencies. Different authors have used the FFT to calculate and determine the oscillation modes [12] [13] [14].
- The Prony analysis is a least square approximation technique of fitting a sum of exponential terms to the measured data. It identifies the amplitudes, damping factors, frequencies, and phase angles inside the data [15]. Different authors use the Prony analysis to monitor Interarea Oscillation [15] [16] [17]. Some authors compare the results obtained with Prony Analysis with those obtained using the FFT [18].

- The Matrix Pencil Method approximates a given signal by a sum of complex exponentials. The idea originates from the approach of pencil-of-function. This method uses Hankel matrices and Singular Value decomposition to fit complex exponential sums. MPM finds all parameters, i.e., the magnitude, the damping factor, the frequency, and the phase angle [19]. The Matrix Pencil Method is used in [19] for oscillation monitoring. Moreover, some authors compare the performance of the Prony Analysis and Matrix Pencil Method for monitoring power oscillations [20].

This article first explains the FFT, the Prony Analysis, and the Matrix Pencil Method, performing a state of the art. Subsequently, a comparison of the three methods is made theoretically, analysing their pros and cons, as well as in a simulated form, where the results are compared. The input used is a simulated signal measured in an electrical system simulated in PowerFactory DIgSILENT (DSPF). The expected outcome of the study is to identify the most suitable method for practical applications in power systems and to provide recommendations for implementing oscillation detection techniques in the field.

2 Definition FFT, Prony, MPM

2.1 Fast Fourier Transform (FFT)

The Fast Fourier Transform (FFT) algorithm is widely used to analyse the frequency content of power system signals and to identify the presence of power oscillations and their frequencies, including the detection of oscillatory modes, as reported in [12] [13] [14].

The FFT transforms a time-domain signal into its frequency domain representation, providing information about the frequencies and amplitudes present in the signal. In this way, the frequency contribution of the signal can be analysed. In the context of interarea oscillation detection, by applying the FFT to the measured signal, the oscillation frequencies of interest (between 0.1 and 0.7 Hz [5]) can be analysed and detected.

For a real-valued signal, such as the measured frequency signal, the FFT is symmetric around the centre frequency [21]. This symmetry means that the negative frequency components of the Fourier transform are only the complex conjugates of the positive frequency components, with about half of the operations being redundant [22]. Thus, the Real-Valued Fast Fourier Transform (RFFT) function is optimised for such signals and can calculate the real part of the Fourier transform much faster than the FFT. This saves memory and computing resources while providing all the frequency information needed for most applications. Therefore, RFFT is the function used for this analysis.

The procedure used to detect the interarea oscillation of a simulated signal using RFFT is explained in **Figure 1** and can be summarised in the following steps.

- Execute the RFFT of the input signal, which contains the sampled values of the signal in the time domain. The output is an "fft" matrix of complex values representing the frequency domain spectrum of the input signal.
- The amplitude of 'fft' is normalised to the maximum absolute value of 'fft'. The result is a normalised amplitude spectrum representing the relative strength of each frequency component in the signal. In this way, it is possible to detect which frequency range dominates the measured signal.
- A threshold is set for the frequency of interest (0.1-0.7 Hz). Thus, when the frequency component of the signal within that range exceeds the threshold, an interarea oscillation is detected, sending a message and a trigger signal.

2.2 Prony Analysis

Prony analysis is a signal processing technique that extends Fourier analysis by directly estimating the frequency, damping ratio, amplitude, and phase angle of the modal components present in a given signal. Prony analysis for the evaluation of electrical systems was initiated in 1990 [23]. Since then, Prony analysis has been used by different authors to monitor interarea oscillation. In addition, some authors have improved Prony analysis, resulting in different versions [15] [16] [17] [20].

Prony analysis is a method based on a least-squares approximation technique of fitting a sum of exponential terms to the measured data [15]. In this way, the original waveform can be reproduced by plotting the obtained exponential sum. In the context of interarea oscillation detection, Prony analysis can be used to identify the frequency and damping ratio of electromechanical modes by detecting eigenvalues whose frequency is within the range of interest, i.e., between 0.1Hz-0.7Hz [5].

