Master thesis

Test Scenarios for Validation of the Offline Workflow of the iTesla Toolbox for Small-Signal Stability Assessment

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Abstract

Transmission System Operators (TSOs) are facing new challenges due to the larger amount of renewable and intermittent energies injected into the electric grid and to new power electronics devices with fast dynamics. Keeping the balance between production and consumption is the responsibility of TSOs and it is becoming more challenging due to these increased uncertainties.

These new challenges were the main motivation for the iTesla project. The project aims to develop a tool to help the TSOs evaluating the risks of a given situation, by simulating a lot of different scenarios beforehand. The idea is to create security rules thanks to the work done beforehand that will serve to judge the safety of the real-time situation. In order to assess the severity of a fault, several indicators have been developed. Concerning the validation of the small signal stability index, a set of test signals with inter-area oscillations would be appreciated.

This is the goal of this master thesis: to create a set of inter-area oscillating signals from a given network topology.

A brief introduction to inter-area oscillations and to the model used for analysis of inter-area oscillations is first presented. Existing methods for estimation of modes from ringdown analysis are introduced. The small signal stability index used for power system dynamic impact assessment in iTesla is presented and tested on different scenarios. A comparison between existing modules based on Prony's method has been done on some test signals.

The French network has been studied in order to scan the modes inherent to the power system. Thanks to this analysis, some well chosen regulators of generators have been modified so that poorly damped oscillations with a low frequency may appear. This operation has been automated so that the simulations can be done and analyzed on a larger time window, creating the set of tests that was needed.

This set of test will be used to validate the small signal stability index in the case of inter-area oscillations.

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Chapter 1 – Introduction

iTesla project (Innovative Tools for Electrical System Security within Large Areas)

Transmission System Operators (TSOs) are facing new challenges due to the larger amount of renewable and intermittent energies injected into the grid and to new power electronics devices with fast dynamics. It is becoming more challenging for TSOs to keep the balance between supply and demand while staying within the safety margin because of these reasons. As a consequence, there is a need for tools which can help the TSO evaluating the potential risks of a given situation and which takes into account the uncertainties due to renewable energies and the dynamics of the system.[1][14]

The iTesla project aims at creating a toolbox which will increase the coordination between European TSOs, improve the global security and therefore optimize the electricity transit in the grid.

iTesla's goal is to provide technical solutions to face the following European TSOs challenges[2]:

- The increasing uncertainties due to renewables development and integration
- The dynamic behaviors understandings over the power grids (especially regarding new devices such as FACTS, HVDCs, renewable generation like wind, solar, tidal, ocean wave etc.)
- The need for an increased cooperation between the European TSOs due to the increasing cross boarder connections and the energy market
- An efficient and automatic way which would offer each player a set of preventive and remedial actions

In order to take into account the uncertainties, the idea is to simulate a lot of different scenarios representing different possible states of the system and see whether they are safe or not. However simulations can't be run in real-time in large numbers, that is why the idea of iTesla is to have an offline module in which computations are made beforehand, and an online security assessment module. Figure 1 introduces the place of the offline security assessment module (Work Package 4 (WP4) on which this master thesis is about) within the iTesla project[1]. Moreover, the goal of WP4 is very well introduced by [1]:

> "The main function for the Offline Security Assessment module is to compute 'Offline Security Rules' that can be used in WP5. These rules essentially compress the results of numerous dynamic simulations in a set of security rules to denote the safe operation boundaries of pre-fault state variables. The online module can make use of these rules to classify probable future operating points as stable/unstable without running a large number of detailed dynamic simulations in real-time. This way, available resources can be focused only to specific and highly dangerous scenarios that must be fully analyzed in real-time."

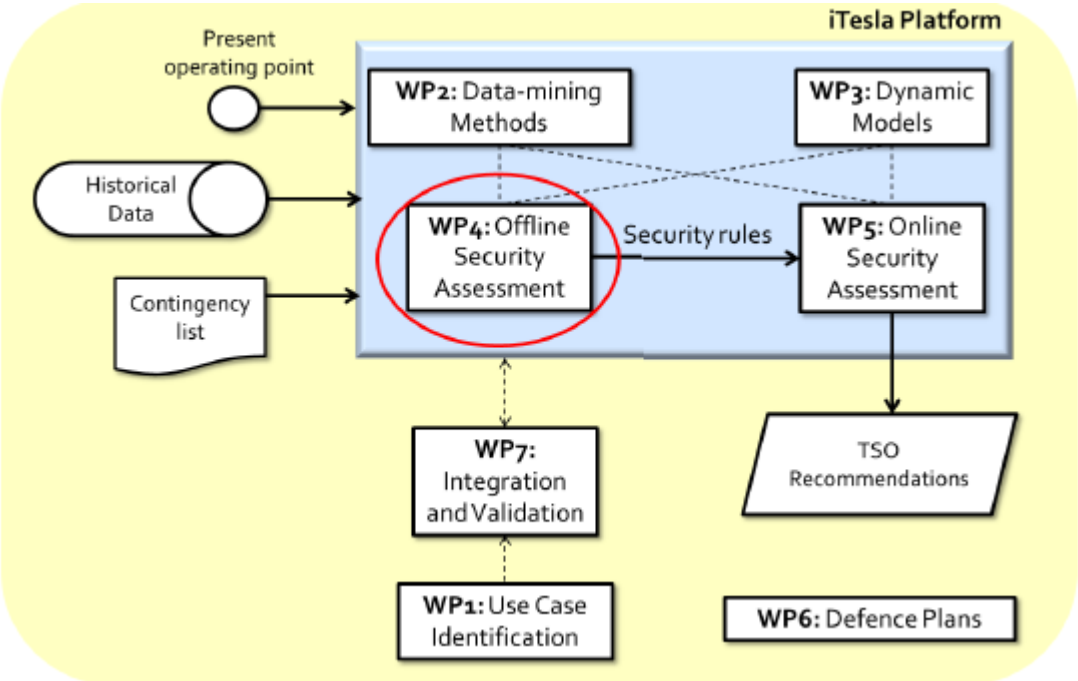

Figure 1: The Offline Security Assessment module within the overall iTesla platform workflow

Work Package 4

First, [1] is quoted to describe how WP4 works:

> "The logic of the offline security assessment model can be described as:
> • Anticipate which operating points the system is likely to encounter in the medium-term horizon to which the off-line analysis is applied. Generate a number of operating points according to the historical data.
> • Analyze each of these operating points against a list of credible contingencies via dynamic simulations. Determine which operating point-contingency pairs result in an unsafe post-fault situation.
> • Using of all the pairs' state variables and class as a training set, derive the offline security rules using Decision Trees to classify the pre-fault state-space into acceptable and unacceptable performance regions [figure 3].

The above procedure and how it is partitioned in different tasks within iTesla is shown graphically" in figure 2.

One of the important sections of WP4 is the post-contingency classification made by KTH and comprises different indexes evaluating the severity of the contingency from different stability point of views. This master thesis is mainly focused on the small signal stability index.

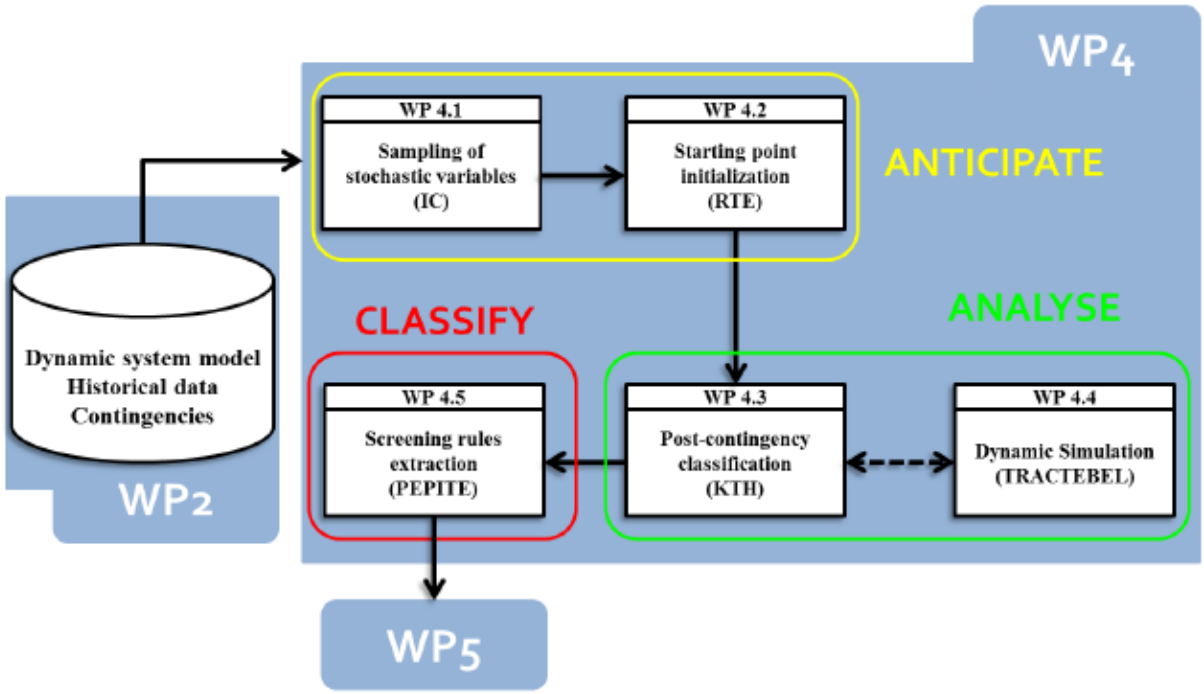

Figure 2: Offline Security Assessment workflow [1]

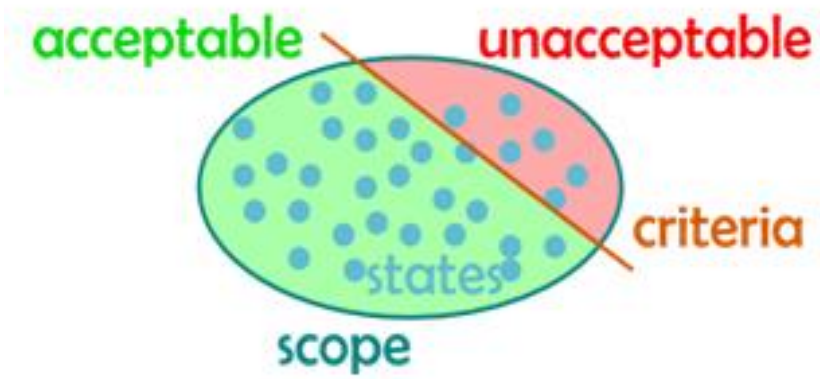

Figure 3: Illustration of the border between safe and unsafe regions [3]

Aim of the master thesis

In the validation process, the small signal stability index has to be tested in a situation presenting inter-area oscillations. However, so far no such situation exists with complete dynamic data in the scale of Europe or France. Indeed, complete historical data in RTE are only available for the French network and since 2013. Since this recording, no interesting oscillations have been observed.

The aim of the master thesis is then to establish a set of tests to validate the offline part of iTesla project in the case of inter-area oscillations. This set of tests will serve to demonstrate the utility of iTesla platform in detecting this kind of instability and to validate the small signal stability index in this case.

This master thesis will deal with how to build an unsafe situation in the case of small signal stability: how to artificially create low frequency oscillations in a power system (between 0.1 and 2 Hz).

In the first part some theoretical background will be treated to introduce the concepts needed in the following sections. Then a comparison will be done between different tools whose aim is to compute modes using ringdown analysis. Finally the method used to create slow oscillations with the simulation software Eurostag will be presented.

Chapter 2 – Literature review

1. Brief introduction to inter-area oscillations

The phenomena of inter-area oscillations and their impact on the stability of the power system. Main content comes from [4], [6] and [10].

1.1. Synchronous machine and power /angle relationship

The synchronous machine is composed of the field in the rotor and the armature in the stator. A prime mover (turbines moved by steam, water, wind …) rotates the rotor on which is set a direct current winding (the field winding) creating a rotating magnetic flux which will induce currents in the three phase winding of the armature. In the case of the synchronous machine, frequencies of quantities in stator and rotor are synchronized. The field induced by the stator and the one from the rotor interact and an electromagnetic torque maintain the link between these two components. In steady state the angle between the rotor field and the stator field is constant. However in a generator for example, if more mechanical power is inserted the rotor field will advance compare to the stator field.

If one uses the example of a single line (modeled by its reactance X_L) network between a generator and a motor (without regulators), the power transferred from the generator to the rotor would be:

$$P = \frac{E_G E_M}{X_T} sin(\delta)$$

with

$$X_T = X_G + X_L + X_M$$
$$X_G: \text{reactance of the generator}$$
$$X_M: \text{reactance of the motor}$$

δ: angular separation between the rotor of the generator and the rotor of the motor(i.e. the angle by which the generator rotor leads the revolving field of the stator plus the angle by which the stator field of the generator leads that of the motor plus the angle by which the motor rotor lags the revolving motor stator field)

In a more complex network, the power through the lines is still affected in a similar way by the machines angle displacements.

1.2. Stability

The stability phenomena is very well explained in [4] as:

> "Stability is a condition of equilibrium between opposing forces. The mechanism by which interconnected synchronous machines maintain synchronism with one another is through restoring forces, which act whenever there are forces tending to accelerate or decelerate one or more machines with respect to other machines. Under steady-state conditions, there is equilibrium between the input mechanical torque and the output electrical torque of each machine, and the speed remains constant. If the system is perturbed this equilibrium is upset, resulting in acceleration or deceleration or the rotors of the machines according to the laws of motion of a rotating body. If one generator temporally runs faster than another, the angular position of its rotor relative to that of the slower machine will advance. The resulting angular difference transfers part of the load from the slow machine to the fast machine, depending on the power-angle relationship. This tends to reduce the speed difference and hence the angular separation."

The electrical torque is responsible for keeping the machines oscillating at the same frequency and can be divided in two components: the damping torque and the synchronizing torque. The damping torque can be compared to an elastic torque, when a perturbation occurs and some machines accelerate or decelerate, the damping torque will compensate this acceleration or deceleration in order to return to the original state. The synchronizing torque intervenes for more significant events in order to keep the rotors in phase with each other. When the synchronizing torque is too low, there is an aperiodic drift in rotor angle leading to a loss of synchronism for one machine or a group of machines.

