A MATLAB/GUI© Case-Study Environment for Nonlinear Control Learning

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Abstract

In this work a Matlab based environment is proposed to illustrate the concept of zero dynamics appearing in nonlinear control design. This is done through the study of the stability of a (torque/flux) oriented control of an AC-motor. This environment is used by the students of a french engineering school as a part of a advanced nonlinear control course. Some related experiments are reported as well as some suggested relevant scenarios. The proposed tool is realized using the MATLAB© GUI facility and is accessed[1] for educational purposes.

Keywords: Nonlinear Control Education; User friendly environment; Zero dynamics stability; Asynchronous motor.

1 Introduction

Recent advances in information and communication technologies make easier the design and the realization of user friendly graphical interfaces. A quick look at the related specialized literature underlines an extensive use of such tools in educational purposes. The main advantage in using such tools is the dynamic interactivity they offer and the possibility to underline causal links between concepts through graphical dependencies. Another powerful aspects of new technologies is the distance learning capabilities that enable a sophisticated software and even hardware to be easily shared.

In the few last years, such educational environments began to appear in within the control community to illustrate the already mature theoretical backgrounds [11]. In that context, educational tools have been developed covering among other aspects, linear control systems [9, 5, 12, 15], nonlinear robot control [14], nonlinear stabilization theory [10]. Nowadays, many universities offer a great deal of control oriented educational materials[2].

The purpose of this paper is to present the simulation environment ZERODYN dedicated to nonlinear control learning. The proposed facility enables the concept of zero dynamics to be illustrated. This is done through the study of the zero dynamics stability when an AC-motor is regulated in the (torque/flux) variables.

Since the last year, ZERODYN is integrated in the nonlinear control theory program at the ENSIEG[3] which is one of the high engineering schools of the INPG[4], the biggest educational institution for engineers in France.

Zero dynamics appear in nonlinear framework when differential geometric tools [8] are used to derive a nonlinear state feedback after a partial linearization. It defines the dynamic of internal states that may be destabilized by the underlying regulation state feedback. The study of the stability of zero dynamics is a difficult task in general because of the lack of systematic approaches (generally, Lyapunov functions are to be exhibited in order to prove the stability).

In the case studied herein, while the related zero dynamics is two-dimensional, only one variable is of interest since the other is

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[1] For reviewers, corresponding files may be downloaded at www-hayate.ensieg.inpg.fr, user name: hayate, password: hayate01

[2] See for example (www.engin.uminch.edu/group/ctm/), (www.control.lth.se/~ kursdr), (www-lag.ensieg.inpg.fr/~ exel)

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nothing but an angle. This enables a graphical based study to be performed which is particularly appreciated in an educational context. Furthermore, this study can easily be made parameter-dependant giving deep insights on the zero dynamics related risk of instability w.r.t to both control specifications and system's physical parameters.

The paper is organized as follows :

First, the system equations is recalled together with the control derivation and the resulting zero dynamics. In section 3, the structure of the proposed environment is presented in a somehow user's manual manner. Finally, some layouts of special pedagogical interest are underlined.

2 Theoretical Background

We consider the equations of an AC-motor in the (α, β)-system of coordinates :

$$\dot{x} = A(\Omega)x + Bu \tag{1}$$

where $x = \begin{pmatrix} I_{s\alpha} & I_{s\beta} & \Phi_{s\alpha} & \Phi_{s\beta} \end{pmatrix}^T$ is the state whose components are the statoric currents and fluxes respectively while u is the voltage input. $A(\Omega)$ and B are respectively a mechanical speed-dependent matrix and a constant matrix of convenient dimensions. (See equations (20)-(21) in the appendix for analytical expressions of $A(\Omega)$ and B).

Consider the regulated output y given by :

$$y = h(x) := \begin{pmatrix} \Psi \\ \Gamma \end{pmatrix} := \begin{pmatrix} \|\overrightarrow{\Phi_s}\|^2 \\ \\ p\overrightarrow{\Phi_s} \wedge \overrightarrow{I_s} \end{pmatrix} = \begin{pmatrix} x_3^2 + x_4^2 \\ \\ p(x_2x_3 - x_1x_4) \end{pmatrix} \tag{2}$$

where Ψ and Γ are respectively the squared norm of the flux and the torque. The aim of the control design is to stabilize the regulated output y around some desired setpoint y_d.

