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Research Paper

# Modal estimation in distributed synchronous generation systems under three-phase unbalanced conditions☆

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ABSTRACT

Underdamped electromechanical oscillations (EMO), which are a typical problem of transmission systems, can also appear in power distribution systems (PDS) where synchronous generators are present. The tools to study EMO in bulk power systems are well established. Nevertheless, distributed synchronous generators have a different behavior from the ones connected to balanced three-phase bulk power systems. In these cases, some well-consolidated tools used to study EMO in bulk power systems are not adequate, since in distributed generation systems the load fluctuation is proportionally much higher and, therefore, it is not possible to define a good approximation for an equilibrium point. In this paper, a set of appropriate tools, which does not depend on the system model, is utilized to assess the presence of EMO in unbalanced PDS with synchronous generators. The obtained results show that the measurement-based methods which use ambient and ringdown responses can be applied to estimate the parameters of EMO in unbalanced PDS with high accuracy.



## 1. Introduction

Electromechanical oscillations (EMO) have been an usually observed phenomenon in transmission systems since the early 1950s, when large synchronous generators were connected to transmission networks through long transmission lines. Basically, these oscillations occur when the equilibrium of the system is perturbed due to a disturbance, such as a fault or a quick load change. In these cases, due to a temporary power imbalance, the rotors of the machines oscillate against each other exchanging power through transmission lines [1].

In recent years, the significant installation of distributed energy resources (DER), like photovoltaic systems, wind turbines, biomass and small hydropower plants, has led to a fundamental paradigm change of operation and planning of electrical power systems [2,3]. The connection of DER equipped with synchronous generators to power distribution systems (PDS) may cause the appearance of underdamped EMO [4–6]. Since PDS generally present a high level of imbalance, the well-stablished tools used to estimate the EMO in bulk power systems may not be useful to study such phenomenon in unbalanced systems. In [4,7], the authors show that the level of imbalance in PDS can indeed affect the dynamic behavior of synchronous generators. Hence, in this paper, we propose a set of appropriate tools to study the EMO in this type of system.

In bulk power systems, the study of EMO is often performed in the context of small-signal stability analysis. In this analysis, the modal information is frequently determined through the linearization of the nonlinear parametric model of the system and a set of linear tools which can be applied to this model.

Over the years, several improvements were done in order to clarify the dynamic behavior of a system, based on this linear approach. However, since the analyses are carried out through simulations of a mathematical model, the precision of the results is limited by the ability of the model to accurately represent the power system dynamic behavior [8,9]. Since the advent of phasor measurement units (PMU), an alternative procedure based on the computation of modal information from time domain data has emerged. The main advantage of this method is that it is not limited by the accuracy of the linear model or by its ability to describe the dynamic behavior of the system [8,10].

Unlike transmission systems, where a consolidated set of tools is applied for the analysis of these oscillations, there are few works in the technical literature, like [4–6], about stability studies of distribution systems considering their inherent characteristics. For

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this reason, in this work, a particular set of measurement-based tools is investigated to study the presence of EMO in PDS with synchronous generators. The objective of this investigation, which is the main focus of this paper, is to determine whether this set of tools is adequate for the proposed application. In [7], the identification of EMO in an unbalanced system was performed by applying a modal estimation technique to a response signal obtained when a transient event occurs in the system. However, this type of analysis can only be applied when a significant disturbance takes place. Hence, this method cannot identify EMO when the system is under a steady-state condition or subject to small load variations typical of PDS.

That way, the main contribution of this paper is the proposal of a framework, which is independent of the system model and the operation point, to estimate the EMO by using signals measured from a PDS. It is worth mentioning that the proposed framework considers intrinsic characteristics of PDS, such as the three-phase unbalanced operation and the high level of random load variations. To examine EMO for a large range of possible scenarios, the Prony [11] and ESPRIT [12] methods are used to study the response of the system during a transient event while N4SID [13] method is applied to steady-state data.

## 2. Linear approach

In the system model-based approaches, although the power system has a nonlinear behavior, a set of linearization-based techniques can be applied to study the small signal stability of the system when it is subjected to a small disturbance. Therefore, the nonlinear differential-algebraic equations that describe the system can be linearized around an equilibrium point. And the typical model obtained by this type of approach is given by [1]:

$$\Delta\dot{x} = A\Delta x + B\Delta u \quad (1)$$

$$\Delta y = C\Delta x + D\Delta u \quad (2)$$

where $\Delta x$, $\Delta y$ and $\Delta u$ are vectors of the state, output and input variables.