1.3. Small signal stability

Small signal stability is "the ability of the power system to maintain synchronism under small disturbances"[4]. Small disturbances as variation of load or generation, faults as short circuits or line tripping are part of the normal operation of the system and therefore it is important that the system remains stable when these occur. An event is studied from a small signal stability point of view as long as the impact of the event is small enough so that the system of equations can be linearized. Two kinds of instabilities are possible: one with a lack of synchronizing torque leading to a rotor angle deviation and one with a lack of damping torque leading to rotor oscillations with increasing amplitude.

1.4. Local oscillations and inter area oscillations

There are different kinds of oscillations in power systems depending on their origins; one can regroup them in five types[6]:

- Intraplant mode oscillations
- Local plant mode oscillations
- Control mode oscillations
- Torsional modes between rotating plant
- Inter area mode oscillations

First, local modes are defined as a unique generator oscillating against the rest of the power system which is assumed to remain constant. Its oscillating frequency is between 1 to 2Hz.

Inter area mode oscillations involves a larger part of the system and is consequently more dangerous. It consists of two coherent groups of generators oscillating against each other usually through weak ties at a frequency lower than 1Hz. Inadequate damping ratio for inter area modes often leads to system separation[6], that is why automatic controls are important in power systems to improve mode damping.

2. Model-based analysis of inter-area oscillations

In this section some concepts about the model used for the small signal stability studies of dynamic systems will be seen. The whole theoretical background has been taken from [4].

As said previously in 1.3, in the case of small-signal stability the equations describing the system can be linearized. The instability that will be treated in the following lines will be the one due to a lack of damping torque which causes some poorly damped oscillations.

2.1. State-Space Representation

2.1.1. Model

In the case of an autonomous power system, the state-space representation can be described as:

$$\dot{x} = f(x, u) \qquad (1)$$
$$y = g(x, u) \qquad (2)$$

where $x = \begin{bmatrix} x_1 \\ x_2 \\ \dots \\ x_n \end{bmatrix}$ is the state vector, n the order of the system, x_i the state variables, y the vector of outputs of the system and u is the vector of inputs to the system.

In case of small motion around an equilibrium point where x_0 is the state vector at the equilibrium point and Δx the small deviation compared to x_0, the equations (1) and (2) can be linearized into:

$$\Delta\dot{\mathrm{x}} = \mathrm{A} * \Delta\mathrm{x} + \mathrm{B} * \Delta\mathrm{u} \qquad (3)$$
$$\Delta\mathrm{y} = \mathrm{C} * \Delta\mathrm{x} + \mathrm{D} * \Delta\mathrm{u} \qquad (4)$$

where
A is the state matrix
B is the control matrix
C is the output matrix
D is the feedforward matrix

Moreover, for each eigenvalue λ of the state matrix there exist one right eigenvector φ which satisfies equation (5) and one left eigenvector Ψ which satisfies equation (6).

$$A * \varphi = \lambda * \varphi \qquad (5)$$

$$\Psi * A = \lambda * \Psi \qquad (6)$$

2.1.2. Modes

Once equations (3) and (4) solved each state variable can be written as the following form (e.g. for the ith state):

$$\Delta x_i(t) = \varphi_{i,1} * c_1 * e^{\lambda_1 t} + \varphi_{i,2} * c_2 * e^{\lambda_2 t} + \cdots + \varphi_{i,n} * c_n * e^{\lambda_n t} \qquad (7)$$

Consequently, each state variable can be written as a linear combination of the n dynamic *modes* corresponding to the n eigenvalues of the state matrix.

The interesting modes for this study are the electromechanical modes. These modes are complex modes (with a complex eigenvalue) whose system of greatest participation is the rotor. The corresponding eigenvalues have this shape:

$$\lambda = \sigma \pm j\omega \qquad (8)$$

with the frequency

$$f = \frac{\omega}{2\pi} \qquad (9)$$

and the damping ratio associated to the mode

$$\zeta = \frac{-\sigma}{\sqrt{\sigma^2+\omega^2}} \qquad (10)$$

2.1.3. Mode Shape and Participation Factor

The right eigenvector gives the mode shape and the left eigenvector gives the amplitude of the mode[4]. Rather than using these two components separately, the participation factor can be used. It is defined for mode i as:

$$p_i = \begin{bmatrix} p_{1,i} \\ p_{2,i} \\ \dots \\ p_{n,i} \end{bmatrix} = \begin{bmatrix} \varphi_{1,i} * \Psi_{i,1} \\ \varphi_{2,i} * \Psi_{i,2} \\ \dots \\ \varphi_{n,i} * \Psi_{i,n} \end{bmatrix} \qquad (11)$$

where

$$\varphi_{k,i} = k\text{th element of the right eigenvector } \varphi_i$$
$$\Psi_{i,k} = k\text{th element of the left eigenvector } \Psi_i$$

The participation factor $p_{k,i}$ is "a measure of the relative participation of the kth state variable in the ith mode"[4].

2.2. Power System Stabilizer

Power System Stabilizer (PSS) is a key element for damping inter-area oscillations in a power system. When its parameters are correctly tuned, it avoids inter-area oscillations.

Usually a PSS aims at adding some damping torque component to generator rotors. Its input is generally the rotor speed and its output a voltage. It is mainly composed of a gain which determines the amount of damping introduced by the PSS, a phase compensation block in order to "compensate for the phase lag between the exciter input and the generator electrical (air-gap) torque"[4] and a washout block which is a high-pass filter which blocks the very low frequency so that steady changes in speed don't affect the reference voltage. One PSS (among others, this one is the simplest) is illustrated on figure 4. Once the phase is compensated, the damping torque can be modified by changing the PSS gain. For more details about PSS, please refer to [4].

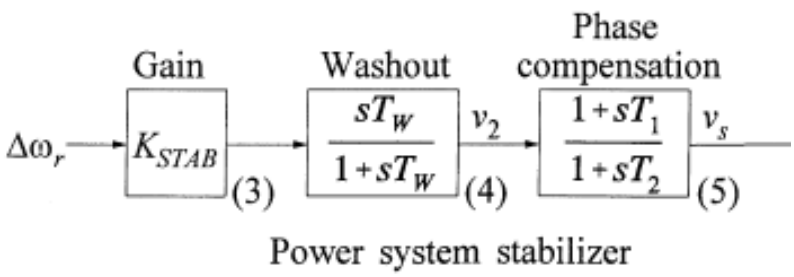

Figure 4: Power system stabilizer [4]

3. Measurement-based estimation of inter-area oscillations

Although model-based analysis may be very interesting to estimate inter-area oscillations, the power systems are too complex to be modeled correctly. On the contrary measurement-based analysis provide the advantages of analyzing directly system outputs such as power through the lines or generator speed and of not being limited by the size of the system [13]. Analyzing time domain simulation curves enables one to avoid loosing information by the use of order reduction techniques

for model-based analysis. Two methods for measurement-based estimation of oscillations are quickly introduced in this section: prony's method and ERA (Eigensystem Realization Algorythm).

3.1. Prony's method

The principle of the Prony analysis is well explained in [13] and can be summarized as[8]:

> "Prony was designed to estimate the exponential parameters of [the equation below] by fitting a function to an observed measurement. Prony's method is a "polynomial" method and includes the process of finding the roots of a characteristic polynomial.

$$y(t) = \sum_{i=1}^{n} A_i e^{\sigma_i * t} cos(\omega_i t + \theta_i) \text{ "} \qquad (1)$$

with n being the number of modes to be determined. If the system is discretized with $t = k * \Delta t$:

$$y[k] = \sum_{i=1}^{n} B_i z_i^k \quad (2)$$

$$z_i = \exp(\lambda_i \Delta t) \quad (3)$$

It is possible to find a polynomial of degree n so that the z_i are its roots. The z_i would verify:

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

where the a_i have to be found.

First this equation is transformed into a Toeplitz matrix (for the covariance problem)(N being the length of the sampled signal):

$$\begin{bmatrix} y_n & y_{n-1} & \cdots & y_0 \\ y_{n+1} & y_n & \cdots & y_1 \\ \vdots & \vdots & \ddots & \vdots \\ y_N & y_{N+1} & \cdots & y_{N-n-1} \end{bmatrix} \begin{bmatrix} -1 \\ a_1 \\ \vdots \\ a_n \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ \vdots \\ 0 \end{bmatrix} \quad (5)$$

Then this equation is solved with a discrete linear prediction model, for example the least squares method.

The z_i are computed thanks to the a_i and the modes can be obtained. To reconstruct the signal, the B_i are computed thanks to the set of N equations from equation (2).

3.2. Eigensystem Realization Algorithm

The ERA method is based on a Hankel matrix and singular value decomposition. It allows modal identification and model reduction of linear systems [13]. One of its advantages compared to the prony method is to provide an approximation of the order of the system. For more details about the algorithm, please refer to [13].

4. Dynamic Security Assessment

The tendency to increasingly interconnect strong network between weak links makes necessary to take into account dynamic stability and therefore small signal stability.

Inter-area oscillations often led to system separations in the past years, among these incidents[6]:

- Detroit Edison – Hydro Québec (1960s, 1985)
- Finland-Sweden-Norway-Denmark (1960s)
- Saskatchewan-Manitoba Hydro-Western Ontario (1966)
- Italy-Yugoslavia-Austria (1971-1974)
- Western Electric Coordinating Council (WECC) (1964, 1996)
- Mid-continent area power pool (MAPP (1971, 1972)
- South East Australia (1975)
- Scotland-England (1978)
- Western Australia (1982, 1983)
- Taiwan (1985)
- Ghana-Ivory Coast (1985)
- Southern Brazil (1975-1980, 1984)

The assessment of dynamic security is mainly done with the value of the damping ratio. It has to be of course positive to avoid divergent oscillations, but it also should be superior to a specified value. This value depends on the TSOs but this typical value should be around 3% to 5%[12]. In this study, this value will be taken at 5% as it would imply the safest situation.

This evaluation of the damping ratio is already done in some softwares[13], but as a result and not a pre-contingency assessment as it is done in iTesla.

5. Computation of stability indicators using iTesla

This section introduces the index made by KTH [R. Segundo, L. Vanfretti][1] computed from time domain simulations that assesses the stability of the power system in the case of small signal stability. There exists other indexes in the iTesla project about overload, under/over voltage, transient stability and voltage stability but they will not be presented as they are not used in this master thesis.

The aim of the index is to provide a numerical value capable of synthesizing the small signal stability characteristics of a given time domain simulation.

The interpretation of the small-signal stability index is given in [11] and summarized below. The index is composed of 3 layers (SMI: Single Mode Index, AMI: All Mode Index, GMI: Global Modes

[1] Paper presented in the IEEE ISGT Europe 2014 Conference and available at http://www.itesla-project.eu/papers

Index), the SMI being the most detailed layer it will be introduced first below. First, modes are estimated along with their damping ratios by prony's method thanks to the module inside the iTesla project. Then the damping ratio of each mode is compared with a set of three pre-defined damping ratios chosen by the TSO. The resulting SMI is a matrix in which each row corresponds for one estimated mode, and each column of this row represents the distance between the computed damping ratio of the estimated mode and one pre-defined damping ratio from the set. This is illustrated on figure 5 with [0% 5% 10%] as the set of predefined damping ratio. This figure represents the mode corresponding to the complex value $\lambda_i = -\sigma_i + j\omega_i$ in a complex plan, and its distance compared to modes whose damping ratio is 10% ($\tilde{\theta}_{i,\zeta_{10}} = \theta_i - \theta_{\zeta_{10}}$), 5% ($\tilde{\theta}_{i,\zeta_5} = \theta_i - \theta_{\zeta_5}$) and 0% ($\tilde{\theta}_{i,\zeta_0} = \theta_i - \theta_{\zeta_0}$). The SMI value is then:

$$SMI = \begin{bmatrix} \tilde{\theta}_{1,\zeta_0} & \tilde{\theta}_{1,\zeta_5} & \tilde{\theta}_{1,\zeta_{10}} \\ \vdots & \vdots & \vdots \\ \tilde{\theta}_{i,\zeta_0} & \tilde{\theta}_{i,\zeta_5} & \tilde{\theta}_{i,\zeta_{10}} \end{bmatrix}$$

$$\tilde{\theta}_{i,\zeta_j} = \theta_i - \theta_{\zeta_j}$$
$$\theta_i = cos^{-1}(\zeta_i)$$
$$\theta_{\zeta_j} = \pi - cos^{-1}(\zeta_j)$$

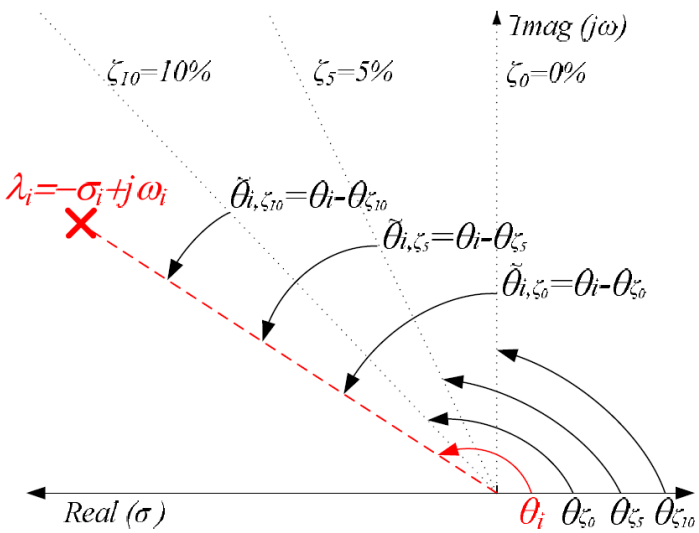

Figure 5: Distance $\tilde{\theta}$ (in radians) from the ith mode (λ_i) to different pre-defined damping ratios $\zeta_0 = 0\%$, $\zeta_5 = 5\%$ and $\zeta_{10} = 10\%$ respectively [11]

As a summary, "SMI provides the individual distance of each mode to a predefined damping ratio, e.g. $\zeta_0 = 0\%$, $\zeta_5 = 5\%$ and $\zeta_{10} = 10\%$. If any of the elements of SMI is negative, this indicates that the mode corresponding to the specific row, has a damping ratio less than the required for that column."[11]. The index enables the user to quickly know which mode is poorly damped and which value it violated, by observing whether the index is positive or negative.

The AMI is a vector corresponding to the row of the SMI corresponding to the most poorly damped mode. The AMI will basically show that if one of its values is negative then there is at least one mode that violated the corresponding damping ratio. The GMI is the last layer and corresponds

to the lowest value in the SMI. If the GMI is negative then one of the modes has violated one damping ratio reference.