An even short surveys of induction motor's control literature is clearly beyond the scope and the aims of this paper. Interested reader can see [2, 3] for differential geometric based approaches, [7, 13] for sliding mode approaches, [1] for optimal control strategies while state estimation related works are referenced in [6, 4]. Here only the principle of the differential geometric based state feedback derivation is recalled in order to use it in our zero-dynamics illustration environment.

In the remainder of this section, first, the corresponding state feedback law is derived. Then, the definition of the zero dynamics is briefly recalled.

2.1 Derivation of the state feedback law

Consider a more general nonlinear system given by[5] :

$$\dot{x} = f(x) + g(x)u \quad ; \quad y = h(x) \tag{3}$$

where y stands for the output to be regulated.

In the differential geometric approach, the state feedback is chosen so as to infer the following dynamic to the regulation error $e = y - y_d \in \mathbb{R}^2$:

$$\dot{e} = -\Lambda e \tag{4}$$

where

$$\Lambda := \begin{pmatrix} \lambda_\Psi & 0 \\ 0 & \lambda_\Gamma \end{pmatrix} > 0 \qquad ; \qquad \lambda_\Psi > 0 \qquad ; \qquad \lambda_\Gamma > 0 \tag{5}$$

Differentiating y gives :

$$\dot{y} = F(x) + G(x)u \tag{6}$$

[5] the case of system with 2 outputs and 4 states are used to illustrate the concepts, generalization to the general case is straightforward

for some convenient $F(x) \in \mathbb{R}^2$ and $G(x) \in \mathbb{R}^{2\times 2}$.

Now since y_d is supposed to be constant, one has $\dot{e} = \dot{y} = F(x) + G(x)u$ and therefore, using (4), the state feedback can be analytically derived (recall that $y = h(x)$) :

$$u = k(x, y_d) := -G^{-1}(x)\Big[F(x) + \Lambda(h(x) - y_d)\Big] \tag{7}$$

2.2 The zero dynamics associated to a setpoint $\mathbf{y_d}$

The concept of zero dynamics has been invented in order to study the overall stability of a nonlinear system when the control is chosen so as to force the output to behave in a pre-determined manner.

Roughly speaking, the aim of the study of the zero dynamics is to answer the following question:

"Can the system do what I am asking it to do ?".

The possibility for the system *to do* is to be understood w.r.t the fundamental feature of the resulting closed loop behavior: The stability.

To obtain the zero dynamics of the controlled nonlinear system, the following steps are to be performed :

- First, define a change of coordinates :

$$z = \begin{pmatrix} z_1 \\ z_2 \\ z_3 \\ z_4 \end{pmatrix} = T(x) \qquad \text{such that} \qquad \begin{pmatrix} z_1 \\ z_2 \end{pmatrix} = y = h(x) \tag{8}$$

  this supposes to choose z_3 and z_4 in order for (8) to be a diffeomorphism.

- Write the system's equations in the new system of coordinates z :

$$\begin{aligned} \dot{z} &= \frac{\partial T}{\partial x}(T^{-1}(z))\Big[f(T^{-1}(z)) + g(T^{-1}(z))u\Big] \\ &=: \bar{F}(z) + \bar{G}(z)u \end{aligned} \tag{9}$$

- Replace u by its expression in z, namely :

$$u = k(x, y_d) = k\Big(T^{-1}(z), y_d\Big) =: \bar{k}(z, y_d) \tag{10}$$

  so that (9) becomes :

$$\dot{z} = \bar{F}(z) + \bar{G}(z)\bar{k}(z, y_d) =: D(z, y_d) =: \begin{pmatrix} D_1(z, y_d) \\ D_2(z, y_d) \\ D_3(z, y_d) \\ D_4(z, y_d) \end{pmatrix} \tag{11}$$

  the closed loop system's dynamic in the z-coordinates.

- Remember that $\begin{pmatrix} z_1 \\ z_2 \end{pmatrix} = y$. Therefore, using (4), it comes that :

$$\begin{pmatrix} z_1(t) \\ z_2(t) \end{pmatrix} = y_d + e(t) \tag{12}$$

Finally, using (12) in (11) gives the so-called zero dynamics of the controlled system associated to the setpoint y_d :

$$\dot{z}_3(t) = \bar{D}_3\Big(z_3(t), z_4(t), y_d, e(t)\Big) \quad (13)$$

$$\dot{z}_4(t) = \bar{D}_4\Big(z_3(t), z_4(t), y_d, e(t)\Big) \quad (14)$$

$$e(t) = \exp(-\Lambda t)e(0) \quad (15)$$

for straightforward definitions of $\bar{D}_3(.)$ and $\bar{D}_4(.)$

2.3 Discussion

A quick look to the expression of the zero-dynamics given by (13)-(15) permits to underline the following facts :

Fact 1: The stability of the zero dynamics depends on **the desired setpoint $\mathbf{y_d}$**.

