Paper accepted for presentation at 2009 IEEE Bucharest Power Tech Conference, June 28th - July 2nd, Bucharest, Romania


# Estimation of power system dominant modes

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*Abstract*-- **The aim of this paper is to propose an approach to estimate the nature (damping and frequency) of a dominant mode. The suggested method, based on Prony analysis, aims to directly evaluate dominant modes of electromechanical oscillations. The basic idea is to fit the given oscillation with a fitting function having one mode only whose parameters need to be identified by any identification process. When the transient of the given signal vanishes, modes having high damping attenuate reaching a quasi linear behavior and revealing the dominant mode only. In this sense, the fitting function gains characteristic parameters (damping and frequency) of the dominant mode. For the identification process we suggest a nonlinear analysis approach based on the Lyapunov method applied to the Sensitivity theory.**

**The proposed methodology is tested on the New England 39-bus system.**

***Index Terms*—dominant mode, Lyapunov method, modal analysis, Prony analysis.**

## I. Introduction

Today's power systems are more and more stressed due to economical forces, demand increase, insufficient generation, transmission limits, and environmental factors. As a result, these systems operate closely to their stability limits, thus requiring exceptional efforts from researchers and operators to accomplish these needs. As pointed out by several studies, power system stability is a dynamic non-linear phenomenon which mainly depends on the poorly damped low-frequency oscillations following a contingency. These oscillations play an important role in power system small-signal stability analysis [1]. If they are not sufficiently damped, an unstable operation may occur and, potentially, may lead to a network collapse. For this reason, if the power system stability analysis and control is concerned, a parametric estimation of these low-frequency oscillations is necessary.

Mode estimation can be accomplished using two basic approaches, respectively, dynamic model-based and measurement-based approaches [2].

Current techniques for estimating electromechanical modes based on dynamic models are described in [3-9]. These methods lack of accuracy in the modelling process, thus it is preferable to use the measurement-based methods developed in time or frequency domain, such as the Discrete Fourier Transform (DFT) [10-13], the Kalman filter [14] or the Prony analysis [15-20]. Practical experiences, with these well consolidate techniques for modal analysis of linear signals demonstrate that they degrade their performances when they are applied to nonlinear signals, such as power system oscillations. This has led to an increased need to develop analytical techniques for a better characterization of power system oscillations, especially under stressed operating conditions. Among these techniques, there are some procedures based on nonlinear analysis of time series, such as the wavelet transform [21] and Hilbert analysis [22-24]. However, among all these linear and nonlinear modal analysis techniques, the Prony method can be considered as the widely used method for analysis of electromechanical oscillations of a power system. As fitting signal, it adopts a linear combination of damped sinusoids whose frequencies and damping factors characterize the modes of each power system oscillation. Thus, observing the resulting spectrum of modes its dominant mode can be revealed. This method requires high computational effort since it must provide the overall spectrum of modes of power system oscillations. With the same aim to determine the dominant mode of a power system oscillation, a novel procedure based on Lyapunov method applied to the Sensitivity theory is proposed. In particular, this paper has been structured with the Section II in which is proposed the mathematical formulation of the method able to investigate on dominant mode of a generic signal. As application of the proposed method, in Section III, we investigate on dominant modes of angular velocities of power system's machines. In this sense the paper focuses its attention on the modal analysis of local oscillations. An extension on inter-area mode oscillations can be carried out analyzing inter-ties oscillations between coherent areas. Section IV presents simulation results to demonstrate the effectiveness of the proposed methodology. In Section V are reported the conclusions.

## II. Mathematical Formulation Of The Identification Method

The goal of this section is to develop a novel methodology to estimate the dominant mode of a given signal. The methodology derives from the Prony analysis.

Prony analysis is a method able to fit a given signal, *y(t)*, by a linear combination of damped sinusoids as

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follows[25]:

$$\hat{y}(t) = \sum_{i=1}^{q} e^{-\sigma_i t}\left[A_i sen(2\pi f_i t) + B_i sen(2\pi f_i t)\right] + \sum_{j=1}^{p} C_j e^{-\sigma_j t} \quad (1)$$

where subscript $i$ represents the *i-th* complex mode, whereas $j$ is representative of the real one, and $q$ and $p$ are, respectively, total number of real as well as complex modes. $\sigma \in \Re$ is the damping factor and $f$ is the frequency of complex modes. $A$, $B$ and $C$ are constant values.