This index will help to categorize whether a simulation in the offline analysis of the project will lead to an unsafe situation or not from the small signal stability point of view. For example, if the GMI is negative then the situation can be considered as unsafe and if it is positive the situation is safe.

It is this index that needs to be tested on an unacceptable situation, artificially created in this master thesis.

Chapter 3 – Measurement-based Prony methods

This section aims at using different existing modules based on Prony's method on different test signals. The idea is to compare the results given by these different modules. It is important to notice that these modules are compared with a SISO (Single input Single Output) point of view, which means only one signal is analyzed. On the contrary, some MIMO (Multiple Input Multiple Output) methods exist (e.g. the one used in the iTesla project) but are not the object of this section.

One can see below the different tools used for modal analysis using Prony's method for one signal in order to observe their efficiency:

a) A simple Laplace transform of the system, followed with a pole identification
b) The Matlab function prony.m
c) The "Prony toolbox (PTbox)" implemented in Matlab (University of Wyoming)
d) The "DSI toolbox" implemented in Matlab (Pacific Northwest National Laboratory)
e) A prototype in C implementing ideas based on ERA and Prony's method presented in the master thesis "Development of a portable software tool for time response modal analysis" (Ecole de Technologie Supérieure, Québec). It will be called in the following "C tool".
f) The "pronyItesla function" implemented in Matlab (KTH, Sweden) used in the iTesla project

These tools are compared with three situations: one synthetic signal, one simple signal generated with Eurostag and signals more complex made with Eurostag. The signals made with Eurostag are taken from one of the simulations of chapter 4.

1. Numerical-made signal

In this part, the signal to be analyzed is the following:

$$s(t) = \sum_{k=1}^{3} e^{\sigma_k t} * \sin(2\pi f_k t)$$

$$\begin{Bmatrix} f_1 = 0.8\ Hz \\ \sigma_1 = -0.1 \end{Bmatrix} \begin{Bmatrix} f_2 = 1\ Hz \\ \sigma_2 = -0.05 \end{Bmatrix} \begin{Bmatrix} f_3 = 0.4\ Hz \\ \sigma_3 = -0.01 \end{Bmatrix}$$

The frequencies are in the frequency range of interest of low speed oscillations. The signal is sampled every 0.01s and the time window is 10s.

The main parameter to be chosen in these methods is the order model. For this analysis, a model order of 10 (order of numerator equal to 9 and order of denominator equal to 10 for method a) has been chosen for methods a, b, c, f whereas the order is automatically chosen for methods d and e.

As a result of this experimentation, the three expected modes are found very accurately with every method. Even the simplest method (Laplace transform) yields satisfactory results. As the six curves are identical the graph is not shown.

2. Signals with one mode poorly damped coming from a Eurostag simulation

These six methods will be compared in this part using a signal extracted from a EUROSTAG simulation presenting a slow oscillation (figure 6).

The time window for the analyzed signal is the same for every method. The order of the system in method e is set to 10 in order to compare the results with method f. The mean is subtracted to every signal and only modes whose frequencies are lower than 2.5Hz are presented. The results are listed in Table 1.

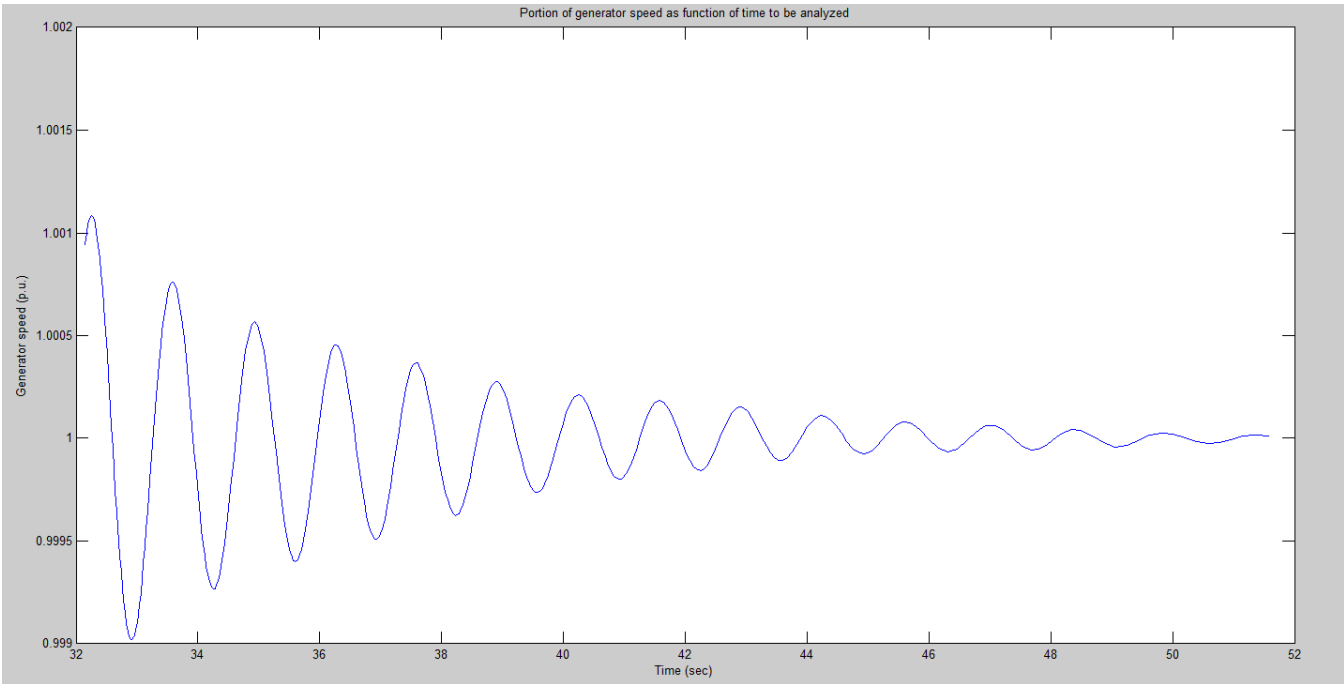

Figure 6: Portion of the analyzed signal

Table 1: Computation of the modes according to different tools

Laplace trans.		prony.m		Prony tool		pronyiTesla		DSI tool		C tool	
F(Hz)	D(%)	F(Hz)	D(%)	F(Hz)	D(%)	F(Hz)	D(%)	F(Hz)	D(%)	F(Hz)	D(%)
0,062	34,730	0,748	4,365	0,750	4,452	0,751	4,446	0,749	3,825	0,743	4,141
0,721	4,515							1,037	21,166	0,977	37,705
0,753	5,415							2,044	19,431		
0,921	59,534										

As a result, every method has found a mode around 0.75 Hz and a damping ratio around 4% which is the main mode of the signal (in terms of damping). The Laplace transformation yields however two modes around 0.75 and their characteristics are slightly different from the other

methods: either lower frequency or higher damping ratio. It could be expected that every methods would give good results as the signal presents only one mode with low damping ratio and all the others are rather fast. Consequently these methods will now be tested on a more complex signal.

As a remark, some slight differences in the mode computations may also be due to the interpolation of the signal: here all the methods use a linear interpolation with 0.01s step except the PronyiTesla function which uses a cubic spline interpolation (spline Matlab function) with 0.1s step. This remark is still true for the next paragraphs.

3. Signals with two modes poorly damped coming from a Eurostag simulation

The same methods are tested with an event showing two poorly damped modes with the same parameters than previously. The test curve is presented on figure 7 and the computed modes in table 2.

One can see in the table that the Laplace transformation, the prony.m function and Prony tool module find different results than the pronyiTesla function, the DSI tool and the C tool. Prony.m and Prony tool end up with similar results (Prony tool uses the prony.m function as well). However this mode at 1Hz – 6.2% doesn't seem to be the same than the 1.1Hz 9% computed by the other methods, as a consequence these two methods are discarded. Moreover the Laplace transform yields four modes below 2.5Hz, two of them seem accurate enough (0.799Hz -9.4% / 1.089 – 9.07%) however two other modes seem inappropriate with damping ratio rather low that is why this method will be discarded as well. Finally the three last methods yield the same results except for the mode 2.239Hz 18%. If this mode exists, it doesn't present any problem if it is not detected.

Finally, methods "PronyiTesla", "DSI tools" and "C Tool" seem more adequate for industrial purposes.

Table 2: Computation of the modes according to different tools

Laplace trans.		prony.m		Prony tool		pronyiTesla		DSI tool		C tool	
F(Hz)	D(%)	F(Hz)	D(%)	F(Hz)	D(%)	F(Hz)	D(%)	F(Hz)	D(%)	F(Hz)	D(%)
0,2816	4,1379	1,0143	6,0529	1	6,2	0,784	8,255	0,79172	7,8974	0.808271	8,5739
0,799	9,4359					1,089	9,513	1,09229	9,248	1.106691	8,7395
0,94	4,6396					2,239	18,651	2,15934	17,9139		
1,0885	9,0718										

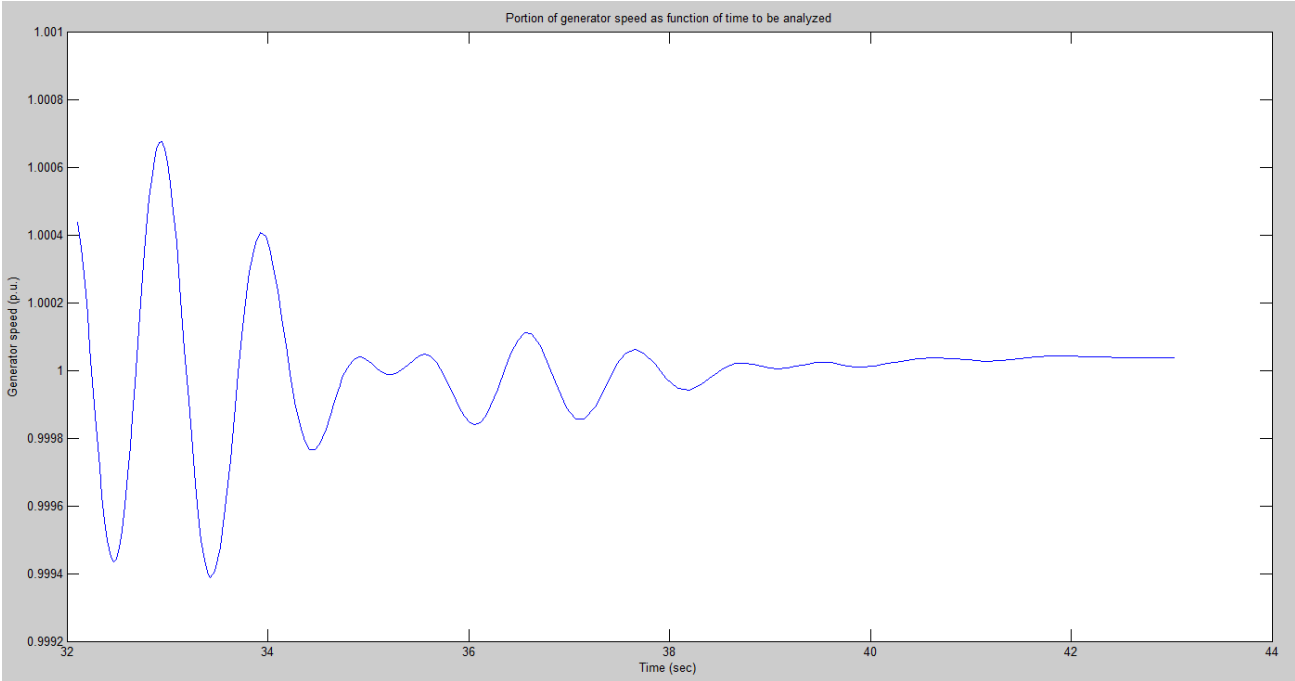

Figure 7: Portion of the analyzed signal

4. More comparisons

In this part two more comparisons are done between pronyiTesla, DSI tool and C tool and the results are listed in tables 3 and 4 below and on figures 24 to 27 in appendix D. The results of this comparison can not be taken as a global truth as the efficiency of the method used may depend on the signal on which the study is made.

On this two comparisons, it can be seen that the frequencies of the mode are globally the same with every methods, but the damping ratio may differ and it results in a magnitude a bit higher than expected in the second part of the reconstructed signal with pronyiTesla and DSI tool (figures 24 and 26) compared to the C tool (figures 25 and 27).

Table 3: Computation of the modes according to different tools for comparison 1

pronyiTesla		DSI tool		C tool	
F(Hz)	D(%)	F(Hz)	D(%)	F(Hz)	D(%)
0,754	1,276	0,75521	2,0699	0.751005	3,962
1,097	7,494	1,10094	6,004	0.906822	11,7
				1.078582	7,6315

Table 4: Computation of the modes according to different tools for comparison 2

pronyiTesla		DSI tool		C tool	
F(Hz)	D(%)	F(Hz)	D(%)	F(Hz)	D(%)
0,744	3,361	0,752148	4,7382	0,746307	7,0529
1,087	7,12	1,092545	5,6176	0,899466	9,2829
				1,074607	6,997

5. Conclusion

As a conclusion, C tool may be the best adapted for the kind of signals used in this study with a single input signal. C tool, pronyiTesla function and DSI tool are more viable to compute modes than the prony.m function and the Prony toolbox. Furthermore the C tool and DSI tool can be set in auto-set mode so that the order of the system is chosen automatically.

However it has been noticed that the C tool has some input parameters (frequency range of interest, system order) to set that can modify a lot the resulting modes. The parameters have to be set carefully in order to get correct results. Moreover, it can only analyze one signal by one signal while pronyiTesla and DSI tool can analyze multiple signals simultaneously. On one hand analyzing simultaneously multiple signals can enhance the observation of inter-area modes but on the other hand some local oscillations may be lost in the middle of other oscillations. Therefore the choice of the method also depends on the goal of the study.

Chapter 4 – Development of test scenarios and method for revealing inter-area oscillations – Assessment of small signal stability indicators in iTesla

In this section it will be explained how it has been achieved to create some poorly damped slow oscillations in a given network topology, in order to validate the offline module of iTesla project in the case of inter area oscillations.

1. Choice of the mode to excite

The final goal of this study was to simulate some inter-area oscillations in Europe. However at this stage of the iTesla project, static and dynamic data are only available on the French network. The reduced scale of the network makes it impossible to observe slow inter-area oscillation around 0.3Hz or less. That is why the aim is to simulate oscillations as slow as possible. A more detailed documentation about this part is available in Appendix A.

