

Impact of Non-Synchronous Generation on Transmission Oscillations Paths

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Abstract—The large scale penetration of non-synchronous generation has been causing several impacts on the power systems dynamics. The low-frequency oscillations affect the power exchanged along the transmission lines/corridors. This paper uses the Multi-Prony Analysis mode estimation technique to monitor and suggest the dominant oscillation modes which can be useful for wide-area control purposes. Moreover, the oscillation modes are also monitored under gradual cases of non-synchronous generation integration in the system. The methodology is applied to two different test transmission systems: i) the two area system and, ii) the Nordic 32 system. The results illustrate the similarity and differences in the scenarios proposed.

Index Terms—Non-Synchronous Generation, Transmission Corridors, Oscillations Paths, Prony Analysis, Moving Window, System Inertia, Wide Area Measurements

I. INTRODUCTION

RENEWABLE power has seen dramatic expansion in recent years due to the global governmental initiatives that looks for the reduction of Green House Gas (GHG) emissions caused by the burning of fossil fuels. But this growth has raised several challenges for power-system operators and energy policy regulators.

Systematic measures for integrating variable renewable power is a priority for many countries where the share of renewable power is growing rapidly. For instance, in nordic countries, variable renewable power is becoming an important component in the pool source of power, and therefore a comprehensive study of the power system is necessary.

The composition of Wide Area Measurement Systems (WAMS) are based on operational tools that are continuously monitoring various signals (e.g., voltages, currents, speed of machines) in the grid. The inclusion of distributed Phasor Measurement Units (PMUs) in the system has allowed to

transmit, process and comprehend these signals in order to improve and protect the system to undersirable events [1].

One of the objectives of WAMS is to identify/estimate dominant low-frequency oscillations modes along the power grid and, in real-time, activate the alarms, protection systems or controllers involved in the oscillations monitoring and restoration process (e.g., Power System Stabilizers) [2].

Additionally, with the current expansion of non-synchronous generation interconnection on conventional generation (synchronous generators), several power planners and researchers, have reported significant dynamical challenges during the past years [3]. One of the aspects which can be adversely affected by the inclusion of non-synchronous generation is the oscillatory stability [4]. Hence, low frequency electromechanical oscillations deteriorate the power transfer exchanges, degrade the power system security, and occasionally, provoke cascading failures or even provoke a system blackout [5]. Therefore, it is important to understand how these oscillations vary under non-synchronous generation inclusion.

Several studies have shown that the large scale inclusion of wind power degrades the damping of the electromechanical modes. This displaces them to a different stability operation region, thereby affecting the response of the system under small and large disturbances [6].

Signal processing and spectral decomposition methods play a key role for the oscillation estimation methods in power systems based on measurements. The main methods applied to this topic include Hankel Singular Value Decomposition (HSVD) [7], Hilbert Spectral Analysis [8], the Extended Complex Kalman Filter (ECKF) [9], and wavelet-based method [10], [11].

Another method which has been used extensively for the estimation of oscillatory modes is the *Prony* analysis [12]. In [13], *Prony* Analysis (PA) method is used to detect poorly damped oscillations in early stages of the disturbance based on a size-controlled sliding window. In a recent contribution [14], and tested in a benchmark power system, PA method has been improved and used for extracting the dominant modes including a shrinking window.

The oscillation tracking paths along power systems have been studied in [15] and [16], however the only research proposal tracking oscillations including renewables is presented in [17], therefore the motivation of this paper is to analyse the

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oscillation paths under gradual inclusion of non-synchronous generation.

A preliminary version of this work has been published in [18]. This work contains substantial improvements to the proposed study and new simulations that do not appear in [18]. In contrast to [18], this paper focuses on tracking the oscillations along the entire system in order to recognise the oscillations path. Moreover different scenarios for tracking the signals are presented. Multi-*Prony* Analysis (MPA) method also uses a sliding window with the purpose of emulate the PMU sampling and to have a better understanding of the propagation of the oscillations in the system through graphical observation. Furthermore, it is demonstrated that the proposed study can be used as a monitoring tool due to it is based on the measurement of the system. This paper, analyses the effect of gradually increasing replacement of synchronous generators by high penetration of aggregated non-synchronous generation on power systems, including full converters as an interface on the transmission oscillations paths applying the MPA.