Fact 2: The stability of the zero dynamics depends on the **initial state**. Indeed, the initial state defines initial values of e, z_3 and z_4.

Fact 3: The stability of the zero-dynamics depends on the **control parameters** (λ_Ψ,λ_Γ).

Fact 4: Finally, it is clear that the stability of the zero-dynamics depends on the **system's parameters** that implicitly affect the maps $\bar{D}_3$ and $\bar{D}_4$ in (13)-(14)

These facts show that the study of the stability of the zero-dynamics is a quite complicated issue. This is the reason why, often, only a sub-problem of the above one is tackled. Namely, the one obtained by setting e to 0. This amounts to study the feasibility of the steady state regime associated to the desired setpoint y_d. One then studies the stability of the following dynamic :

$$\dot{z}_3(t) = \bar{D}_3\Big(z_3(t), z_4(t), y_d, 0\Big) \quad (16)$$

$$\dot{z}_4(t) = \bar{D}_4\Big(z_3(t), z_4(t), y_d, 0\Big) \quad (17)$$

that is nothing but the asymptotic version of (13)-(15).

2.4 Application to the AC-motor

When applying the above methodology to the AC-motor, the following correspondences are used [2] :

$$\begin{aligned} z_1 &= \Psi := \|\overrightarrow{\Psi_s}\|^2 \\ z_2 &= \Gamma := p\ \overrightarrow{\Phi_s} \wedge \overrightarrow{I_s} \\ z_3 &= S := \overrightarrow{I_s}.\overrightarrow{\Phi_s} \\ z_4 &= \arctan\left(\frac{\Phi_{s\beta}}{\Phi_{s\alpha}}\right) \end{aligned}$$

The first two equations are compatible with the theory recalled in the preceding subsections since the regulated output is $y = (\Psi \quad \Gamma)^T$ according to (2). The choice of z_3 and z_4 clearly completes the change of coordinates.

The interesting features that are of great importance in what follows can be resumed in the following two points :

- The stability of the internal state z_4 is not an issue since z_4 is an angle.
- In the particular case of the AC-motor, the equation (16) describing the steady state zero dynamics for z_3 **is independent of** z_4.

Combined together, the two preceding features state that the study of the steady state zero dynamics stability for the AC-motor amounts to the study of the stability of a one-dimensional dynamic of the form (recall that we note $S = z_3$) :

$$\dot{S} = \bar{D}_3(S, y_d)) \tag{18}$$

(See appendix for the analytical expression of $\bar{D}_3(S, y_d)$).

This is a particularly attractive feature from a pedagogical point of view. Indeed, the stability of such scalar autonomous differential equations can be made using graphical plots in the $(S, \dot{S})$ coordinates. This can be easily shown on Figure 1 where the variations of $\bar{D}_3(S, y_d)$ in (18) as a function of S are plotted for some particular choice of the set point y_d.

Indeed, using the plot of $\dot{S}$ as a function of S (for given setpoint y_d) enables the stability/instability regions to be easily