The base case situation used to start this study is the French EHV network (400kV and 225kV only) of the 15th January 2013 at 18:45. The idea is to scan the modes inherent to the power system for this given time stamp. To do so the software SMAS3[2] has been used. A first approximation of the result is given in table 8 in appendix A. A posteriori result is that mode N°1 and mode N°2 have been inconclusive in this research. This may be explained by the specificities of the set of participant generators, by the fact that the method is not efficient for 'exciting' these modes, or because some non-linear blocks in the network model may interfere with the accuracy of the modes found by the software. That's why the procedure will be presented on electromechanical mode N°3 around 0.8Hz.

2. Method for revealing inter-area oscillations

2.1. Presentation

The idea is to analyze which generators are the most significant in the mode, to upset these generators and excite the mode by creating a short circuit nearby. A more detailed documentation is available in Appendix B.

In order to get the most significant generators, the participation factors of mode 3 are computed and presented on table 5.

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2 Software made by L. Rouco in the university Institute for Research in Technology — Instituto de Investigación Tecnológica (IIT), Madrid.

As indicated on table 5, three main groups of generators have been selected to be modified. N0000263, N0000266 and N0000268 correspond to generators situated in Cattenom in the North East of France. N0000612 and N0000613 correspond to generators situated in Golfech. Finally, N0000125, N0000126, N0000127 and N0000128 are generators located in Blayais. Golfech and Blayais are cities in the South West of France.

As the network is strong and generators' regulators are well adjusted, no slow oscillations are likely to be detected. Consequently the idea is to modify generators' regulators so that some inter-area oscillations may appear. As seen in 1.2, the PSS is responsible for the regulation of the damping torque. Therefore the PSS gains of the above selected machines are decreased in order to decrease the damping torque. 15 has been chosen as the division factor by experience.

Then it has been chosen to excite this mode by creating a short-circuit very near to the generators in Golfech (N0000612, G0000107).

Table 5: Participation factors over 10% of mode N°3

NAME	Participation factors
N0000266	100.00000
N0000268	99.63573
N0000263	89.06192
N0000612	56.82607
N0000613	56.44656
N0000127	43.72573
N0000982	43.52565
N0000125	43.50089
N0000126	43.48323
N0000124	43.34651
N0000984	42.32415
N0000983	42.29655
N0000985	41.86634
N0000921	38.54920
N0000541	37.40994
N0000920	37.07570

NAME	Participation factors
N0000542	36.91248
N0001003	33.02792
N0001004	32.88272
N0001274	26.98627
N0000446	25.61121
N0000331	16.60184
N0000329	15.91811
N0000337	15.27542
N0000338	15.25357
N0000633	14.72046
N0000630	14.71553
N0000632	14.70581
N0000631	14.68406
N0000629	14.62153
N0000634	14.51687
N0001273	13.91500

In order to check the relevance of the modifications made, a new SMAS3 study is made after the modification of the regulators. It can be seen on table 9 in appendix B that there are two modes at 0.69 and 0.78 Hz whose generators of highest participations are the ones modified. It is noticed that most of the generators which were significant (between 10 and 40%) in this mode before the modifications are now less significant. In other words, the modified generators are now more significant over that mode.

2.2. Results

In this part are presented the resulting curves of the simulation before and after the modifications.

First, these results are obtained by simulating the event in EUROSTAG and then analyzing the curves in MATLAB. The computations of the modes are done with the PRONY method thanks to iTesla small signal stability module (more details in appendix C). The module parameters chosen are the following:

- Step_min=0.05
- Var_min=0.1
- f=[0.1; 2.5]

The value of step_min has been chosen so that the time window used for the Prony analysis would start when the transitory period is finished, so when the oscillations are established. Therefore the computed modes will be more accurate. In the case of well damped oscillations, then the time window may be a bit late (starting after the main oscillations) and the results less accurate but that does not matter as this case is not critical for the system. On figure 9, the Prony analysis starts around 34s so that it avoids the non linearities of the post-fault situation. It starts around 32.5s on figure 8.

The event is a 3-phase short-circuit happening at 30s during 50ms with a reactance equal to 0.001p.u. at the middle of the line. This kind of short-circuit is quite common. On figure 8 is presented the generators speed without the modifications and on figure 9 with them. On these figures are only drawn the speed of generators with highest oscillations. The Matlab results are presented on table 6.

As a result it can be seen on figure 8 that no low frequency oscillations are produced whereas on figure 9 one can notice that two groups of generators are oscillating against each other at a frequency of 0.75 Hz which is quite close to the mode aimed (N°3 in table 8).

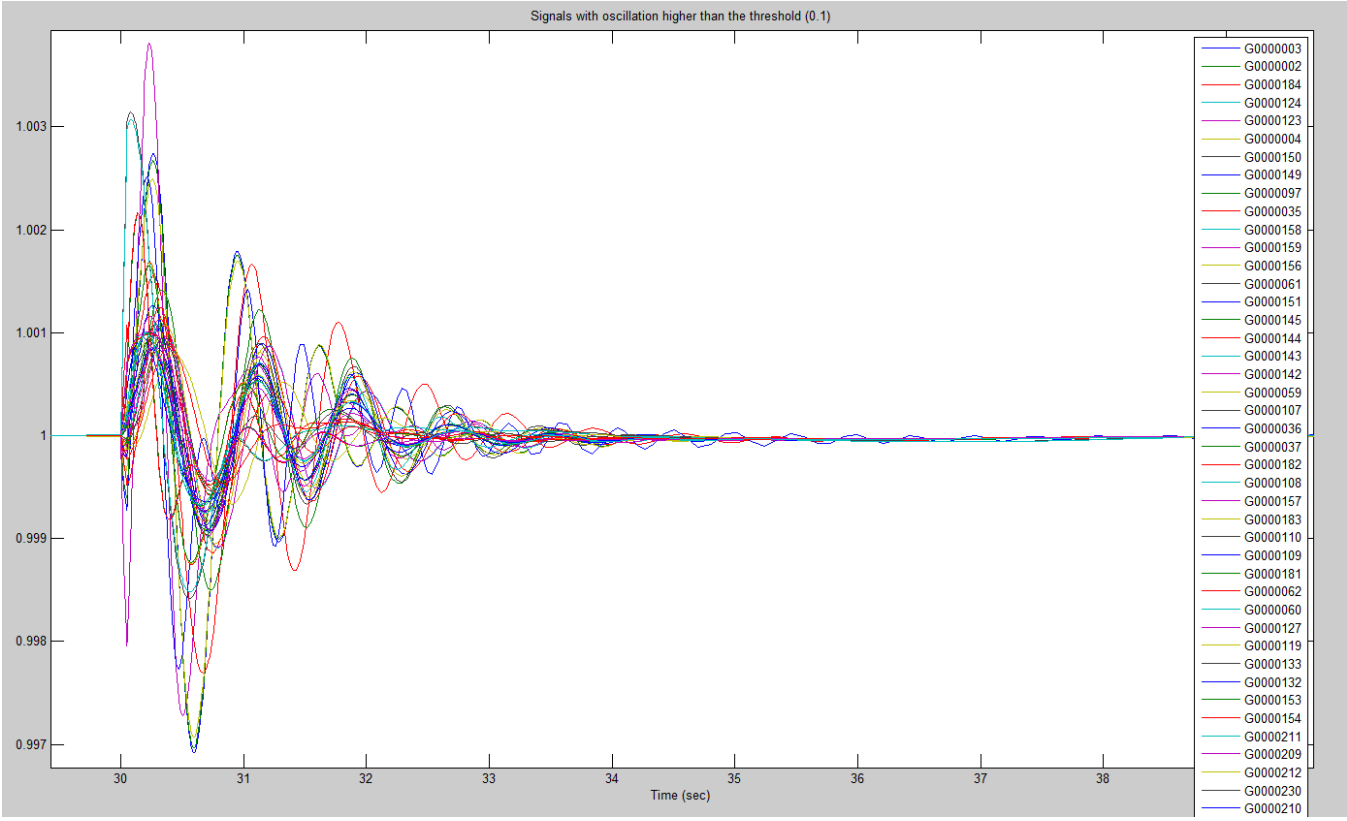

Figure 8: Generators speed after a short-circuit without the regulators modification

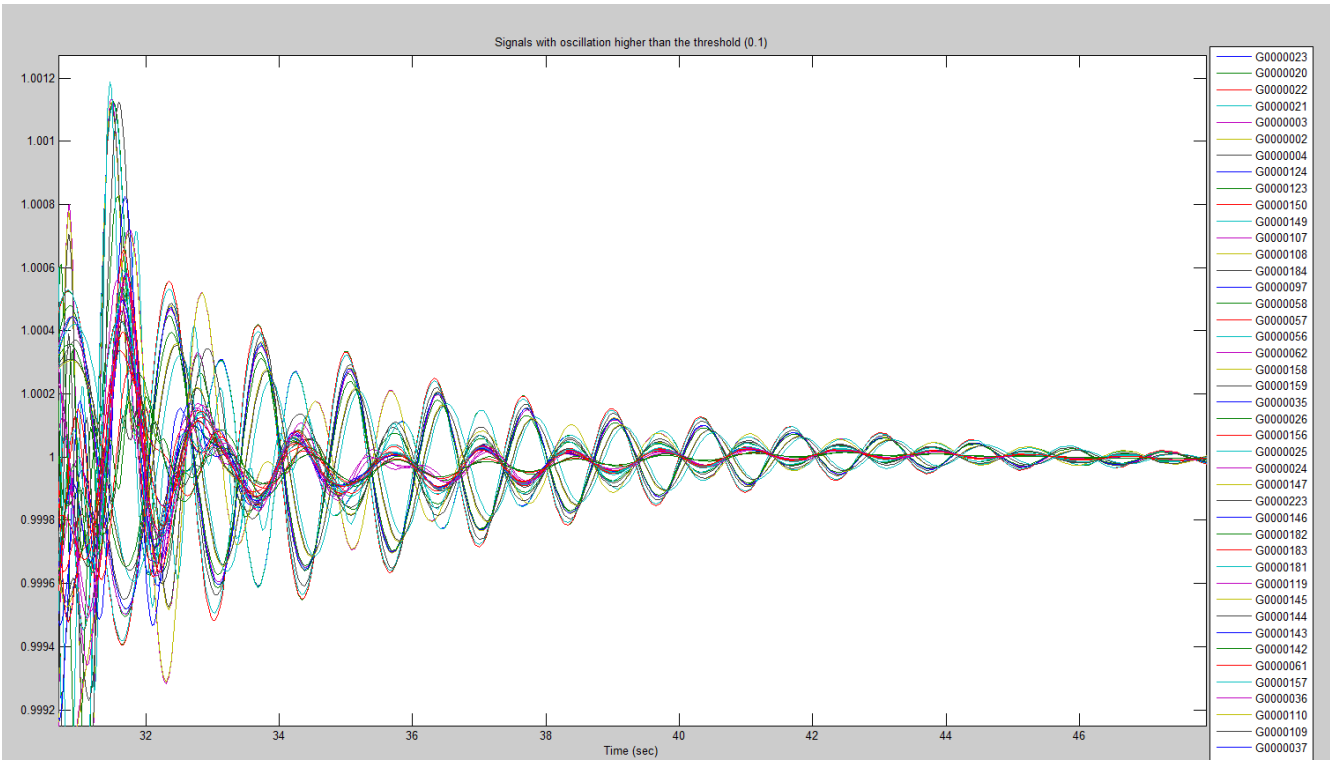

Figure 9: speed after a short-circuit with the regulators modification

Table 6: SSS module results before and after the modifications of the regulators

Without modifications		With modifications	
freq (Hz)	damp (%)	freq (Hz)	damp (%)
1.302	16.118	0.748	4.379
1.879	13.624	1.078	10.790
2.249	7.361	2.312	4.653

Figure 10: Localization of the two groups of generators

The two groups of generators are in two different areas as it can be seen on figure 10. One group is shown with the red dots and the other one with the black triangle.

A double check has been made by computing the modes on active power flow through the lines and the same result has been observed (figure 11 and table 7) with 0.75 Hz oscillations on the lines between Golfech/Blayais and Cattenom.

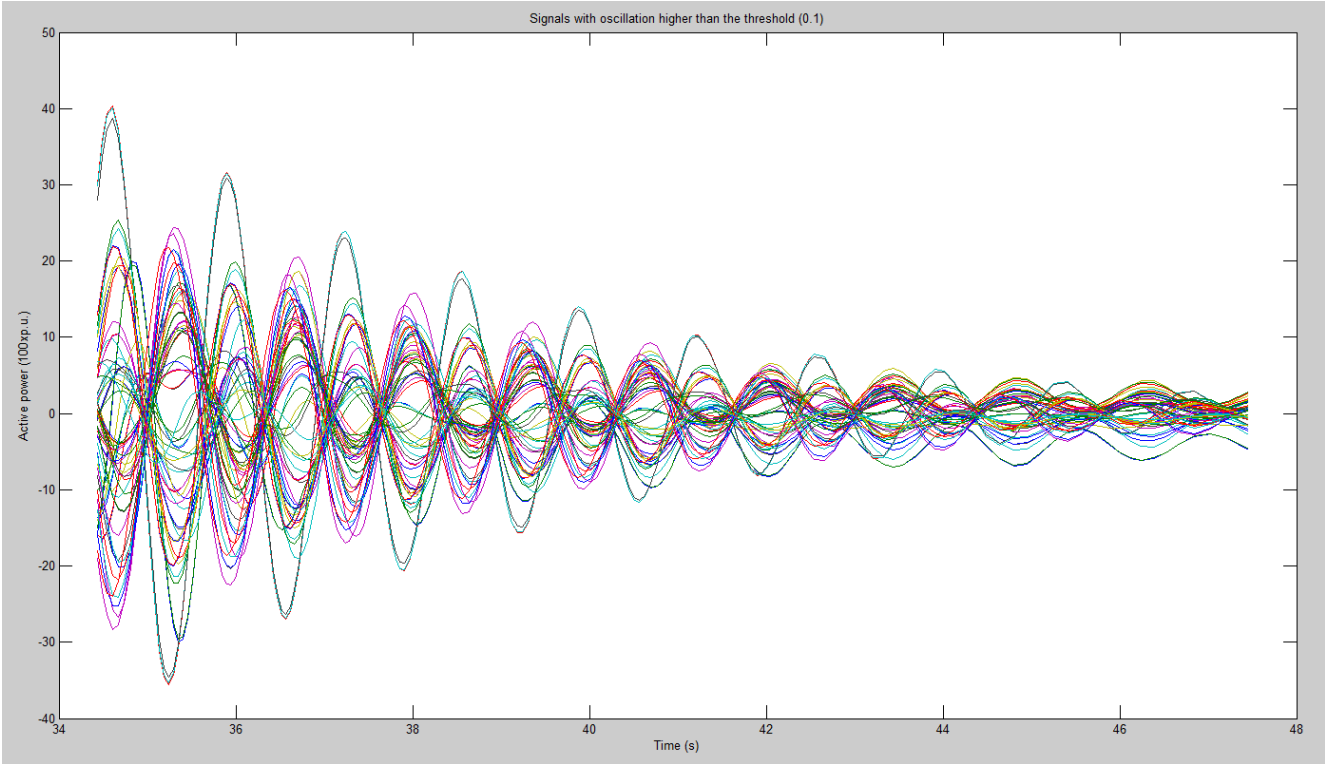

Figure 11: Active power flow with modified generators after the short circuit

Table 7: Mode values computed with the active power flow measures

freq (Hz)	damp (%)
0.749	4.276
1.076	8.665
2.235	6.661

2.3. Conclusion

As a conclusion, by deregulating the PSS of some well chosen generators and exciting the mode with a short-circuit, it has been possible to reveal inter area oscillations.[3]

3. Simulation over a larger time window

Once this unsafe solution has been found, the idea is to simulate the same kind of events with the same generators modifications over a selected period of time around the previous situation (January, 15th 2013) in order to see how the chosen mode evolves. The analyzed period is from

[3] The large inter area oscillations are usually between 0.1 and 0.7Hz[4] but as the study is uniquely in France and sometimes oscillation lower than 1Hz are also called inter area oscillation[6], one may speak of inter area oscillations in this case.