Unknown parameters $A_i$, $B_i$, $C_j$, $\sigma_i$, $\sigma_j$, and $f_i$ of the Prony's series can be estimated by an adequate identification parameter process.

For this reason Prony Analysis fits the recorded data samples of the signal under investigation, constructing a discrete linear AutoRegressive (AR) model. The methodology processes, simultaneously, all the available samples of the entire signal. As a result of it, a wide spectrum of power system modes can be revealed, even if operators are interested in the dominant mode only. However, when the transient of the signal $y(t)$ vanishes, modes having high damping attenuate reaching a *quasi* linear behavior and revealing the dominant mode only. Knowing that, we propose to limit eqn. (1) to one term only in order to directly estimate the dominant mode. For this purpose, we define the following Monomodal Fitting Function (MFF):

$$\hat{y}(t,\boldsymbol{p}(t)) = e^{-\hat{\sigma}_0(t)t}\left[\hat{A}_0(t) sen\left(2\pi \hat{f}_0(t)t\right) + \hat{B}_0(t) cos\left(2\pi \hat{f}_0(t)t\right)\right] \quad (2)$$

where $\boldsymbol{p}(t) = \left[\hat{A}_0\ \hat{B}_0\ \hat{\sigma}_0\ \hat{f}_0\right]^T$ represents the (4×1)-dimensional vector of the unknown parameters. The subscript $0$ refers to parameters related to the dominant mode.

In our procedure, we perform an identification process aimed to evaluate these unknown time-varying parameters giving rise to an adaptive model $\hat{y}(t,\boldsymbol{p}(t))$ that fits the given signal $y(t)$. For this purpose, we define the fitting error as:

$$e(t,\boldsymbol{p}(t)) = y(t) - \hat{y}(t,\boldsymbol{p}(t)) \quad (3)$$

The goal of this procedure is to change $\boldsymbol{p}$ until $e(t, \boldsymbol{p}(t))$ is either zero or it assumes a minimal value. This condition can be achieved turning to the Lyapunov method applied to the sensitivity theory based on [26]. We assume the following positive definite Lyapunov function:

$$V\left(e(t,\boldsymbol{p}(t))\right) = \frac{1}{2}e^2 > 0 \quad (4)$$

If the time derivative of $V$ can be defined negative, then $e(t,\boldsymbol{p}(t))$ approaches the origin (or the minimum of $e$) asymptotically. By determining $\dot{V}$ from eqn. (4), we obtain:

$$\dot{V} = e\dot{e} = e\left(\frac{\partial e}{\partial \boldsymbol{p}}\right)\dot{\boldsymbol{p}} \quad (5)$$

If $\dot{\boldsymbol{p}}$ is chosen according to the following position:

$$\dot{\boldsymbol{p}} = -\boldsymbol{\chi}\left(\frac{\partial V}{\partial \boldsymbol{p}}\right)^T = -\boldsymbol{\chi}\left(\frac{\partial e}{\partial \boldsymbol{p}}\right)^T e \quad (6)$$

where $\boldsymbol{\chi} = diag(\chi_i)$ with i=1,…,4 is a diagonal matrix in which the i-th generic positive element, $\chi_i$, represents an accelerator factor. In order to guarantee the algorithm convergence, $\chi_i$ needs to be negative.

Then substituting eqn. (6) into eqn. (5), the time derivative $\dot{V}$ can be obtained:

$$\dot{V} = -\boldsymbol{\chi} e\left(\frac{\partial e}{\partial \boldsymbol{p}}\right)\left(\frac{\partial e}{\partial \boldsymbol{p}}\right)^T e \quad (7)$$

Equation (7) expresses $\dot{V}$ in a quadratic form, thus it is negative semidefinite. This condition can be held until $p$ is produced according to eqn. (6).