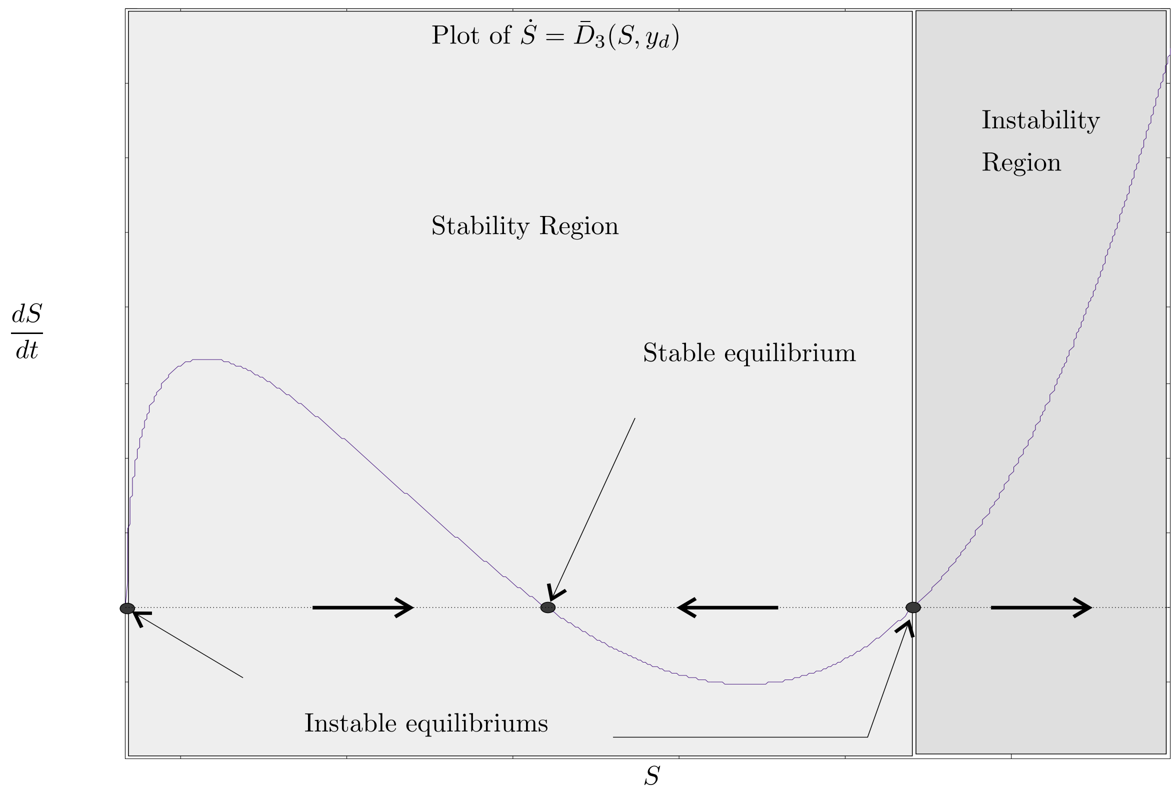

Fig. 1: Stability's Graphical study of (18)

determined. By the same, observing how does this plot change when the setpoint y_d and/or motor's parameters are modified enables the consequence of the latter on stability to be apprehended. Finally, running scenarios with initial conditions that are close to the intersection of the steady state (stability/instability) regions but that do not correspond to the desired steady state enable to underline that the study of the steady state zero dynamics is not sufficient since situations that would seem to be stable based on such study may be instable.

The environment described in the next section enables such manipulations to be done through a user-friendly interface based on the GUI facilities of MATLAB©.

3 Description of the proposed user-friendly environment ZERODYN

In this section, the educational environment ZERODYN is briefly presented. First, the structure of the environment is detailed, then basic scenarios of use are proposed in order to show how ZERODYN enables the zero dynamics notion to be clarified.

3.1 Overview of the environment ZERODYN

The initial appearance of *ZeroDyn* is depicted on Figure 2. On this view, the following thematic zones can be distinguished :