The paper is structured as follows: Section II presents briefly the concept of the method developed. In Section III, the oscillation paths tracking concept is presented. Section IV presents the *Prony* theory and the on-line oscillations path method explained. In section V, the method is evaluated in two test systems. Also, the case studies regarding the gradual increasing of non-synchronous generation integration in one of the test systems is presented. Finally, the conclusions and future work of this research are given.

II. OSCILLATIONS PATHS TRACKING CONCEPT

Monitoring of on-line mode estimation can be achieved by installing PMUs in the main tie-lines, so the active power measurement can be obtained and processed in the control center. Then, special algorithms, like the one presented in this paper, can determine and track the modes, and detect a possible cascading effect, separation of areas, loss of synchronism between machines during early stages of post-contingency state. Therefore, monitoring on-line real-time oscillation paths can straightforwardly distinguish between prevention or not of a partial or total blackout [19].

Figure 1 shows the concept of the on-line oscillations tracking along a signal. After a disturbance, an oscillation is provoked. The signal, as in this case, can be composed of one, two or more oscillatory modes at different frequencies and different damping ratios. As it can be seen in the figure, two sets of data Y_1 and Y_2 are deconstructed by the moving window algorithm based on PA.

III. NON-SYNCHRONOUS GENERATION

In this paper, non-synchronous generation is defined as when the power is provided/absorbed through power electronic converters (DC-AC) to the system. Voltage Source Converters (VSC) have been used for wind power turbines namely, Full Rated Converters (FRC), Doubly-Fed Induction Generator (DFIG), and High Voltage Direct Current (HVDC) and Multi-terminal HVDC connection [20].

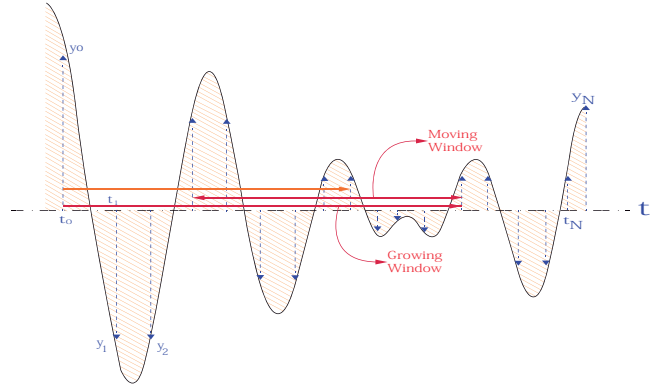


Fig. 1. Moving Window Concept

The non-synchronous generation allows to control active and reactive power control, however the generation is completely decoupled from the system, and is consequently unable to contribute dynamically to the system. Thus, if the synthetic inertia control option is not added, the decoupling displaces synchronous machines [21], [22].

IV. PRONY ANALYSIS AND ON-LINE COHERENCY

Prony analysis is a least-square approximation technique for fitting a sum of exponential terms to the measured data. It then identifies the amplitudes, damping factors, frequencies and phases contained inside the observed signal. For power systems, these estimations are conducted under the assumption that the system has encountered a perturbation set up following line or generator outages [23].

Consider a general continuous signal written as:

$$y(t) = \sum_{i=1}^m R_i e^{\lambda_i t} \quad (1)$$

where R_i are the residues and are directly linked with the amplitude of each mode to form the signal. When it is sampled at a constant sampling period Δt , the following expression represent the sampled signal:

$$y(k) = \sum_{i=1}^m R_i z_i^k \quad (2)$$

where k are the samples, and $z_i = e^{\lambda_i \Delta t}$, with $\lambda = \sigma + i\omega$. Since the real power system is not purely linear, this is an approximation of the adjustment of the measured signals with the aim of identifying the damping of the modes involved in the variables. Damping ratio is defined as the real part of the mode divided by its magnitude. It can be expressed as a percentage.