The Jacobian $(\partial e/\partial \boldsymbol{p})$ appearing in eqn. (7) can be evaluated as follows:

$$\frac{\partial e}{\partial \boldsymbol{p}} = \frac{\partial\left(y(t) - \hat{y}(t,\boldsymbol{p}(t))\right)}{\partial \boldsymbol{p}} = -\frac{\partial\left(\hat{y}(t,\boldsymbol{p}(t))\right)}{\partial \boldsymbol{p}} \quad (8)$$

For clarity purposes, in Figure 1 we show the basic idea of the parameter identification process.

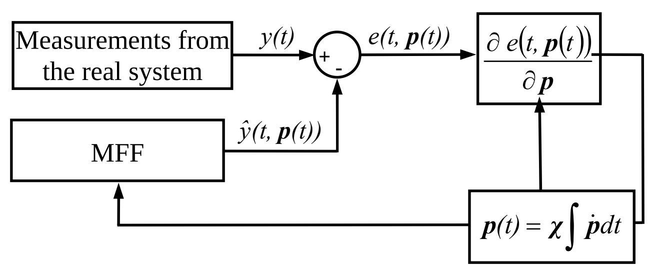


Fig. 1. Block diagram of the proposed identification methodology.

As it can be noted, the procedure adjusts parameters in the continuous time domain until they reach their steady state values. In this context the fitting error starts from its maximum value depending on the initial guess of parameters and decreases until it reaches its minimum.

Multi-solution problems arise with the number of unknown parameters and their initial values as well as the gain factor $\boldsymbol{\chi}$. In order to minimize such a deficiency, we suggest to limit the analysis to a class of signals having the following conditions:

$$y(t) = 0 \qquad for \quad t = 0 \ and \ t \to \infty \quad (9)$$

With this assumption a new fitting function can be obtained:

$$\hat{y}(t,\boldsymbol{p}(t)) = e^{\hat{\sigma}_0(t)t}\left[\hat{A}_0(t) sen\left(2\pi \hat{f}_0(t)t\right)\right] \quad (10)$$

where $\boldsymbol{p}(t) = \left[\hat{A}_0\ \hat{\sigma}_0\ \hat{f}_0\right]^T$ is the (3×1)-dimensional vector of the unknown parameters. As it can be noted, this new MFF contains only three parameters to be identified.

## III. System Modes Estimation of a Power System Using Sensitivity Theory.

In this section we give details about the application of the general identification method developed in the previous Section to a power system, deriving a practical procedure to estimate dominant modes of local oscillations of power system. In particular, our aim is to evaluate dominant modes of speed trajectories of all power system's machines. We must notice that computational problems can arise, especially in the case of power systems having a considerable numbers of machines. However this problem can be minimized if the system is composed by coherent areas. In this case we can reduce the signals under investigation considering those provided by equivalent machines representing coherent areas, for local modes investigations, or those deriving from inter-ties measurements, for inter-area oscillation analysis.

In this preliminary work we analyze on local dominant mode. For this purpose we adopt machine speeds as signals under investigations. These particular signal belong to the class of signals having initial and final values equal to zero. With this assumption we adopt the following monomodal fitting function:

$$\hat{\omega}^j\left(t, \boldsymbol{p}^j(t)\right) = \hat{A}_0^j(t) e^{-\hat{\sigma}_0^j(t)t} \sin\left(2\pi \hat{f}_0^j(t) t\right) \quad j = 1, \ldots, N_G \qquad (11)$$

where $N_G$ represents the total number of generating units and $\boldsymbol{p}^j(t) = \left[\hat{\sigma}_0^j \ \hat{f}_0^j \ \hat{A}_0^j\right]^T$ is the ($3\times1$)-dimensional vector of the unknown parameters.