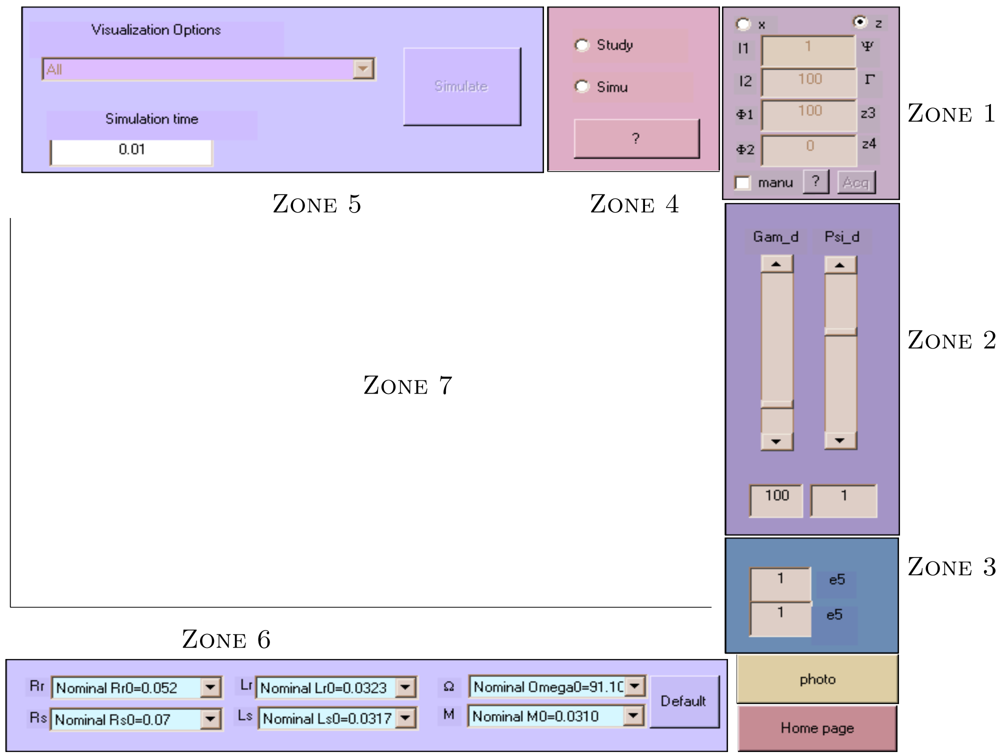

Fig. 2: Initial appearance of the environment *ZeroDyn*: Thematic zones

- ZONE 1: In this zone, user can define the initial conditions for the simulation. These can be defined either in the z-coordinates or in the x-coordinates. The *manu* option enables explicit user entries while the *Acq* button enables a graphical acquisition from the plots associated to the zero dynamics study curves. This is shown later in the following sequel.
- ZONE 2: In this zone user defines the setpoint values for the torque and the squared norm of the flux. Note that minimal and maximal values are imposed (for evident robustness reasons w.r.t the underlying integration facilities) :

$$\Gamma_d \in [10, 600] \quad ; \quad \Psi_d \in [0.1, 1.5] \tag{19}$$

  Therefore, two-side saturation functions are applied to user's entries, namely, if user enters for instance the value $\Gamma_d = 750$, the value $\Gamma_d = 600$ is visualized and used. The same logic is used to the three other bounding limits.
- ZONE 3: This zone enables the control parametres λ_Ψ and λ_Γ to be defined.
- ZONE 4: In this zone, one of the two following modes is to be chosen :
  - The *Study* mode is the one enabling the zero dynamics stability to be analysed.
  - The *Simu* mode is the mode in which simulations can be performed and the corresponding plots visualized.

- ZONE 5: This zone is dedicated to the graphical visualization options where the simulation duration is chosen as well as the variables user hopes to visualize.
- ZONE 6: On this zone, user may change the motor's basic parameters

$$(R_r, R_s, L_r, L_s, M)$$

  as well as the mechanical speed Ω in order to examine their effects on the stability and the tracking capacity of the motor. The *Default* button enables the default initial configuration to be retrieved.
- Finally, ZONE 7 is reserved to the plots used in either the *Study* mode or in the *Simu* mode.

Finally, the *photo* button enables the present view to be saved in an encapsulated postscript file whose name is chosen by the user through a dialog box.

3.2 ZERODYN's typical use scenario

✓ Recall that the initial view obtained when first launching ZERODYN is the one depicted on figure 2. Note that in this configuration default values are used for all possible choices (initial state, set point values, control parameters, time simulation and plots to be visualized). User must choose the mode by clicking on one of the two mutually exclusive radio buttons in ZONE 4 (see figure 2).

✓ Typically, before a simulation is requested, it is quite natural to use the *study* mode in order to analyse the steady state's zero dynamics stability. Recall that the steady state zero dynamics is the simplified dynamic system (16)-(17) in which the steady state is supposed to be already exactly reached.

This is illustrated on Figure 3 where the corresponding radio button is chosen. Automatically the stability regions are plotted according to the logic of Figure 1. Note that only the sign of $\frac{dS}{dt}$ is of interest in the study of the stability regions. The z_3-axis is then divided into **stability/unstability regions of initial conditions on** z_3. Green line is