January, 7th 00:30 to January 16th 23:30. During this period of time the network data (topology, loads, generations, flux…) have been recorded. On these records, the same event and the same modifications than in section 2 are implemented.

A module has been implemented in Python which enables the user to transform directly the 'normal' original situations in Eurostag into resulting curves from the modified network that can be used by Matlab for the prony analysis.

First the simulations are done with a short-circuit located in the same place lasting 200ms with a 0.01p.u. reactance and the same modifications and analyzed with the same Matlab parameters except var_min=0.3 in order to reduce the selected signals for the prony analysis. The results are displayed on figures 12 and 13.

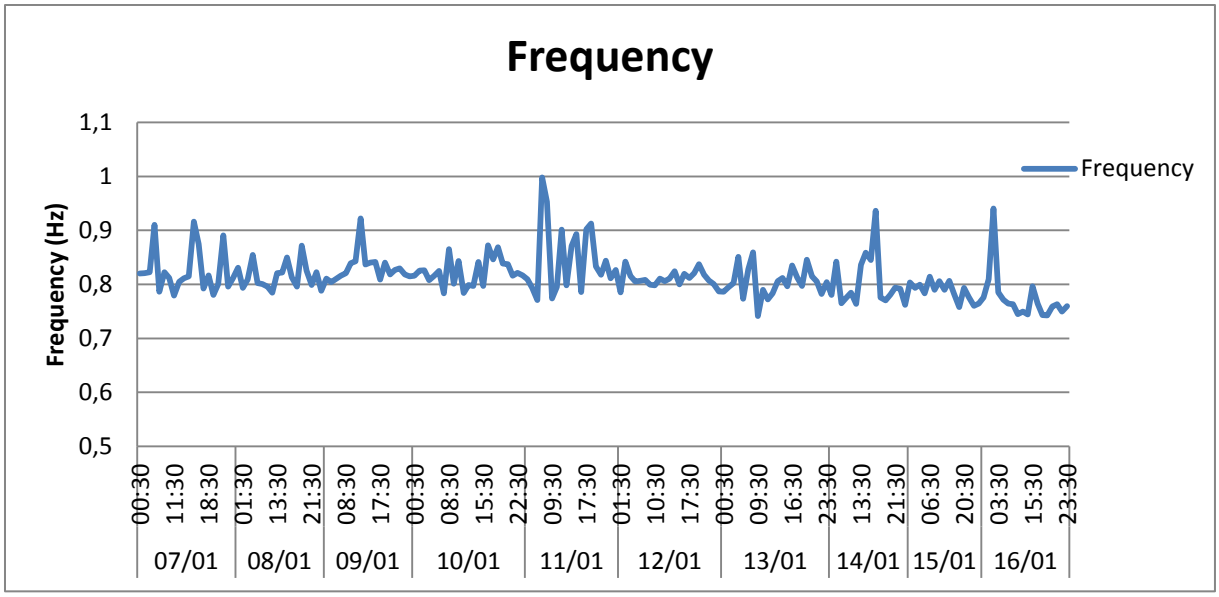

Figure 12: Frequency of the slowest mode over the time with the short-circuit event

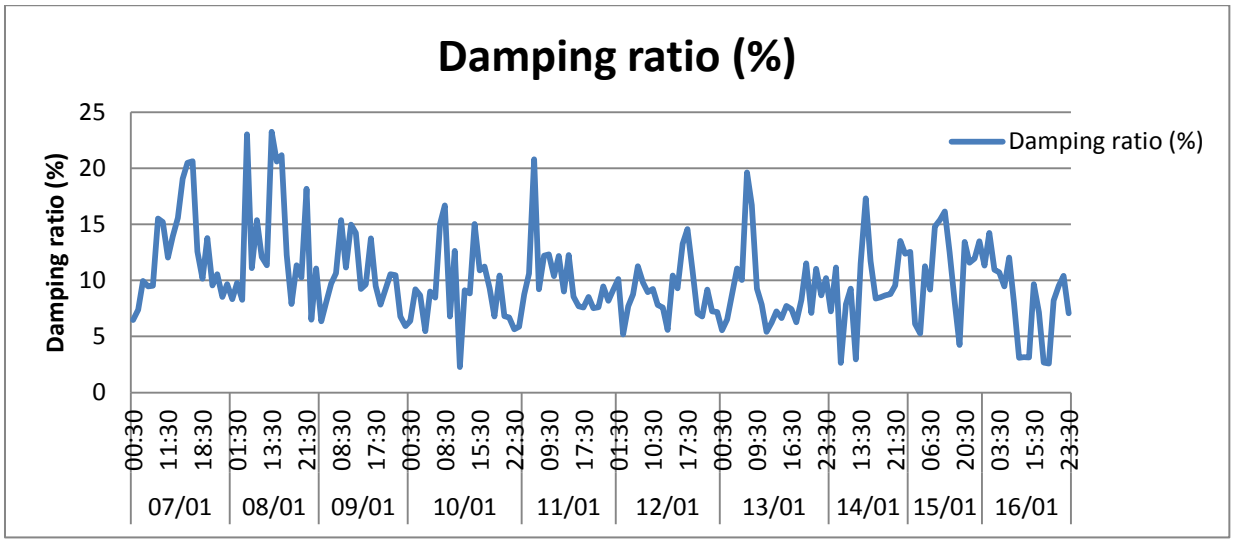

Figure 13: Damping ratio corresponding to the slowest mode over the time with the short circuit-event

One can notice that the first result is that the mode stays around 0.8 Hz. Some variations as the frequency going up until 0.9Hz can be observed but most of the time it is the result of a well damped

signal and therefore it makes it harder for the prony analysis to get an accurate result. That is why a peak of damping ratio corresponds usually to a peak of frequency. It can be seen that on the contrary the damping ratio is varying on a large interval of values [2%; 23%] and there isn't any real trend to observe, except for the 4/5 first days where it can be observed that the damping ratio is decreasing over the evening and quite high the rest of the time.

Then a second event has been simulated in order to get higher oscillations in the power system. The event is a short circuit of 150ms, 0.001p.u. as a reactance, cleared and followed by the opening of the associating branch ("GODINL61VERLH") situated between Golfech and Cattenom. This event is supposed to be more severe than the previous one and therefore more instability is expected. The results are displayed on figures 14 and 15.

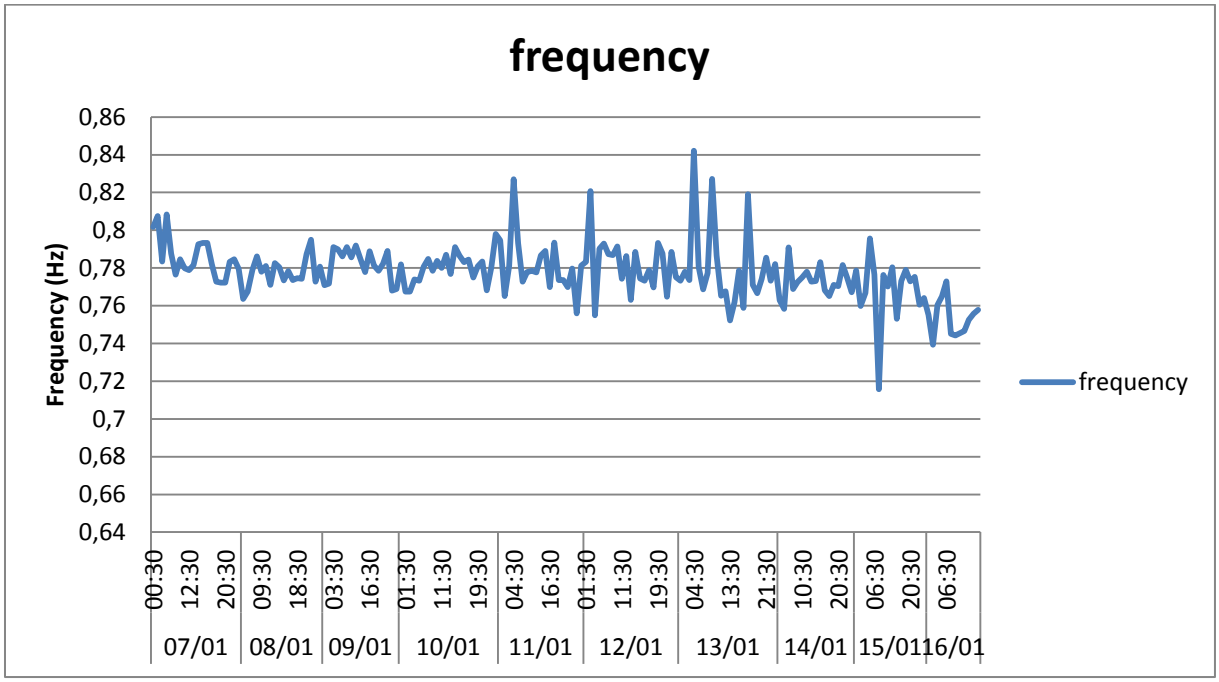

Figure 14: Frequency of the slowest mode over the time with the open branch event

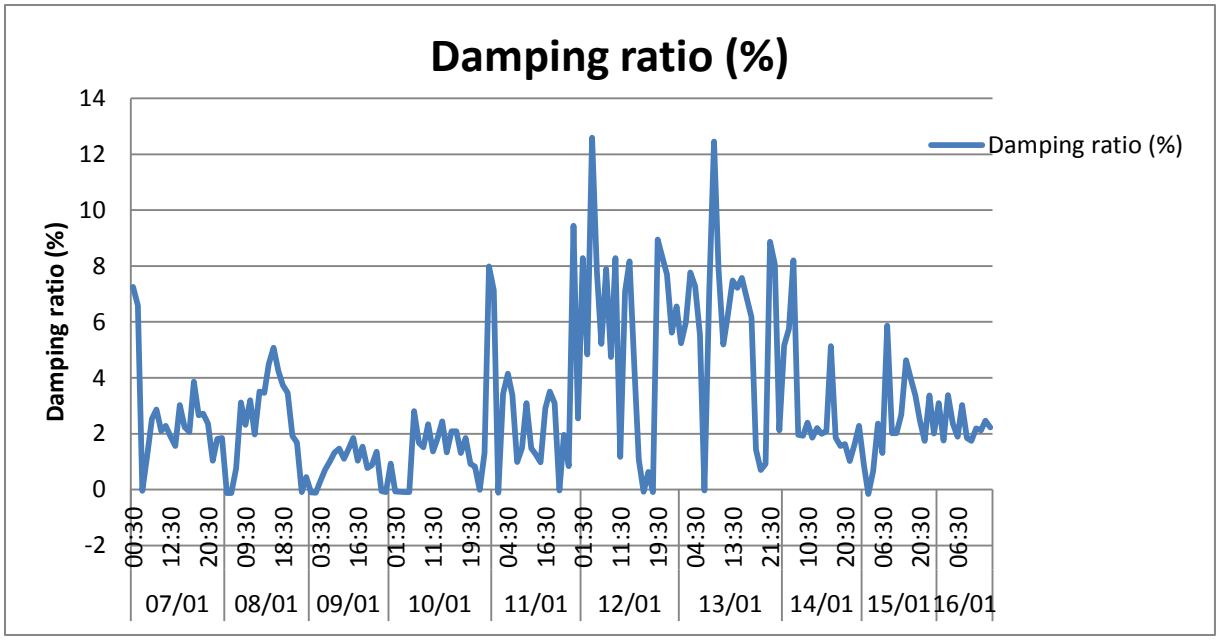

Figure 15: Damping ratio corresponding to the slowest mode over the time with the open branch event

As a result the frequency of the modes is rather constant around 0.78 Hz, and the damping ratio is still varying a lot but has an average lower value, even some are slightly negative. The same trend can be observed for the damping ratios of the first days. It is important to notice that the computed damping ratios with the Matlab module whose values are around 0 can be either slightly positive or slightly negative depending on how the selected window of time has been chosen for the analysis (more details in appendix C).

4. Example of small signal stability indicator assessment in the case of slow oscillations

The small signal stability index is applied to the two previous simulations as an illustration. First the frequency range is set from 0.1Hz to 2.5Hz and the reference damping ratios to [0%, 2%, 5%]. The GMI is then computed compared with the 5% value according to what has been discussed in Chapter 2 – 4. An unsafe situation is characterized by signals whose damping ratios are lower than 5%. The range of frequency allows observing inter-area and local oscillations simultaneously. It is observed on figures 16 and 17 that there are a lot more unsafe situations with the branch opening case than in the short-circuit case. The unsafe situations are easily revealed by a negative GMI. It is important to notice that the value of the GMI may not be based on the inter-area mode of paragraph 3, but it can result from another local mode for example. The GMI has been computed in the case of the short circuit with a frequency range of [0.1Hz – 1Hz] in order to take into account only the inter-area mode. The plot is presented on figure 18 and one sees that there are much more safe situations if the inter-area mode is taken alone.

As a conclusion, this is a basic illustration of the index but it shows its interest: to have a numerical value showing whether the situation is safe from the small signal stability point of view, which will serve to construct security rules in the iTesla project.