We define the ($N_G \times 1$)-dimensional vector of the fitting function errors as:

$$\boldsymbol{e}(t, \boldsymbol{p}) = \boldsymbol{\omega}(t) - \hat{\boldsymbol{\omega}}(t) \qquad (12)$$

where:

$$\boldsymbol{\omega}(t) = \left[\omega^1(t) \ldots \omega^j(t) \ldots \omega^{N_G}(t)\right]^T ;$$

$$\hat{\boldsymbol{\omega}}(t) = \left[\hat{\omega}^1(t) \ldots \hat{\omega}^j(t) \ldots \hat{\omega}^{N_G}(t)\right]^T$$

and

$$\boldsymbol{p}(t) = \left[\boldsymbol{p}^1(t) \ldots \boldsymbol{p}^j(t) \ldots \boldsymbol{p}^{N_G}(t)\right]^T$$

where $\boldsymbol{p}^j(t) = \left[\hat{A}_0^j \ \hat{\sigma}_0^j \ \hat{f}_0^j\right]^T$.

In order to solve the problem an iterative scheme in the continuous time domain needs to be realized as described by the following stages:

1) Import measurements of angular velocities of generators;
2) Assume initial value of the parameter vector;
3) Evaluate the estimated angular velocity by means of eqn. (11);
4) Evaluate the fitting error between the measured value of $\boldsymbol{\omega}$ and the estimated one;
5) Evaluate sensitivities of the error function with regard to the estimated parameters and then evaluate the derivative of unknown parameters;
6) If the modulus of the derivatives of estimated parameters are less than a fixed tolerance, the algorithm stops, otherwise the vector of independent variables, $\boldsymbol{p}$, is updated;
7) Update the unknown parameter vector as follows:

$$\boldsymbol{p}(t) = -\chi \int \dot{\boldsymbol{p}} dt \qquad (13)$$

where $\chi = diag(\chi_i)$ with $i=1,\ldots,3$ and $k=1,\ldots,N_G$ is a ($3N_G \times 3N_G$)-dimensional diagonal matrix whose elements represent positive accelerating factors. The gain factor $\chi$ has to be chosen carefully as in all gradient-based methods. If $\chi$ is chosen too large, the procedure can diverge, if it is chosen too small, the identification takes too much time.

Note that, the architecture of the monitoring system of dominant modes requires that the algorithm runs permanently. It gives the last value of parameters as output if nothing happens on the system. When transient phenomena caused by line switching or generator/load outages occur on the system, the algorithm changes its output giving new damping and frequency values characterizing the dominant mode. On the contrary, the change of damping and frequency values can reveal the occurrence of a contingency.

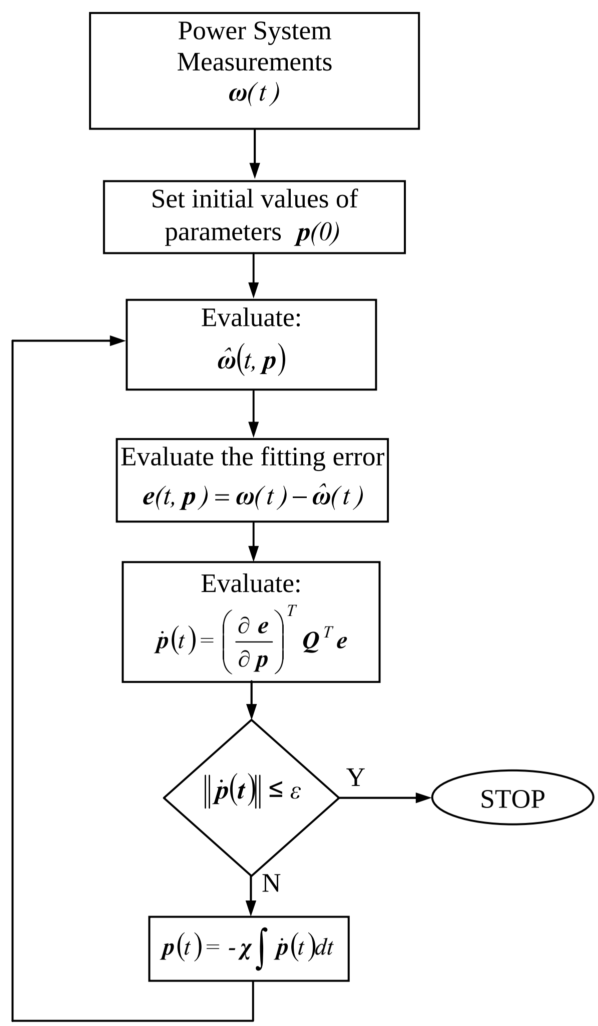


Fig. 2. Flow chart of the proposed algorithm.