Prony methodology is used to estimate the modes of oscillation of a signal, identifying the relative contribution of each mode to form the signal, by the computation of the residues. Rewriting (2) in matrix form:

$$\begin{bmatrix} y(0) \\ y(1) \\ \dots \\ y(N-1) \end{bmatrix} = \begin{bmatrix} 1 & 1 & \dots & 1 \\ z_1 & z_2 & \dots & z_n \\ \dots & \dots & \dots & \dots \\ z_1^{N-1} & z_2^{N-1} & \dots & z_n^{N-1} \end{bmatrix} \begin{bmatrix} R_1 \\ R_2 \\ \dots \\ R_n \end{bmatrix} \quad (3)$$

where N is the number of samples. Additionally, z_i satisfies a polynomial of order n with the coefficients being a_i whose n roots are the modes of the group of signals:

$$z^n - (a_1 z^{n-1} + a_2 z^{n-2} + \dots + a_n z^0) = 0 \quad (4)$$

Multiplying the vector $[-a_n, -a_{n-1}, \dots, a_1, 1, 0, \dots, 0]$, to each side of (3), it is obtained that each sample may be written as a linear combination of the previous data and the coefficients are a_i , that is: $y(n) = a_n y(0) + a_{n-1} y(1) + \dots + a_1 y(n-1)$. This can be written for each sample in a matrix form:

$$\begin{bmatrix} y(n) \\ y(n+1) \\ \dots \\ y(N-1) \end{bmatrix} = \begin{bmatrix} y(n-1) & y(n-2) & \dots & y(0) \\ y(n) & y(n-1) & \dots & y(1) \\ \dots & \dots & \dots & \dots \\ y(N-2) & y(N-3) & \dots & y(N-n-1) \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \\ \dots \\ a_n \end{bmatrix} \quad (5)$$

The methodology of *Prony* can be summarized in three steps:

1. Solve (5) to get the coefficients a_i .
2. Next, obtain the roots of the polynomial in (4). In this step, it is now possible to get the modes: $\lambda_i = \sigma + i\omega = Ln(z_i) / \Delta t$.
3. The third step is to get the complex residues R_i solving (3), by using the solutions of (4). The time between samples from PMU is $\Delta t = 33ms$. This value is assumed for the subsequent simulations.

V. STUDY CASES AND APPLICATION

In order to illustrate the method, two test power systems are proposed as follows:

A. Case 1

The single line diagram of the test case 1 is shown in Figure 2. The test system consists of two fully symmetrical areas linked together by two 230 kV lines of 220 km length. Each area is equipped with two identical round rotor generators rated 20 kV/900 MVA. The nominal power system frequency for the test case model is 50 Hz. It was specifically designed in [24] to study low frequency electromechanical oscillations in large interconnected power systems. The loads are represented as constant impedances and split between the areas in such a way that area 1 is exporting power to area 2. In order to analyze the response of the power system, a large disturbance in the form of three phase to ground fault (4 cycles i.e. 80 ms) at $t = 2$ s is introduced in the middle of one of the two 220 km transmission line connecting Area 1 with Area 2. This results in an undamped oscillation of 0.6 Hz.

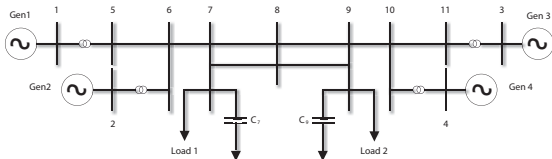


Fig. 2. Two Area Test System

1) *On-line Prony*: From the measurements of the active power through the tie-lines (Figure 3), it is plotted the tracked oscillations based on the on-line PA algorithm proposed. As it can be seen, the samples tracked show a cluster of oscillations around 0.6Hz, which confirms the expected frequency oscillation in the system. Besides, it is plotted the decay factor which shows how the oscillations decay while the oscillations get diminished.

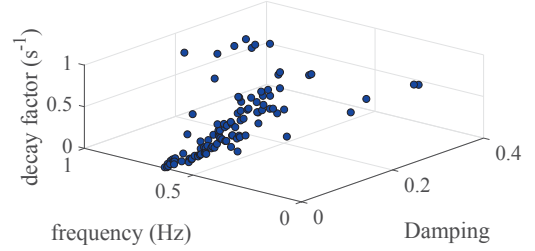


Fig. 3. On-line Frequency Dominant Frequency Modes Estimation

B. Nordic System

Figure 4 shows the single-line diagram of the Nordic test system presented in [25]. This system contains 32 high voltage buses. The transmission system is designed for 400 kV with some regional systems at 220 kV and 130 kV. This system has three identified areas of operation: *North*, *Central*, *South* and *External*. The simulation of this test system has been performed by the software DigSILENT®. The dominant interarea mode frequency of this system is 0.56 Hz (this mode is also reported in the literature [26]).