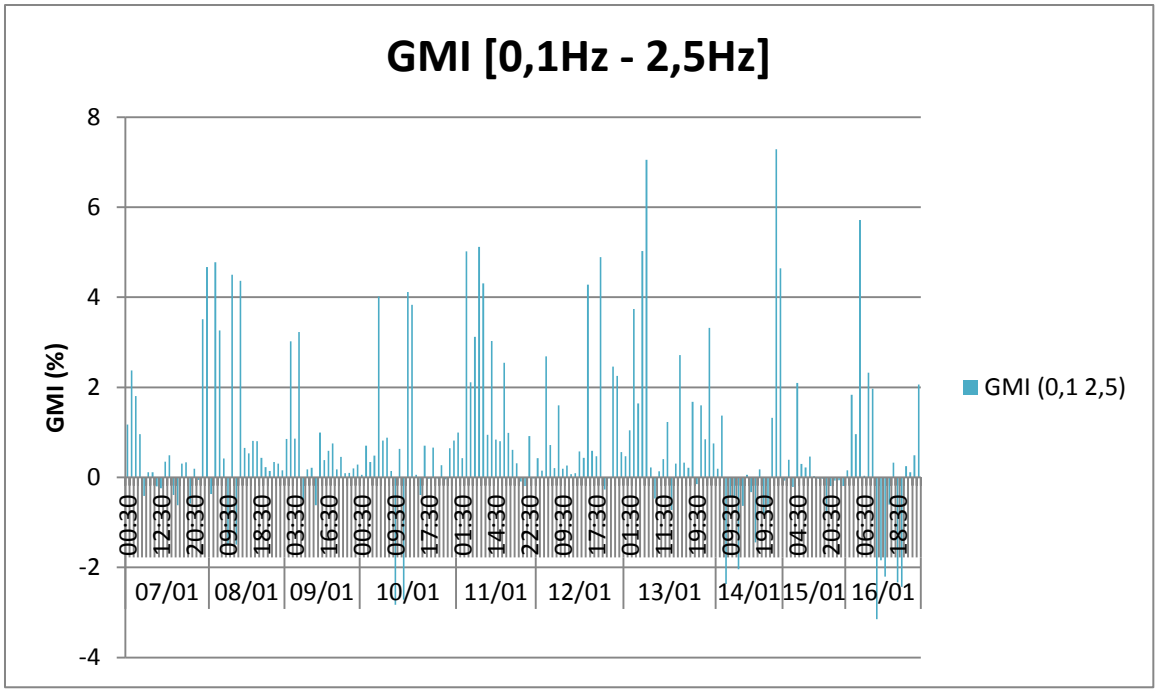

Figure 16: GMI as function of the time for the short-circuit case

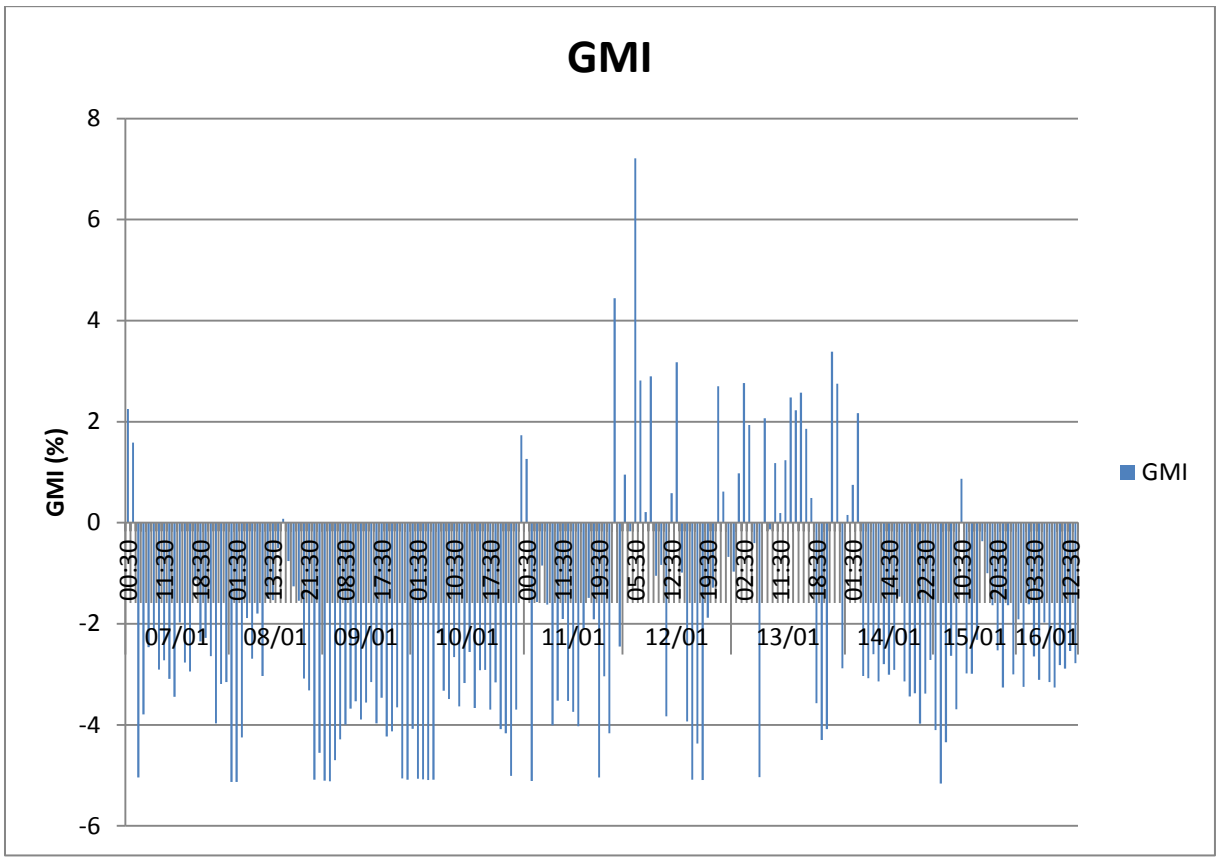

Figure 17: GMI as function of the time for the branch-opening case

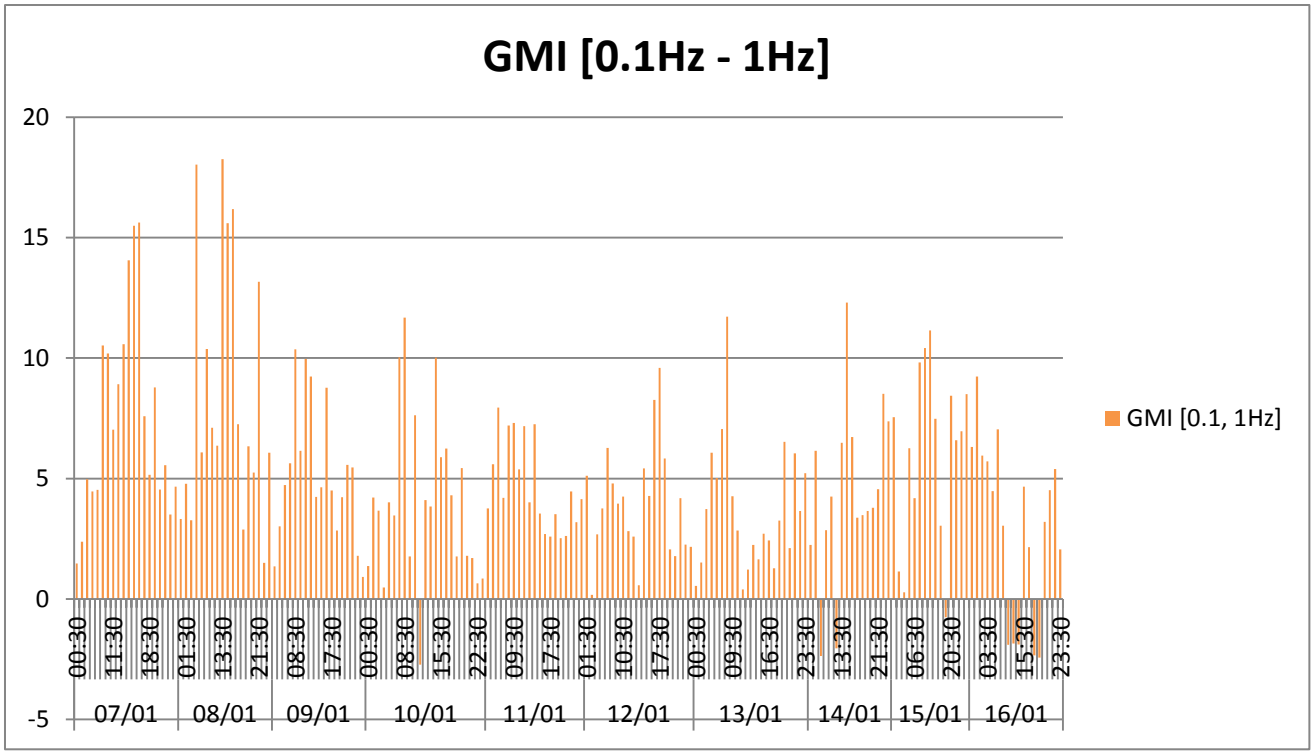

Figure 18: GMI for the frequency range [0.1Hz - 1Hz] as function of the time for the short-circuit case

Chapter 5 – Conclusion and further work

As a conclusion to this study, a generic method has been implemented to enhance some inter-area oscillations from a given 'normal' historical situation. It has been seen that the mode was present during more than some days and the corresponding damping ratio was dependant of the time and the configuration of the network. Among the different values of damping ratio, some can be defined as critical for the system and result as unsafe. This set of test signals will be used to validate the small signal stability index in a case with inter-area oscillations.

Moreover some measurement-based estimation modules have been tested. As a result the choice of the module depends on the type of study, the complexity of the method wished (in term of algorithm and input parameters) and the number of signals in input.

Concerning the method used to reveal inter area oscillations, it can be improved in some points. A research on the weakest connections in the network can be done in order to optimize the short-circuit location so that inter-area modes are better excited. Furthermore, some other methods can be investigated in order to excite modes as change in loads or generation losses.

Concerning the prony analysis, it has been seen that the computed modes may vary according to the method or the input parameters. It would be interesting to add a reliability index associated with the reconstructed signal like a SNR (Signal Noise Ratio) presented in [13] in order to check the veracity of the computed modes. Indeed it is primordial that a situation actually 'unsafe' is not classified as 'safe' due to an error of estimation.

APPENDIX

Appendix A

This appendix deals with how the choice of the mode to enhance has been made.

The topology of the network is to be studied with SMAS3. To do so, the network has to be a bus-branch network (there can't be a link without impedance between two buses).

Then a system linearization has to be done with EUROSTAG, after replacing the "delay blocks" by Padé approximation of order 1 (or after deleting the "WARNING: APPROXIMATE DELAY_1 LINEARIZATION" error message in the .linear file). This linearization creates files that serve as inputs to SMAS3.

A first approximation of the modes can be found using the "iden" method which looks for modes with imaginary eigenvalues whose results are in table 8. A try has been made with GSMA (Generalized Selective Modal Analysis) method but the result found has not been reliable with modes only around 0.4 Hz. GSMA "determines a few electromechanical eigenvalues using as starting guesses the eigenvalues and associated eigenvectors of the classical model of the power system without damping"[5].

After several tries for exciting the two first modes with the presented methods, no conclusive result has been found. That's why the study has been made on mode N°3.

Table 8: First approximation of the available modes

N0.	FREQ(HZ)	GENERATOR NODE WITH GREATEST PARTICIPATION
1	0.5905	N0001383
2	0.6847	N0000127
3	0.7994	N0000266
4	0.9044	N0000541
5	0.9594	N0000203
6	1.0162	N0000982
7	1.0728	N0000612
8	1.0907	N0000623
9	1.1023	N0000331
10	1.1417	N0000623

Appendix B

In this appendix there are some more details about the method used to create oscillations.

The participations factors presented in table 5 are computed by using the methods “iden” and “part”.

The regulators of the generators can be found in the EUROSTAG macroblock “RQB_ALST” as illustrated on figure 19. The PSS comprises branches regulating the speed, the active power and the mechanical power. The gains which are reduced are Ki2, Ki3 and Ki4 selected in red on figure 19. The three gains Ki2, Ki3 and Ki4 of every machine in Blayais, Golfech and Cattenom are divided by 15. The value of the division factor has a decisive role: the higher it is the more oscillations there will be in the network.

After modifying the regulators, the modes are computed again with the methods “redu” and “GSMA” in table 9. This time it seems this method yields more reliable results, there are two low frequency modes at 0.69 and 0.78 Hz with generators of highest participation the ones modified. The participation factors of mode at 0.69 and 0.78 Hz are respectively presented on tables 10 and 11.

Finally, the short circuit has been made on the line named “DONZAL71GOLF5”, situated at the output of generator “GOLF5P7”.