## IV. Test Results

The methodology was tested developing the identification algorithm in the Matlab/Simulink environment [27].

Preliminarily we used a simple example to better understand the algorithm ability in estimating the dominant mode, thus to validate our approach. By doing this we produced a known reference signal, *y(t),* containing more than one mode as follows:

$$\begin{aligned} y(t) = {} & e^{-0.1t}\left(-2.85sin(2\pi 1.114t)+3.46cos(2\pi 1.114t)\right)+ \\ & + e^{-0.11t}\left(1.4sin(2\pi 0.95t)+1.66cos(2\pi 0.95t)\right)+ \\ & + e^{-0.2t}\left(-0.9sin(2\pi 0.8t)+1.9cos(2\pi 0.8t)\right)+ \\ & + e^{-1.5t}\left(-6.5sin(2\pi 1.27t)+3.75cos(2\pi 1.27t)\right)+ \\ & + e^{-2t}\left(-9.7sin(2\pi 1.43t)+5.4cos(2\pi 1.43t)\right)-16.17e^{-3t} \end{aligned}$$

The first term of $y(t)$ is the dominant mode, having damping factor $\sigma_0 = -0.1$ and frequency $f_0 = 1.12\ Hz$. In order to stress the identification ability of the proposed methodology, the subsequent mode has been chosen closely to the dominant one.

The iterative algorithm was initialized by using $\sigma_0 = 0$ and $f_0 = 0$ as initial guess. Moreover, we assigned the following $\chi$ matrix:

$$\chi = \begin{bmatrix} \chi_{\sigma_0} & 0 & 0 \\ 0 & \chi_{f_0} & 0 \\ 0 & 0 & \chi_{A_0} \end{bmatrix} = \begin{bmatrix} 2 & 0 & 0 \\ 0 & 4 & 0 \\ 0 & 0 & 10 \end{bmatrix}$$

The application of the investigation on such a signal gave rise to the damping factor and frequency of the dominant mode whose behavior is shown in Figure 3. As it can be noted, after a brief transient, parameters $\hat{\sigma}_0$ and frequency $\hat{f}_0$ reach their steady-state values equal to, respectively, $\hat{\sigma}_0 = 0.097\ s^{-1}$ and $\hat{f}_0 = 1.098\ Hz$. The resulting error is, respectively, equal to $e_{\sigma_0\%} = 3.0\%$ and $e_{f_0\%} = 1.4\%$.

Figure 4 shows the given signal, *y(t)*, and the reconstructed signal, $\hat{y}(t)$, applying time varying coefficients $\hat{\sigma}_0$ and $\hat{f}_0$. Note that the Monomodal fitting function correctly reproduces the given signal after 3÷4 sec., even if it contains more than one mode, thanks to the time-varying parameters. As time passes modes having high damping factor attenuate. After 40÷50 sec the system approaches a *quasi* linear behavior and parameters reach their steady-state values giving rise to a fitting function revealing the dominant mode only.

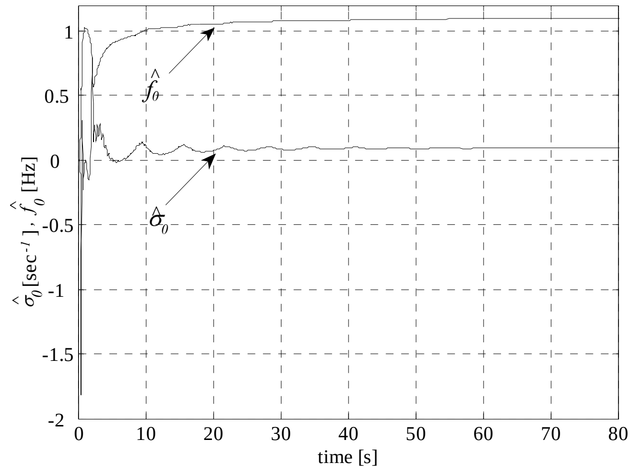


Fig. 3. Time domain behavior of the damping factor $\hat{\sigma}_0$ and the frequency $\hat{f}_0$.