From the resulting matrix equations, qualitative information about the stability of the system around the equilibrium point can be determined. The eigenvalue/eigenvector analysis of matrix $A$ can be performed, and, consequently, the frequency and damping ratio of the EMO can be obtained.

Distribution systems, however, operate with high level of imbalance between their phases, which distinguish them from transmission system. The presence of this imbalance affects directly the behavior of a synchronous generator connected to this type of system. In this scenario, as explained in [4,14], the equilibrium solution is a periodic orbit, which is not a well-defined equilibrium point.

The presence of this sinusoidal oscillation in steady-state conditions can be observed in Fig. 1 where the time-domain response of the rotor speed of a synchronous generator connected to an unbalanced system is presented, taking into account different levels of imbalance. These responses are obtained through three-phase nonlinear simulations that were performed in the Alternative Transients Program (ATP) [15]. The complete set of data for the system used to produce the results in Fig. 1 can be obtained in [4]. This same test system will be used later in this paper. In Fig. 1, the imbalance factor (*IF*) is used to obtain the following powers:

$$S_{il} = (1 + IF)S_{1\phi} \quad (3)$$

$$S_{dl} = (1 - IF)S_{1\phi} \quad (4)$$

$$S_{ul} = S_{1\phi} \quad (5)$$

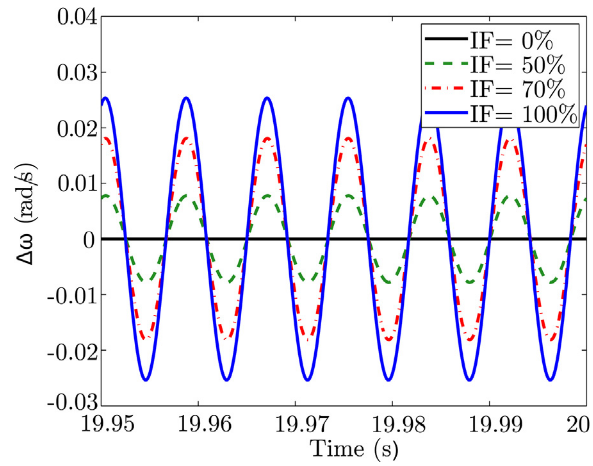


**Fig. 1.** The time-domain response of rotor speed for different levels of imbalance.

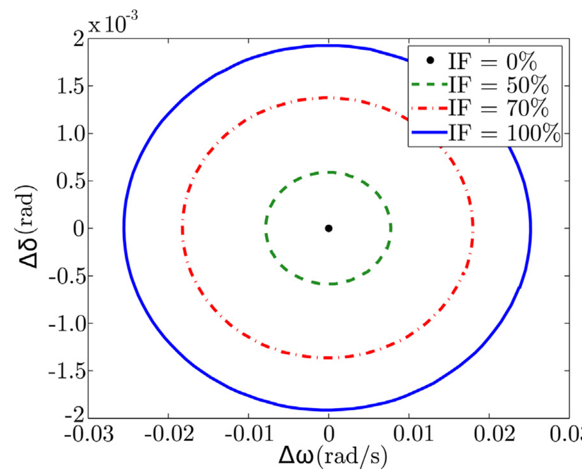


**Fig. 2.** Impact of imbalance in the phase-plane diagram, under steady-state conditions.

where $S_{1\phi}$ is one third of three-phase apparent power corresponding to the balanced case, and $S_{il}$, $S_{dl}$, and $S_{ul}$ are the apparent powers of the incremented, decreased and unchanged load, respectively, with respect to the balanced conditions. In this approach, for each value of load *IF* the three-phase power consumed by the loads remains constant. Therefore, we consider that the three-phase power consumed by the load is the same to create a basis of comparison among balanced and unbalanced operating points.

It is clear in Fig. 1 that when we increase *IF* the amplitude of the sinusoidal oscillation becomes bigger. Analysing this behavior in a phase plane composed by the variations of rotor speed and angle (Fig. 2), we can also see that the periodic orbit becomes greater when the imbalance level increases.

The *IF* used in this paper is not the most widely used indicator of imbalance in power system analysis methods. For example, in power quality studies, it is very common to use the index [17]:

$$V_{IMB} = \frac{V_-}{V_+} \quad (6)$$

where $V_{IMB}$ is the voltage imbalance, $V_-$ and $V_+$ are the negative sequence component and the positive sequence component, respectively, of the load voltage. Indeed, this index shown in (6) is adopted in several standards for power quality analyses and even in other types of power system studies.

The main justification for the use of *IF* is the possibility of comparing balanced and unbalanced cases with the same three-phase