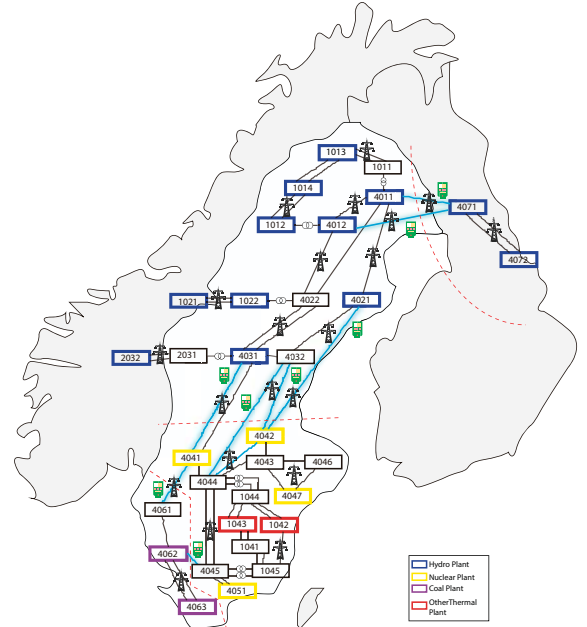


Fig. 4. Nordic Test System Representation

C. Non-synchronous generation

The impact of the integration of non-synchronous generation on the test system oscillations is analysed by replacing some of the synchronous generators with non-synchronous

generation with the same active and reactive power outputs. Note that the power outputs are fixed through the simulation. Case 1 (C_1) to Case 5 (C_5) represent the replacement of synchronous generation by the integration of non-synchronous generation gradually, in order to analyse different levels of power penetration. For example C_1 considers the replacement of one generation only, and C_2 considers the replacement of two generators including the one in C_1 , and so on. It is assumed that the dispersed generation is connected to one established substation. These five scenarios are summarised in Table I. However, only the cases where it has been found significant changes are selected to be presented.

TABLE I
GENERATOR REPLACEMENT FOR EACH CASE

Case	1	2	3	4	5
Generator	G_7	G_{16}	G_{17}	G_{14}	G_6
Bus	1043	4051	4062	4042	1042
Power (MW)%	1.2	5.4	9	13	15

1) *On-line Prony Application:* The method is applied to the obtained measurements from the cases mentioned above and from the tie-lines shown in 4. The tie-lines measurements are located in the operative areas interconnected as follows: South-Central (4062 – 4045, 4061 – 4041), Central-North (4021 – 4042, 4032 – 4042, 4032 – 4044, 4031 – 4041), North-Ext (4071 – 4011, 4071 – 4012). In order to observe the frequency similarities, it is plotted the oscillations along the tie-lines mentioned.

Figure 5 shows two identified frequency sub-clusters for the base case. First cluster frequency mode is around 0.6Hz, and the second one is around 0.8Hz. Figures 6 to 9 (cases C_1 to C_5) show the frequency clusters obtained after the gradual inclusion of non-synchronous generation. Cases C_1 and C_2 do not show a particular change in the frequency modes, but after case C_3 , the dominant mode moves to 0.4 Hz and the second mode moves out of the range of the electromechanical oscillations ($[0.2, 0.8]$)Hz. Case C_4 and C_5 show to be the most drastically change in the dominant mode with a new frequency cluster is around 0.3 Hz. This latest frequency is related to the low-pass filters of the converters at the Point Common Coupling (PCC).