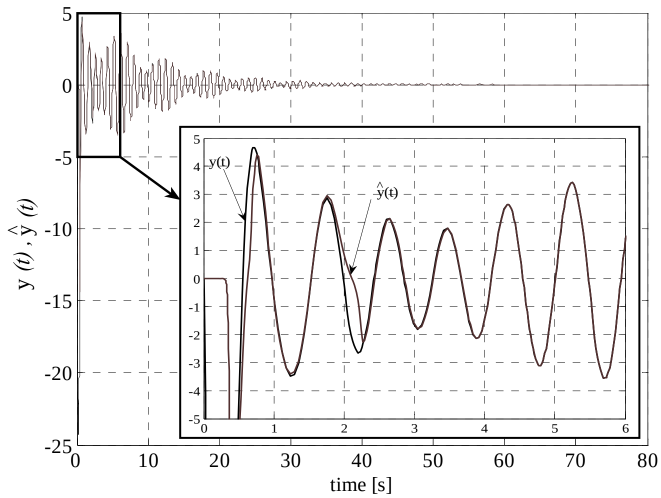


Fig. 4 Comparison between the given signal $y(t)$ and the reconstructed one $\hat{y}(t)$

In order to investigate on the noise rejection ability of the method, we added a white noise with a variance equal to 0.1 to the previous signal $y(t)$.

Figs. 5 and 6 show the resulting signal under investigation and the estimated parameters. In this case the parameters were equal to $\hat{\sigma}_0 = 0.096\ s^{-1}$ and $\hat{f}_0 = 1.098\ Hz$, thus obtaining values similar to those obtained in absence of noise. This result can be justified by the presence of a filtering action due to the integrator in our algorithm.

The precision of results can be considered relatively high, whereas, on the contrary, the accuracy of the measurement chain can influence results obtainable by the method.

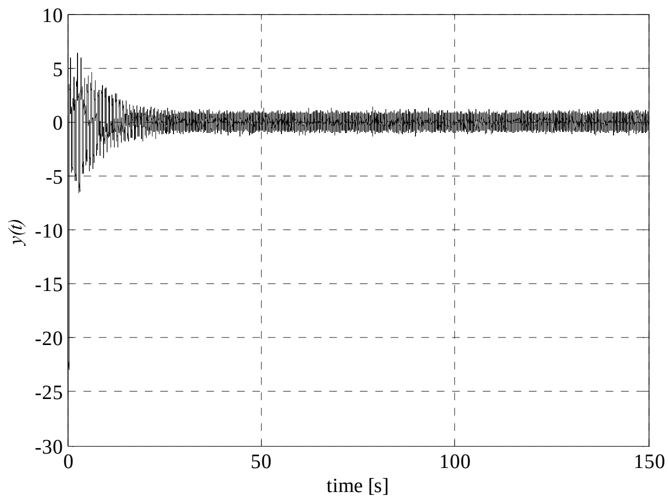


Fig. 5. Time domain behavior of the signal y(t) affected by noise.

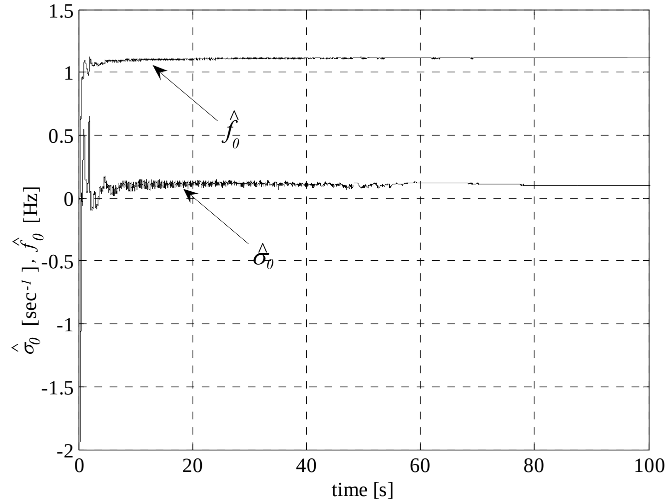


Fig. 6. Time domain behavior of the damping factor $\hat{\sigma}_0$ and the frequency $\hat{f}_0$ of the dominant mode.