The procedure used to detect the interarea oscillation of a simulated signal using Prony analysis is explained in **Figure 1** and summarised in the following steps [15] [17].

- A Linear Prediction Model (LP) is constructed from the observed data (1).

$$-\underbrace{\begin{bmatrix} y[N-1] \\ \vdots \\ y[p] \end{bmatrix}}_{B} = \underbrace{\begin{bmatrix} y[N-2] & \cdots & y[N-p-1] \\ \vdots & \ddots & \vdots \\ y[p-1] & \cdots & y[0] \end{bmatrix}}_{A} \begin{bmatrix} a_1 \\ \vdots \\ a_p \end{bmatrix} \quad (1)$$

  Matrix A is filled with overlapping sub-arrays of the measured signal of length p (p is the number of poles defined by the user). The dimension of the A matrix is [Mxp], where M is the number of samples used to compute the exponential components, mathematically, $M = N - p$ (N is the length of the measured signal). B Vector is filled with the last M samples of the measured signal. This creates a system of linear equations $Ax = B$, where x is a vector of size p containing the coefficients of the exponential components.
- The least-squares method is used to solve the linear system, which returns the coefficients x that will describe a model close to the measured values.

- To connect the x-coefficients to the modal decomposition, the Z-transform is executed, forming the characteristic polynomial (2).

$$1 + a_1 z^{-1} + \cdots + a_p z^{-p} = 0 \quad (2)$$

The characteristic polynomial is factorized to obtain the roots of the polynomial. The roots are complex numbers and represent the poles of the transfer function of the model.

- The eigenvalues are obtained since they are linked to the roots by (3).

$$\lambda_n = \frac{\ln(roots)}{T_s} \quad (3)$$

Where λ are the eigenvalues and Ts is the sampling time of the measured signal.

- From the eigenvalues, the frequency and damping ratios of the modal components are calculated since the real part of the eigenvalues refers to the damping ratio ($\propto_n$) and the imaginary part contains the oscillatory frequency component (f_n) (4), (5). The amplitude and phase angle are estimated by another least-squares approximation.

$$\lambda_n = \ \propto_n + j2\pi f_n \quad (4)$$

$$f_n = \frac{|Im(\lambda_n)|}{2\pi} \qquad \propto_n = \mathrm{Re}(\lambda_n) \quad (5)$$

- A threshold is set for the frequency of interest (0.1-0.7 Hz). Thus, when the frequency of a mode is within the range of interest (0.1-0.7 Hz), an interarea oscillation is detected, sending a message and a trigger signal.

2.3 Matrix Pencil Method (MPM)

The matrix pencil method (MPM) is a signal processing technique used to identify the parameters of a signal model. The MPM approximates a measured signal by a sum of complex exponentials and estimates the frequency, damping ratio, amplitude, and phase angle of the modal components [19]. The MPM was proposed by Hua and Sarkar in the 1980s. Compared to Prony analysis, MPM has better statistical properties for mode estimation, which makes it more computationally efficient. In addition, MPM is less susceptible to noise [24] [25].

The matrix pencil method uses Hankel matrices and singular value decomposition to fit a sum of complex exponentials [19]. Thus, the original signal can be reproduced by plotting the obtained exponential sum. As for the detection of interarea oscillations, the MPM can be used to identify the frequency and damping ratio of electromechanical modes by detecting the eigenvalues whose frequency is within the range of interest, i.e., between 0.1Hz-0.7Hz [5]. The steps used to detect the interarea oscillation of a simulated signal using MPM are explained in **Figure 1** and summarised in the following steps [19] [26].