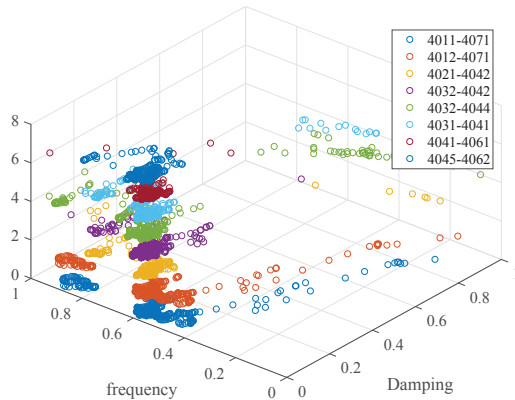


Fig. 5. Base Case

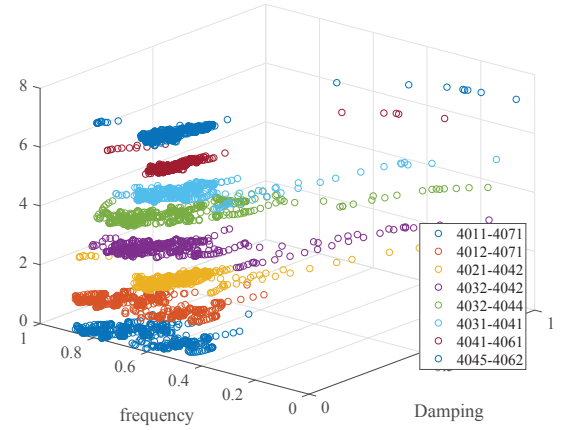


Fig. 6. Case 1

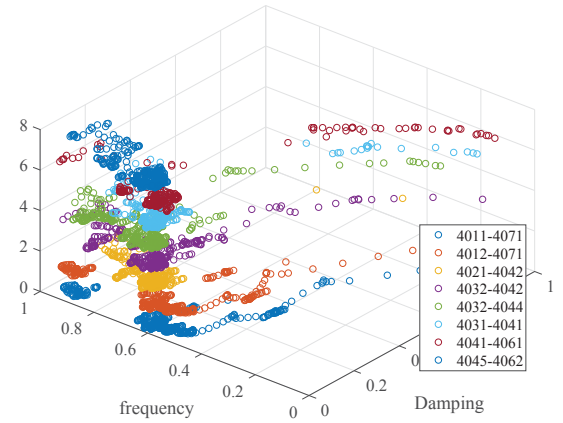


Fig. 7. Case 2

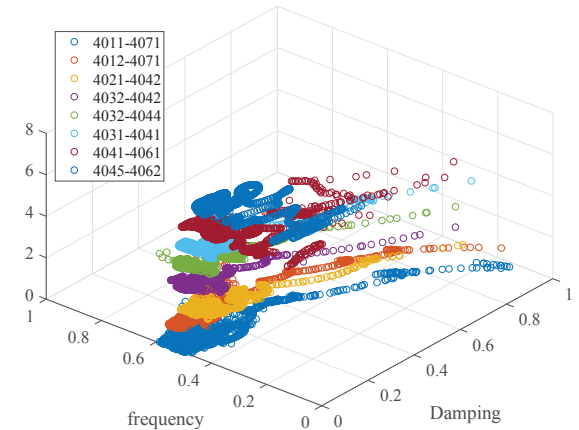


Fig. 8. Case 3

VI. CONCLUSIONS

This document has presented the application of the on-line PA for tracking the oscillations along the tie-lines in the power system. By this method is possible to observe the oscillation frequency groups and the decay rates. The emulation of PMU

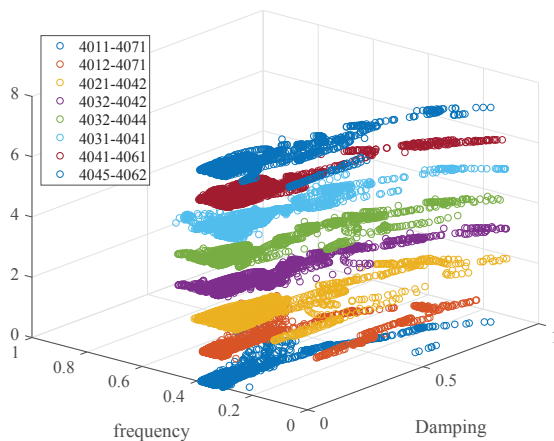


Fig. 9. Case 4 and 5

sampling provides information enough to track the oscillations, and observe their behaviour in the system.

By locating the measurements in the tie-lines the data processing can be reduced; however the location of the measurements depends on the topology of the system. Therefore, it is required more studies in this area.

The gradual increasing of non-synchronous generation drastically change the oscillations frequencies in the system. These changes might require to retune the PSS in the system, or change the location of the controllers in the system in order to do damp the oscillations adequately.

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