We performed another test aimed to estimate dominant modes of local oscillations of power system. For this purpose, we adopted the IEEE-39 bus test system, known as New England system. Figure 7 shows the system whose static and dynamic data can be found in [28]. Time domain simulations were conducted in the Matlab/Simulaink environment [27] by adopting the PST software [28]. Ordinary differential equations were solved adopting the ode23tb solver with a variable time step.

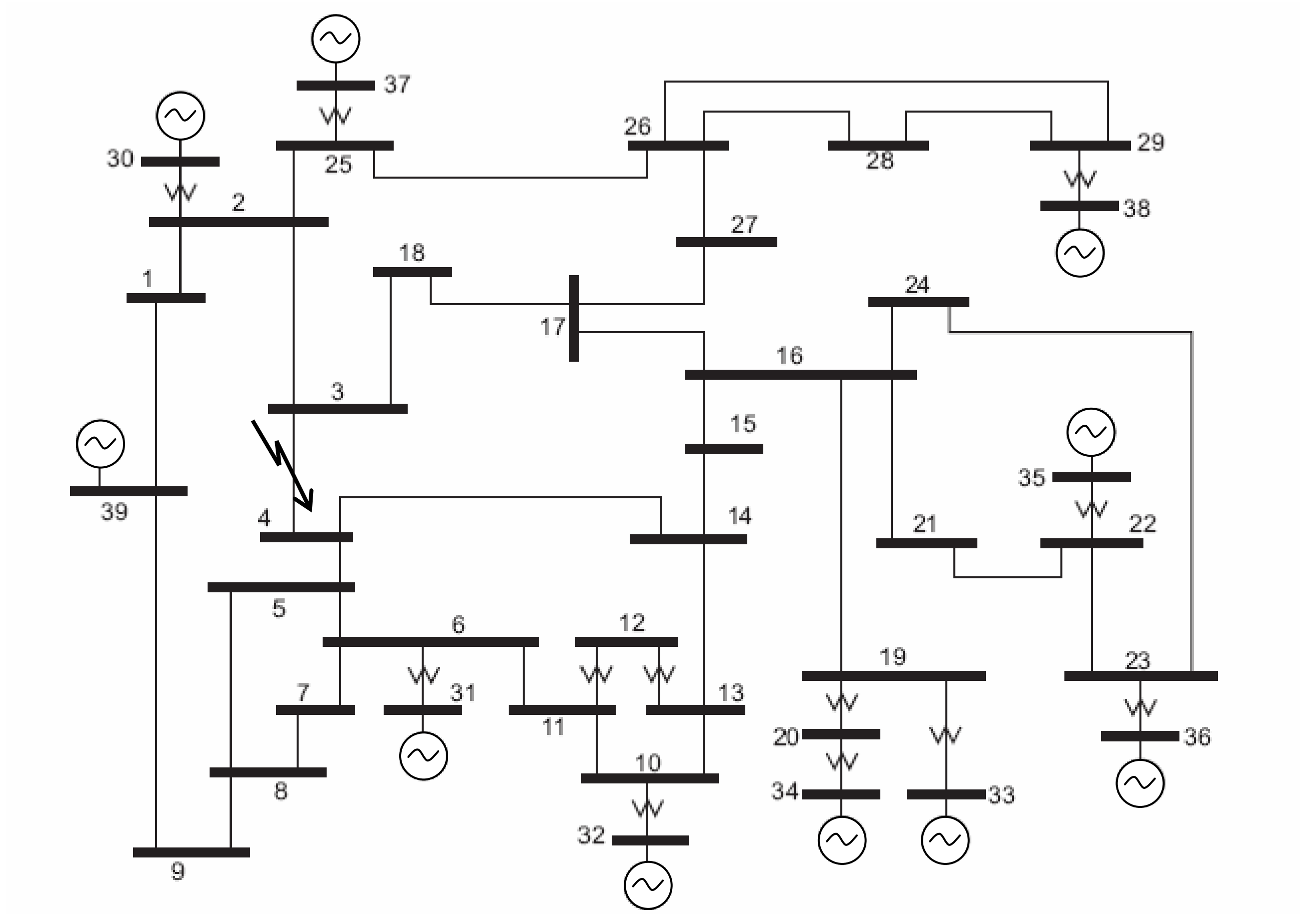

Fig.7. Single-line diagram for the IEEE-39-bus test system.