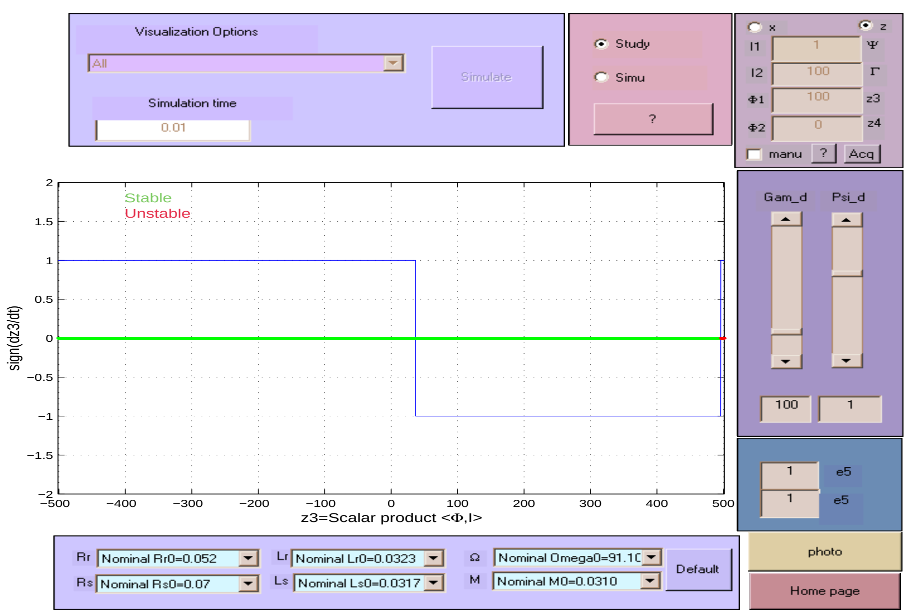

Fig. 3: View after selection of the *Study* mode: Stability/Unstability regions of z_3 initial values.

used to depict the stability region while red line is used to show values of initial z_3 that correspond to unstable steady state behaviour.

✓ At this stage, user may suggest changes in the problem parameters and observe their influence on the stability/Unstability regions. Here are some examples of changes w.r.t the initial configuration of Figure 3 :

  – Figure 4: Increasing the value of the desired torque Γ_d from 100 to 450 reduces the stability region.

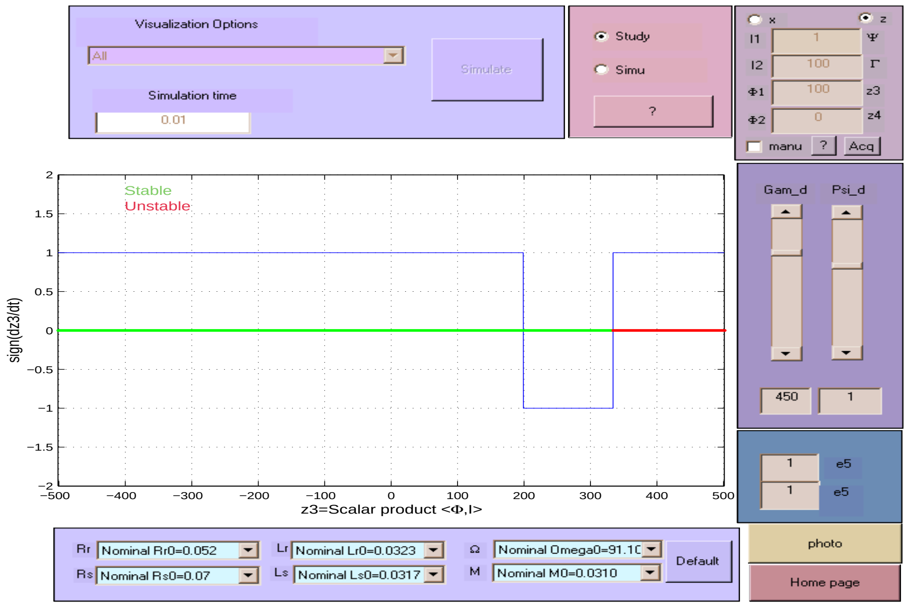

Fig. 4: Increasing Γ_d reduces the stability region. (Compare to Figure 3)

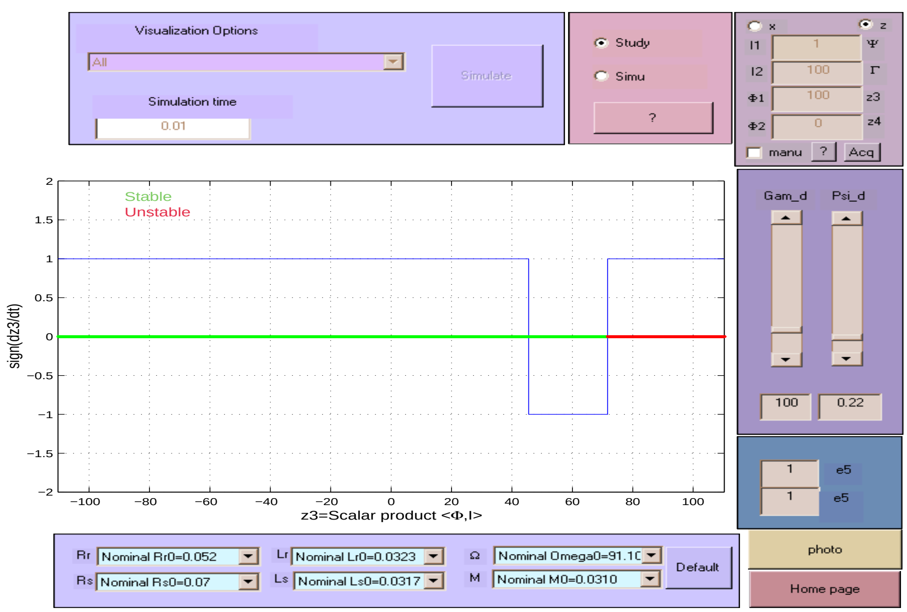

Fig. 5: Decreasing Ψ_d reduces the stability region. (Compare to Figure 3)

– Figure 5: Reducing the value of Ψ_d from 1.0 to 0.22 has the same effect: reducing the stability region.