- A Hankel matrix Y is formed from the measured signal (6), (7). The dimension of matrix Y is [(M-L)x(L+1)], where M is the length of the measured signal and L represents the pencil parameter. The parameter L is useful in eliminating some effects of noise in the data.

$$y(t) = \sum_{i=1}^{N} A_i e^{\sigma_i t} \cos(2\pi f_i t + \theta_i), \qquad i = 1,2,\ldots,N \quad (6)$$

$$Y = \begin{bmatrix} y(0) & y(1) & \ldots & y(L) \\ y(1) & y(2) & \ldots & y(L+1) \\ \vdots & \vdots & \vdots & \vdots \\ y(M-L-1) & y(M-L) & \ldots & y(M-1) \end{bmatrix} \quad (7)$$

From matrix Y (7), two matrices, Y1 and Y2, can be constructed. Y1 is obtained by eliminating the

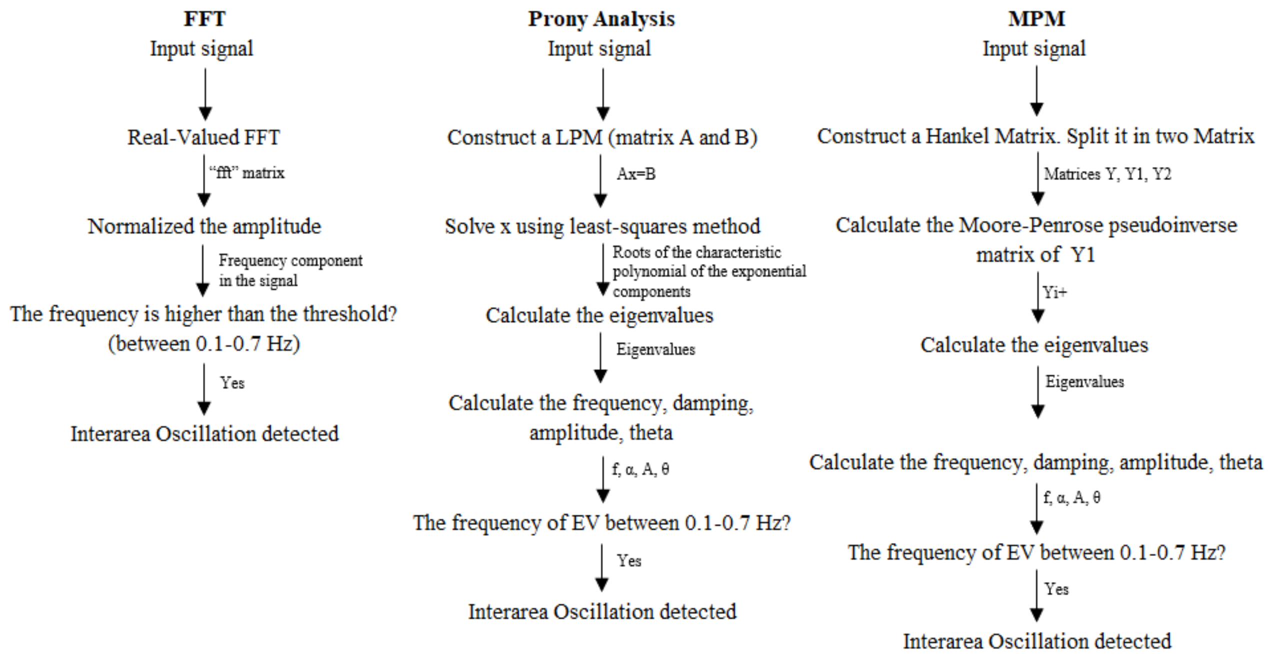

Figure 1. FFT, Prony analysis and MPM procedure to detect interarea oscillations.

last column of Y, while Y2 is constructed by eliminating the first column of Y. Y1 and Y2 are [(M-L)xL] matrices.

- The roots zn are obtained by following the expression (8).

$$z_n = eigenvalues(Y_1^+ Y_2) \quad (8)$$

Where Y1+ is the Moore-Penrose pseudoinverse matrix of Y1, defined by (9).

$$Y_1^+ = [Y_1^H Y_1]^{-1} Y_1^H \quad (9)$$

- The roots zn lead to the frequency f_n. and damping ratios $\propto_n$ using the expressions (10).

$$f_n = \frac{tan^{-1}\left[\frac{Im(z_k)}{Re(z_k)}\right]}{2\pi T_s} \qquad \propto_n = \frac{ln|z_n|}{T_s} \quad (10)$$

The amplitude and phase angle are estimated by solving the original set of linear equations (6).