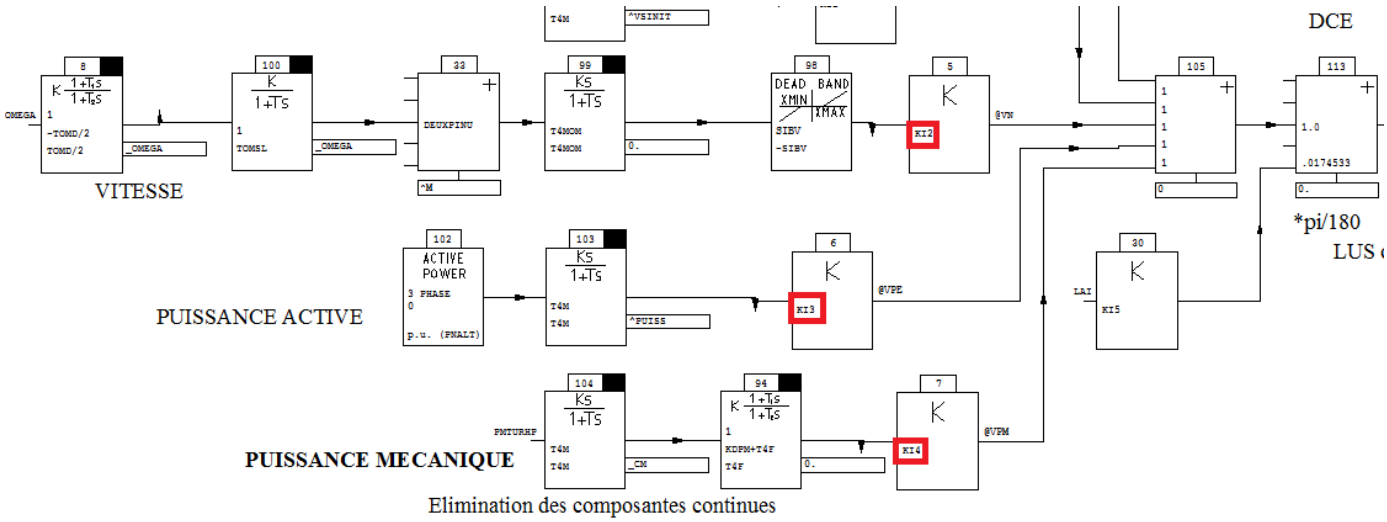

Figure 19: PSS of the quoted generators in EUROSTAG

Table 9: Modes after the modifications

N0.	REAL	IMAG	DAMP (%)	FREQ(HZ)	Generator node with greatest participation
1	-0.0591	4.3535	1.36	0.6929	N0000266
2	-0.3191	4.9190	6.47	0.7829	N0000612
4	-1.7038	6.3731	25.83	1.0143	N0000623
5	-0.4153	2.6798	15.31	0.4265	N0000631
6	-0.8509	2.0480	38.37	0.3260	N0000338
7	-0.6760	2.1674	29.77	0.3449	N0000541
8	- 0.5461	2.4573	21.69	0.3911	N0000541
9	-1.3673	8.9243	15.14	1.4203	N0001218
10	-2.2135	5.9916	34.65	0.9536	N0000623

Table 10: Participation factors of 0.69Hz mode

NAME	Participation factors
N0000266	100.00000
N0000268	99.46580
N0000263	91.95477
N0000612	71.41379
N0000613	71.20496
N0000125	30.37259
N0000126	30.36207
N0000124	30.30608
N0000127	30.28571
N0000920	20.64556
N0000921	19.57355
N0000446	10.40911

Table 11: Participation factors of 0.78 mode

NAME	Participation factors
N0000612	100.00000
N0000613	99.44521
N0000266	62.41948
N0000268	62.40879
N0000263	55.45270
N0000127	28.09470
N0000125	28.04967
N0000126	28.03655
N0000124	27.99595
N0000414	21.24001
N0000415	21.14050
N0000416	21.09125
N0000417	21.06476

Appendix C

This appendix gives some more details about the small signal stability module made for the iTesla project in Matlab and some limitations of this module.

This module takes as inputs time domain simulations and some parameters in order to tune the study. EUROSTAG .exp files used for ASCII exportation can be directly imported in Matlab. The main parameters of the module are:

- *Step_min*: this is a parameter which selects the window of time for which the Prony analysis will be applied
- *Var_min*: this is the minimum normalized variance of the signals which discards signals with lower variance for Prony analysis. It selects signals with higher oscillations.
- f: interval of frequencies for the Prony analysis

The principle of the Prony analysis is well explained in [7] and can be summarized as[8]:

> "Prony was designed to estimate the exponential parameters of [the equation below] by fitting a function to an observed measurement. Prony's method is a "polynomial" method and includes the process of finding the roots of a characteristic polynomial.

$$y(t) = \sum_{i=1}^{n} a_i e^{\sigma_i * t} \cos(\omega_i t + \theta_i) \text{ "}$$

The issue with the step_min parameter design is that it is based on the variable time step of the software (here EUROSTAG). As the variable step varies for every simulation, the time window used in order to select the signal on which the prony analysis is made varies as well and therefore the user has no idea of what the module is exactly computing. This may be a problem especially for oscillations whose damping ratios are above 7-8%. It can be seen on figures 20, 21, 22 and 23 that the prony reconstitution (signal with stars) differs depending on the parameters (step_min and var_min) chosen. Table 12 is summarizing the modes computed on the previous figures and shows the variability between the computations of the same simulation. Consequently the user has to keep in mind that for quite well damped oscillations ($\sim \geq 6 - 7\%$) the modes computed (especially the damping ratio) can vary quite a lot without being really different in reality. One solution could be to take var_min=0.5, in that case very few signals would be analyzed but the analysis would be less dependent on step_min. However, this implies that for a lot of simulations only few signals would be selected and the analysis would be less global. One general rule is that the more signals to be analyzed, the less accurate the reconstructed signals will be. Nevertheless the more oscillatory contents there will be in the signals, the easier the modes will be to detect and therefore the more accurate the computations will be.

That is why it could be interesting to add a reliability index associated with a mode which would compute how close the reconstructed signal is compared to the original signal. This would help in establishing the security rules to check the veracity of the computed index.

Table 12: Summary of matlab studies with different parameters for one simulation

	Var_min	Frequency (Hz)	Damping ratio (%)	Frequency (Hz)	Damping ratio (%)
Step_min		0,04		0,05	
	0,3	0.760	13.884	0.797	9.660
	0,5	0.761	5.672	0.798	7.161

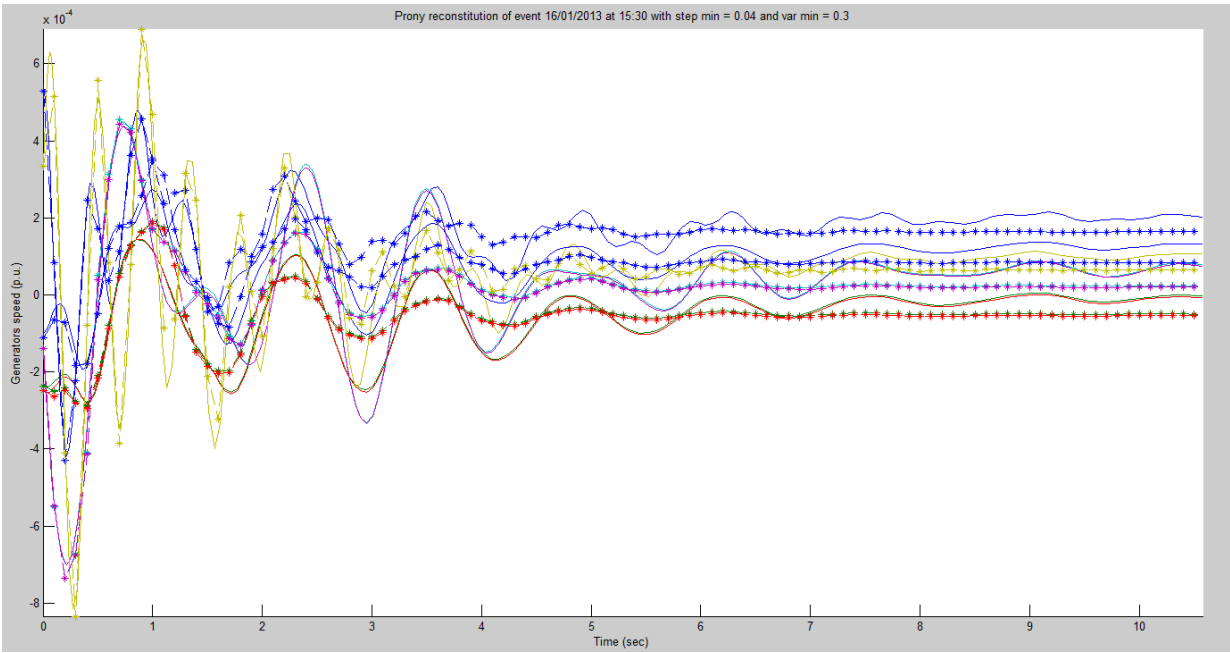

Figure 20: Plot of reconstructed signals with the prony analysis compared to the original signal with var_min=0.3 and step_min=0.04

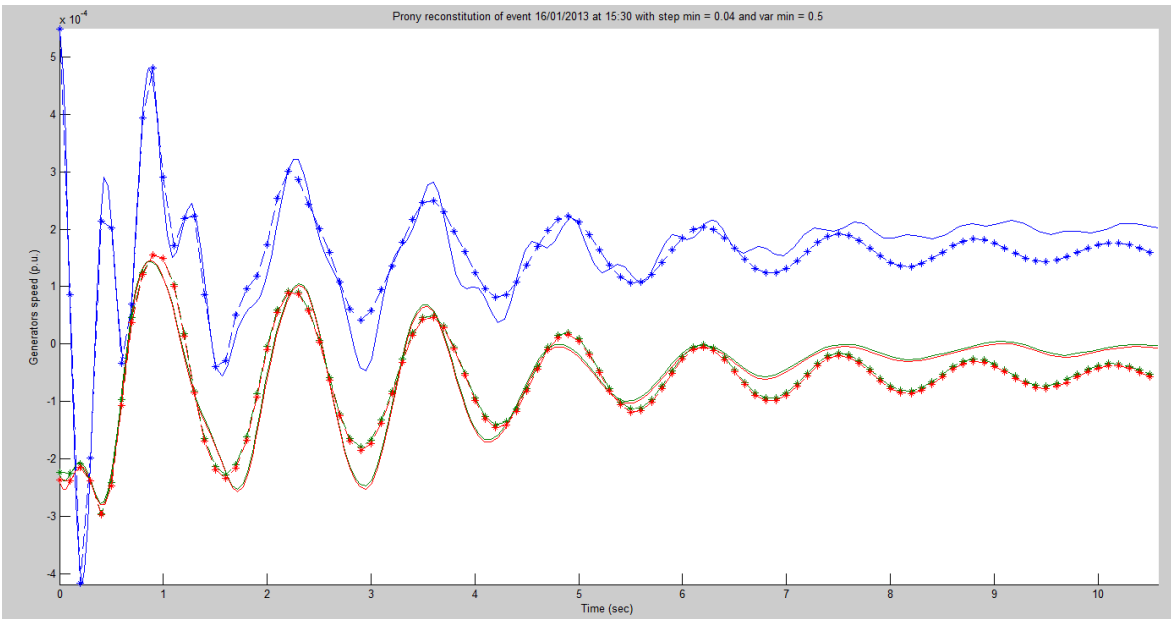

Figure 21: Plot of reconstructed signals with the prony analysis compared to the original signal with var_min=0.5 and step_min=0.04

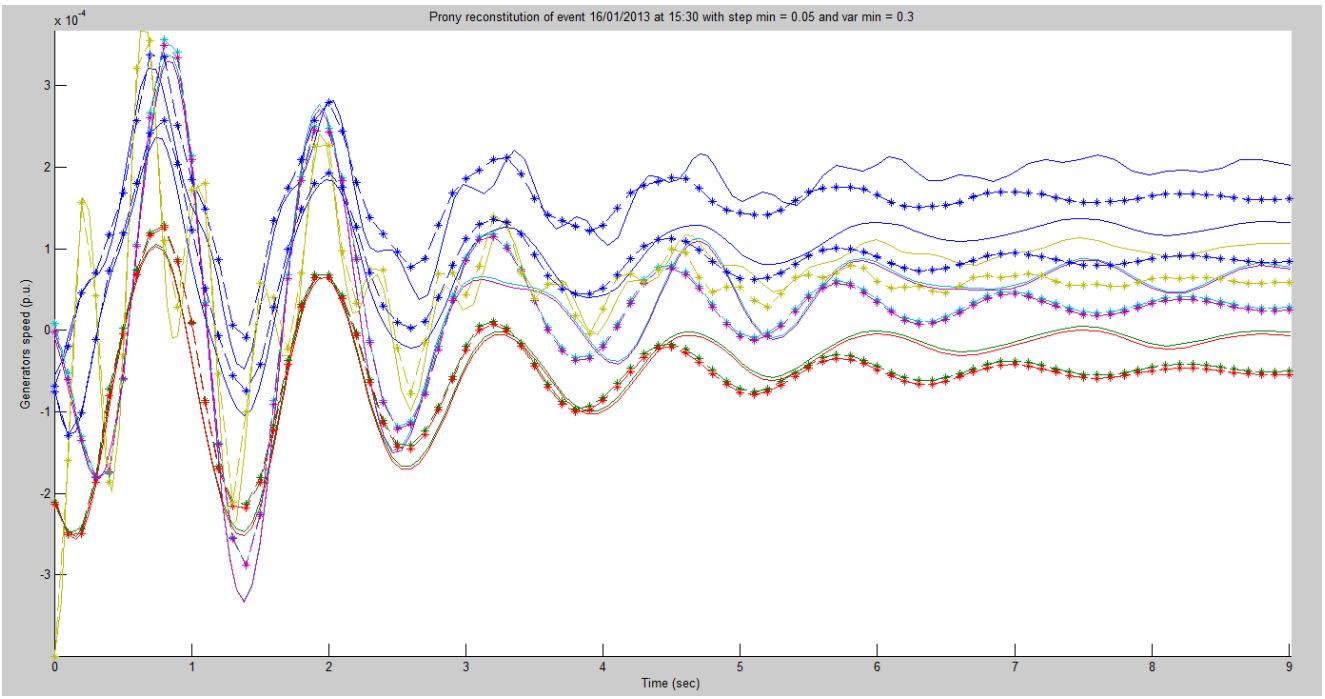

Figure 22: Plot of reconstructed signals with the prony analysis compared to the original signal with var_min=0.3 and step_min=0.05