We perturbed the system by a three phase fault located at bus 3, cleared after 0.25 sec by tripping the line 3-4. The developed code collected all rotor angle behaviors of all the ten generators and then post-processed by the algorithm for the dominant mode detection. Also in this case we initialized the algorithm using $\sigma_0 = 0$ and $f_0 = 0$ .

This investigation identified the dominant modes for all generator behaviors reported in Table I.

The methodology gave rise to almost the same parameters of the dominant modes for all generators.

Figure 8 shows the comparison between angular velocities obtained by the PST simulator and those deriving from the MFFs adopting the estimated parameters.

TABLE I – ESTIMATED DOMINANT MODE PARAMETERS FOR THE NEW ENGLAND'S GENERATORS

| Generator # | Damping [sec$^{-1}$] | Frequency [Hz] |
|---|---|---|
| 30 | -0.16 | 0.53 |
| 31 | -0.22 | 0.54 |
| 32 | -0.21 | 0.56 |
| 33 | -0.20 | 0.56 |
| 34 | -0.20 | 0.56 |
| 35 | -0.21 | 0.56 |
| 36 | -0.18 | 0.53 |
| 37 | -0.19 | 0.56 |
| 38 | -0.19 | 0.56 |

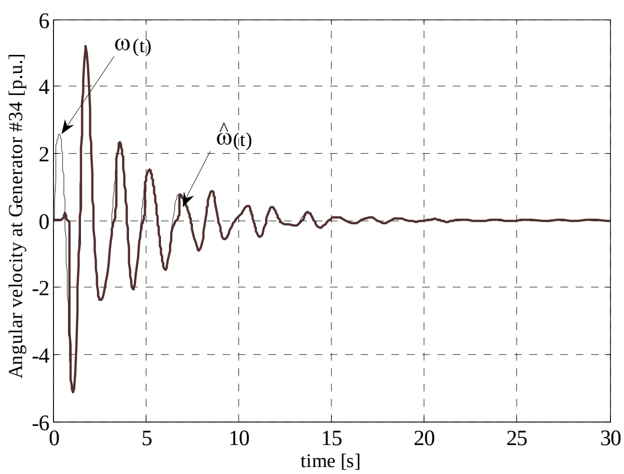


Fig. 8. Time domain behavior of the angular velocity at generator #34: $\omega_0(t)$ measured on the power system; $\hat{\omega}_0(t)$ the reconstructed one.

As it can be noted the two signals are almost overlapped.

## V. CONCLUSIONS

In this paper a novel methodology to estimate dominant modes of generic signals has been developed. This method is based on a parameter identification process adopting the Lyapunov function and it has the advantage to directly estimate dominant modes overcoming the traditional problems related to classical estimation method of nonlinear signals.

In this preliminary work, the methodology has been applied to the analysis of local dominant mode of electromechanical oscillations of power system.

Test results demonstrated a good ability and fast convergence to evaluate dominant modes even if the signal under investigation is strongly corrupted by noise. This is due to an intrinsic integral filtering action of the algorithm. In addition, the considered technique does not require system linearization or any *a priori* information about the system order that generates the given signal.

Future developments should be focused on the application of the methodology to inter-area oscillations analyzing inter-ties signals.

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## VII. Biographies

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**Francesco Torelli** was awarded a degree in Electrical Engineering in 1966 from the Politecnico di Milano (Italy). In the same year he joined the Electrical Engineering Department of the University of Bari as Assistant Professor and, successively, as Associate Professor of Power Systems. He is presently Professor of Power Systems. His research interests are in power system analysis and control.