– Figure 6: Increasing the rotoric resistance from the nominal value $R_{r0} = 0.052$ to $R_r = 2R_{r0}$ reduce the stability region. For instance in the case of Figure 6, the steady state zero dynamics is unstable for all initial values of z_3.

Modification of R_r

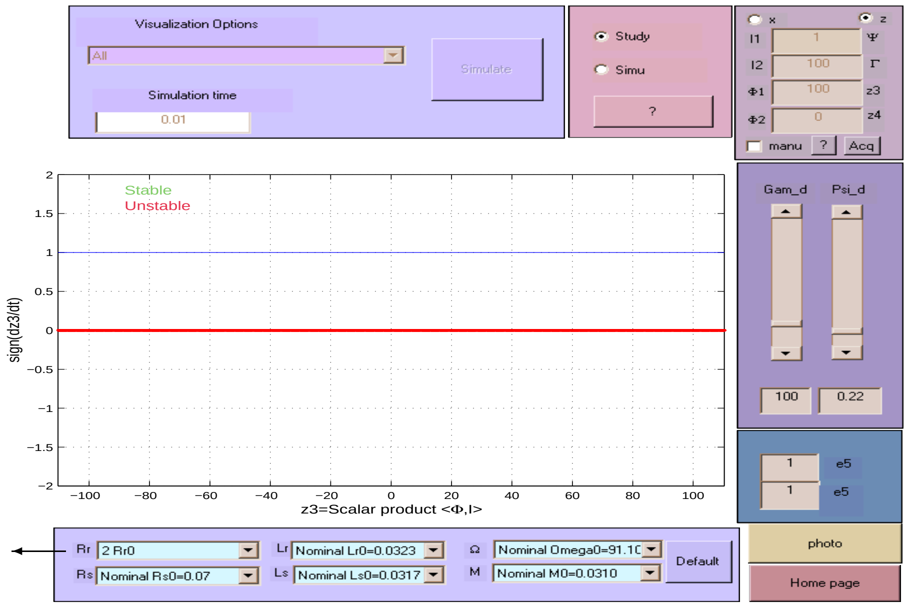

Fig. 6: Increasing R_r reduces the stability region. (Compare to Figure 5)

– Analogue modification can be performed on all the motor physical parameters

$$(R_r, R_s, L_r, L_s, M)$$

using the scrollers in Zone 6 in order to visualize the corresponding effects on the stability of the steady state zero dynamics.

✓ Once the study of the zero dynamics stability is achieved, there are two possibilities to switch to the simulation mode :

1. User may directly pass to the *Simu* mode by clicking on the corresponding button in Zone 4. The *Simulate* button of Zone 5 is then enabled and the plots of the zero dynamics study phase are deleted. When the user press the *Simulate* button, simulation is automatically done with the present values of all possible choices and corresponding plots are displayed with the present choice of the visualization options of Zone 5 (see Figure 7). Note that in this case, there is no reason for the initial state to be compatible with the desired steady state. Namely, $(z_1, z_2)^T$ may be different from (Ψ_d, Γ_d). This is for instance the case of the simulation depicted on Figure 7 where $z_2 = \Gamma = 100$ while $\Gamma_d = 110$.

2. There is another choice the user dispose of before launching the simulation. This choice is to use the *Acq* button of Zone 1 to impose initial conditions that are compatible with the set point values. For this choice to be enabled, user must be initially in the *Study* mode. When so, the *Acq* button is enabled and by clicking on it, user may click on the desired value of $z_3(0)$ to be used in the next simulation. Figure 8 shows a view of such procedure. Note that the new initial conditions are automatically displayed in Zone 1. After this acquisition, the *Simu* mode may be chosen and simulation launched as in the first case. This acquisition mode permits the test of the stability in within the theoretical conditions, namely, when the steady state on Γ/Ψ is exactly reached.