- A threshold is set for the frequency of interest (0.1-0.7 Hz). Thus, when the frequency of a mode is within the range of interest (0.1-0.7 Hz), an interarea oscillation is detected, sending a message and a trigger signal.

3 Comparative FFT, Prony, MPM

3.1 Theorical Comparison

Table 1 provides a comparative between the different parameters that can be obtained using the three methods studied in this article, where:

- f: frequency
- α: damping
- A: amplitude
- Θ: phase angle
- Wave: original wave reconstruction

The FFT method is computationally efficient and easy to implement, making it a popular choice in signal analysis [14]. However, it has some limitations. The accuracy of the results depends on the number of samples taken, and noise in the measurements can affect the results. In addition, the FFT is affected by the phenomenon of spectral leakage and the picket effect, as indicated in [27]. As the FFT converts a time-domain measured signal into its frequency-domain representation, only the peaks of the frequency of the measured signal are obtained. Thus, the damping is not calculated.

Prony analysis has some advantages, such as being able to handle non-stationary and non-linear signals and providing accurate results with a small number of samples [28]. Moreover, Prony analysis retrieves the damping information, which is not possible from the conventional FFT

Table 1. Comparative between the parameters

Method	f	α	A	θ	Wave
FFT	Yes	No	Yes	No	No
Prony Analysis	Yes	Yes	Yes	Yes	Yes
MPM	Yes	Yes	Yes	Yes	Yes

[18]. The original signal can be reproduced since the amplitude and phase angle are also calculated. However, it can be sensitive to noise in the measurements and may require careful selection of model order. Moreover, Prony analysis requires high computational time [20].

The matrix pencil method agrees with some Prony advantages, such as being able to handle non-stationary and non-linear signals. However, MPM requires less computational time compared to Prony analysis and improves its performance concerning accuracy, efficiency, and noise sensitivity [20]. As with the Prony analysis, MPM retrieves the damping information, which is not possible from the conventional FFT. The original signal can be reproduced since the amplitude and phase angle are calculated [29].

3.2 Simulation Comparison

A simulated electrical system is modelled in DSPF. To reproduce the oscillation between zones, the test system of two generator zones connected by a power line, proposed in [30], is used. After performing a time domain simulation, the frequency measurement of one of the terminals is used as input to the power oscillation detection functions. Thus, the simulated measured signal is quite similar to those obtained in a PMU and is represented in **Figure 2**.

In addition, to ensure the accuracy of the results achieved, a simulation is carried out in the frequency domain in the DSPF eigenvalues tool [31]. This tool implements the QR/QZ method and calculates a complete and selective eigenvalue analysis, which is used as a base to compare, validate and confirm the results obtained by the three methods. Thus, the electromechanical pole of the system is obtained, which is defined as:

$$\lambda = \alpha \pm j2\pi f = -0.0717 \pm j2\pi 0.405$$

Where the real part, $\alpha = -0.0717$, corresponds to the damping. From the imaginary part, the frequency is obtained, $f = 0.405\,Hz$.

Therefore, using the frequency measurement of one of the DSPF terminals as input to the functions, the main objective is to obtain the eigenvalue with the same characteristics (damping and frequency) as that obtained DSPF.