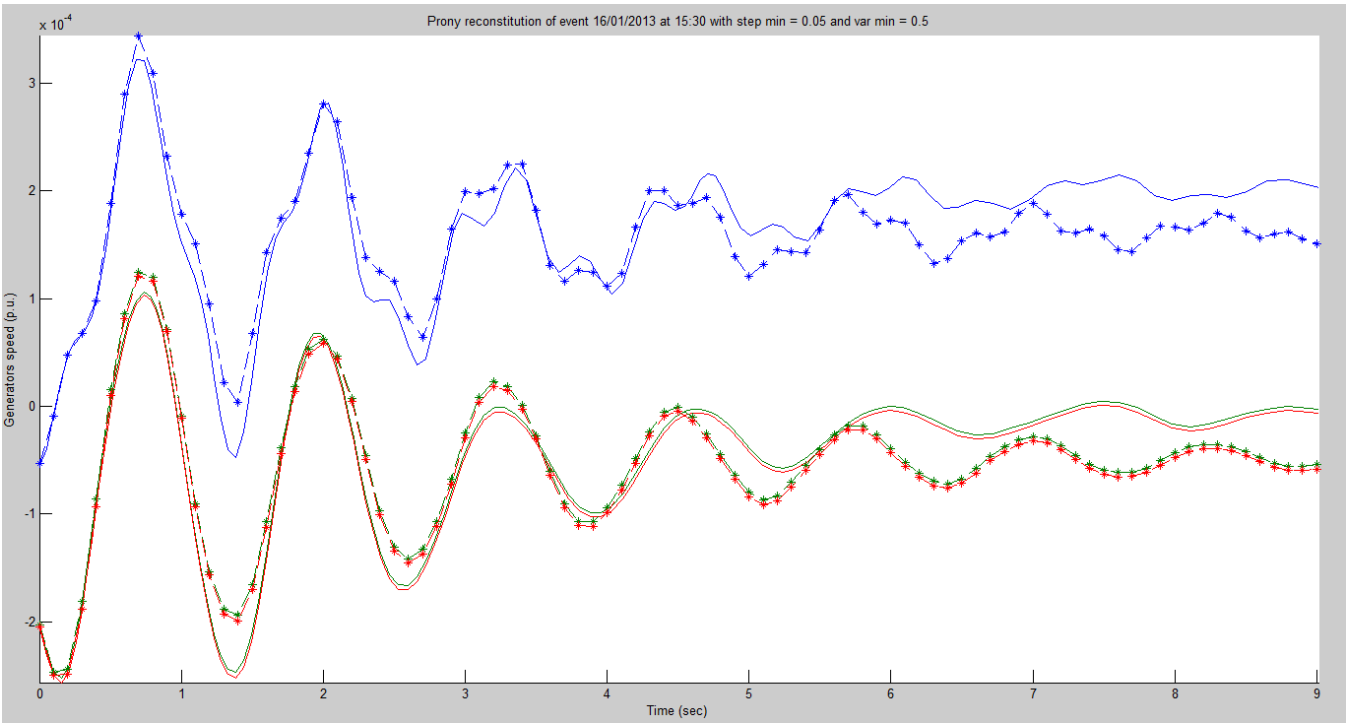

Figure 23: Plot of reconstructed signals with the prony analysis compared to the original signal with var_min=0.5 and step_min=0.05

Appendix D

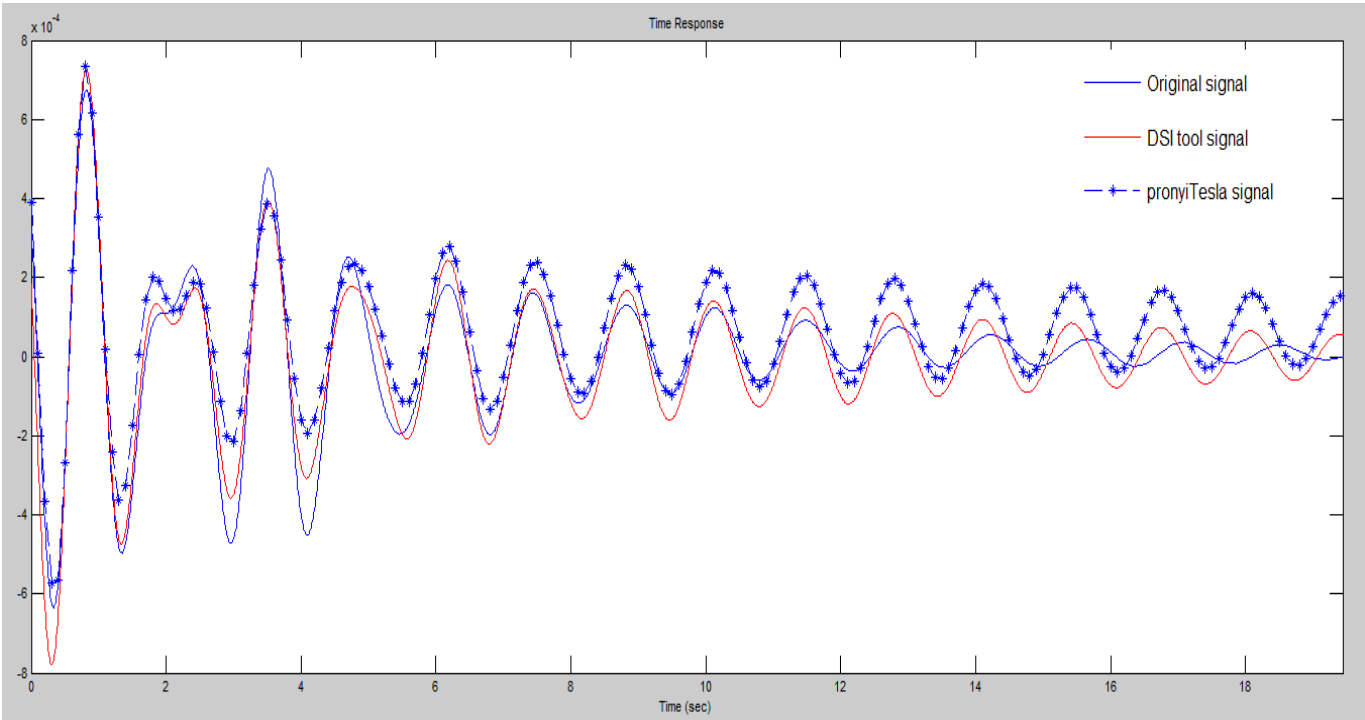

Figure 24: prony reconstruction with methods pronyItesla and DSI tool compared to the original signal for comparison 1

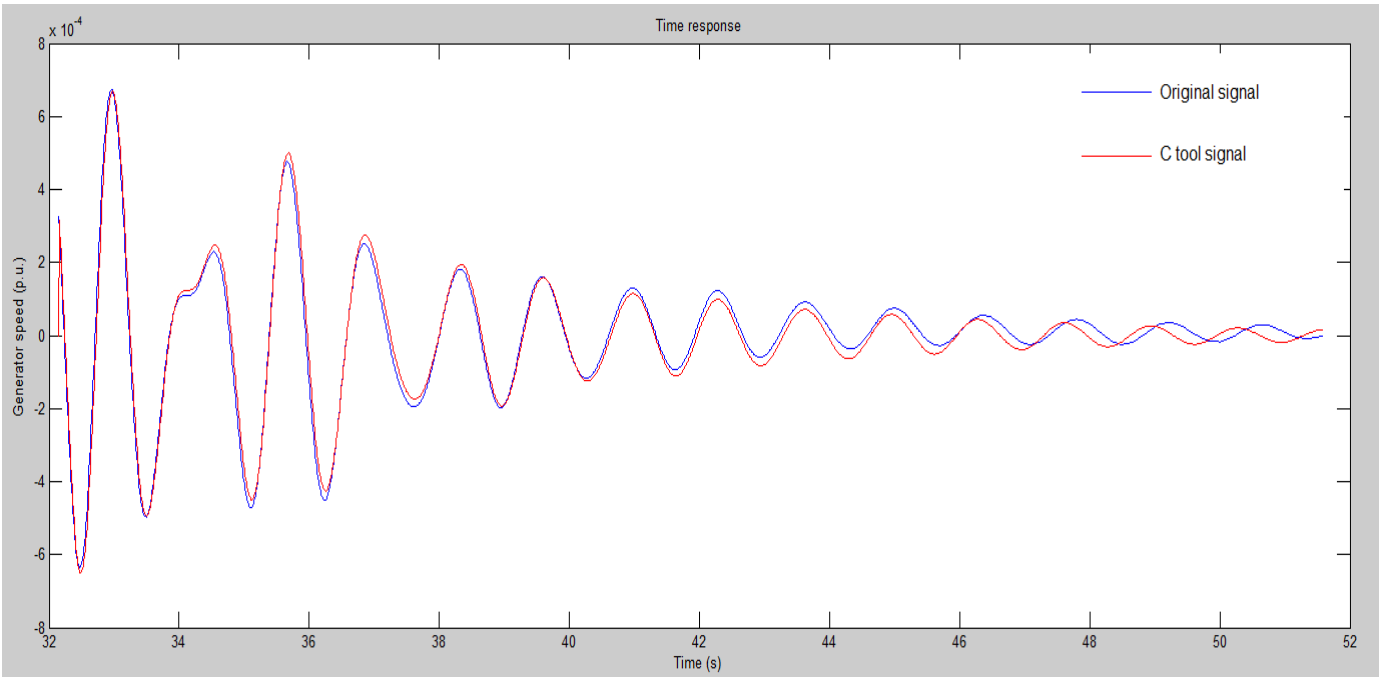

Figure 25: prony reconstruction with the C tool compared to the original signal for comparison 1

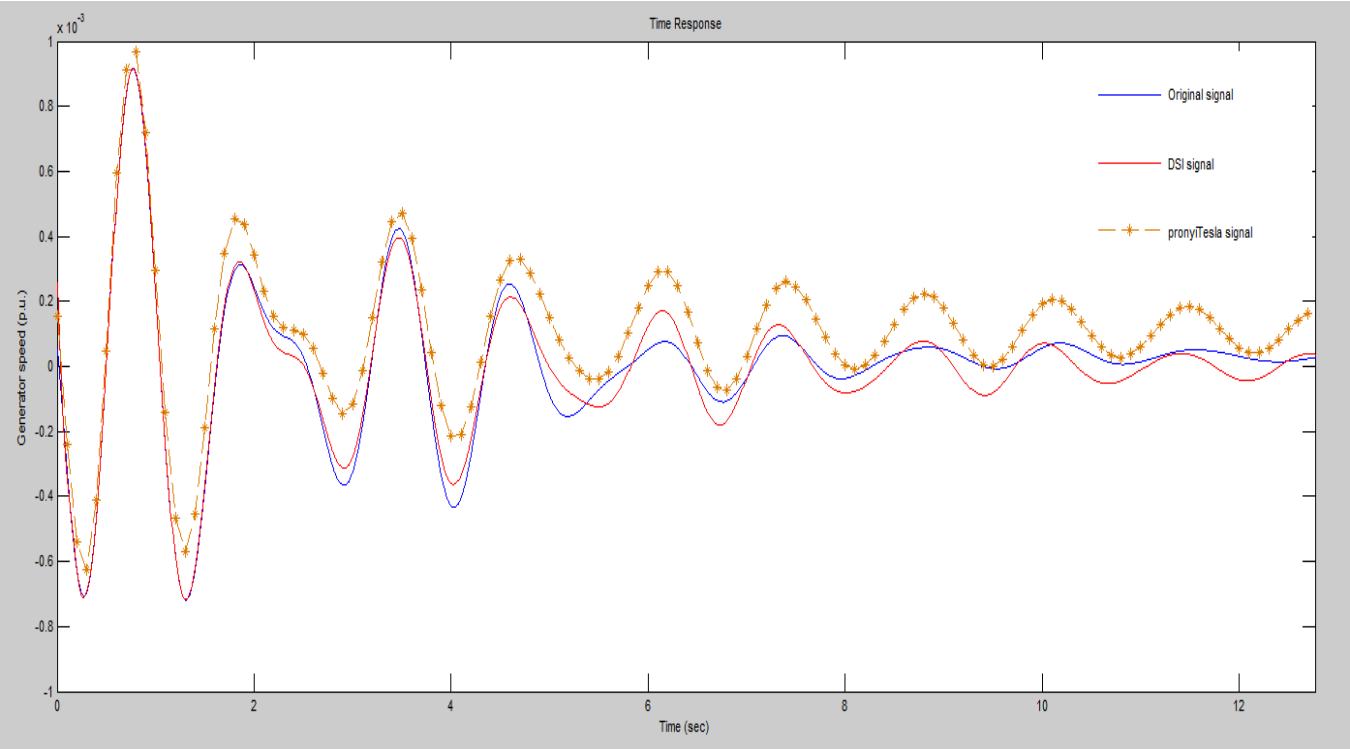

Figure 26: prony reconstruction with methods pronyItesla and DSI tool compared to the original signal for comparison 2

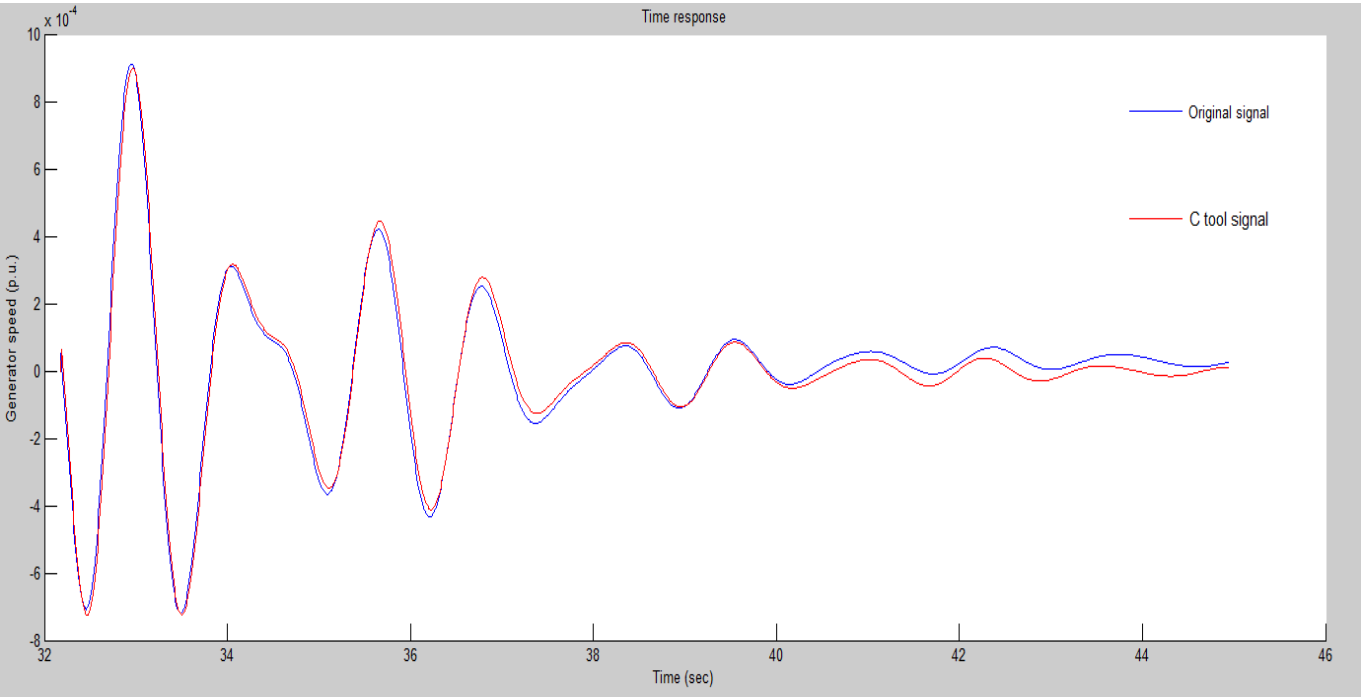

Figure 27 : prony reconstruction with the C tool compared to the original signal for comparison 2

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