The FFT is performed using the frequency measurement as input. The procedure used is the one defined in Section 2.1. The results are displayed in **Figure 3**. The x-axis represents

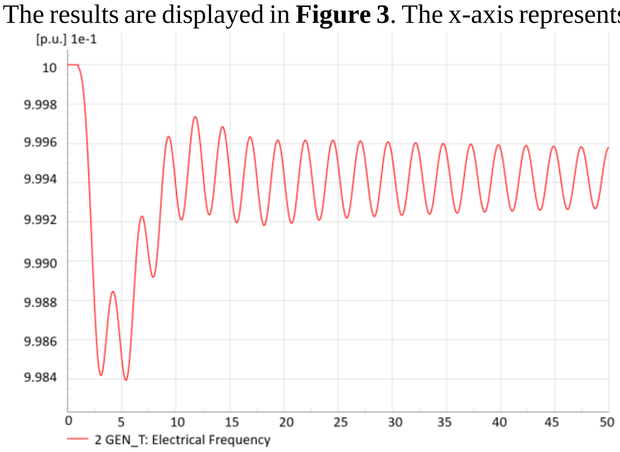

Figure 2. Frequency simulated measured signal

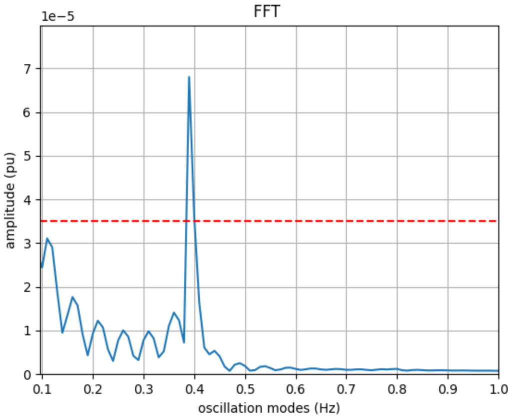

Figure 3. FFT results

the frequency components of the signal, while the y-axis represents the amplitude or power of each frequency component. The horizontal dashed line represents the threshold defined for the detection of interarea oscillations. By analysing the signal, the peak in the FFT represents the dominant frequency components in the signal, $f = 0.395\ Hz$. The frequency exceeds the threshold and coincides approximately with the frequency obtained in DSPF.
The Prony Analysis code is executed using the frequency measurement as input. The procedure used to detect the interarea oscillation is the one defined in Section 2.2.
Among the results the electromechanical pole is found, which approximately matches the one obtained in the DSPF simulation.

$$\lambda = \alpha \pm j2\pi f = -0.062 \pm j2\pi 0.406$$

The MPM code is executed using the same frequency measurement as the input. The procedure used to detect the interarea oscillation is the one defined in Section 2.3.
As with the Prony analysis, the results contain the electromechanical pole, and it matches approximatively with the one obtained in the DSPF simulation.

$$\lambda = \alpha \pm j2\pi f = -0.0719 \pm j2\pi 0.408$$

Table 2 summarises the damping and frequency results obtained with the different power oscillation detection methods. Comparing the results, the damping is quite similar in the Prony analysis and MPM, with the damping obtained using the Prony analysis being slightly different from that obtained using DSPF. The frequency results are similar for all three methods. The largest deviation in frequency is in the FFT and could be due to the results are obtained graphically. Therefore, the FFT is not as accurate as the Prony analysis and the MPM. However, the FFT has a low computation time. On the other hand, if the main objective is to obtain accurate results, both in damping and frequency, giving less importance to the calculation time, the Prony analysis and the MPM could be the right choice, with the MPM being more accurate.

Table 2. Damping and frequency results of the different power oscillation detection methods

Method	**α**	**f [Hz]**
DSPF	-0.0717	0.405
FFT	-	~0.395
Prony Analysis	-0.062	0.406
MPM	-0.0719	0.408

4 Conclusion

Within this paper, three methods for detecting power oscillations (FFT, Prony analysis, and MPM) have been compared.
First, a theoretical comparison has been made, explaining how each method works and focusing on the different implementation steps. Then, the three methods have been compared, both theoretically and in terms of simulation results. As input to the functions, a frequency measurement of a terminal in DSPF has been used. Furthermore, to verify and ensure that the results obtained by the three methods are correct, the results have been compared with those obtained in DSPF.
As a general conclusion, all three methods provide concise results. However, as the frequency obtained with the FFT is less precise, the FFT could be used when computational time takes priority over the accuracy of the results. When run time is not so important and accurate damping and frequency results are required, Prony analysis and MPM are a better choice, since both methods provide accurate results, with MPM being more accurate.

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