✓ The visualization options of Zone 5 may be used to modify the visualized variables whose evolution are plotted. The following choices can be made :

♮ Desired and effective squared norm of the flux (Ψ_d, Ψ).

♮ Desired and effective torque (Γ_d, Γ).

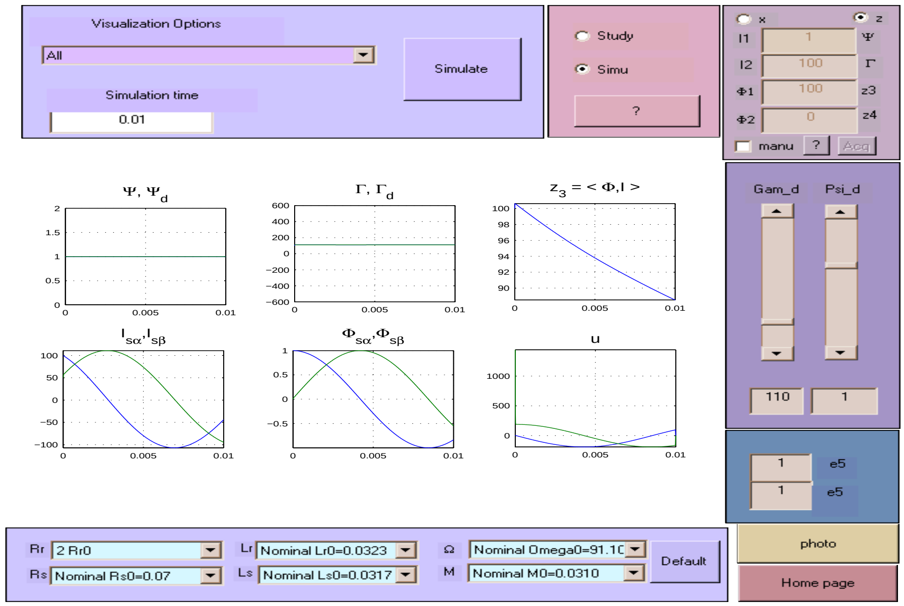

Fig. 7: Example of simulation mode's graphical plots. Note that $100 = \Gamma \neq \Gamma_d = 110$

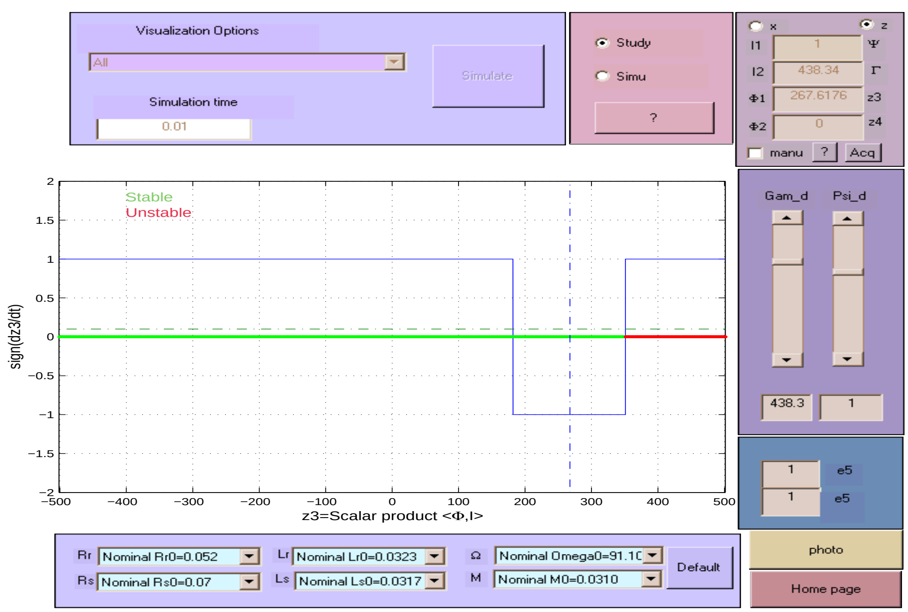

Fig. 8: Graphical Acquisition of setpoint-compatible initial conditions

- ♮ The scalar product $z_3 = \overrightarrow{I_s}.\overrightarrow{\Phi_s}$. This plot is closely related to the study of the zero dynamics stability.
- ♮ Evolution of the flux components.
- ♮ Evolution of the current components.
- ♮ Evolution of the control inputs.
- ♮ All of the above curves together.

The choice is made by using the scroll list of ZONE 5.
As an example, Figure 9 shows the same results than those of Figure 7 when the current components plots are chosen.

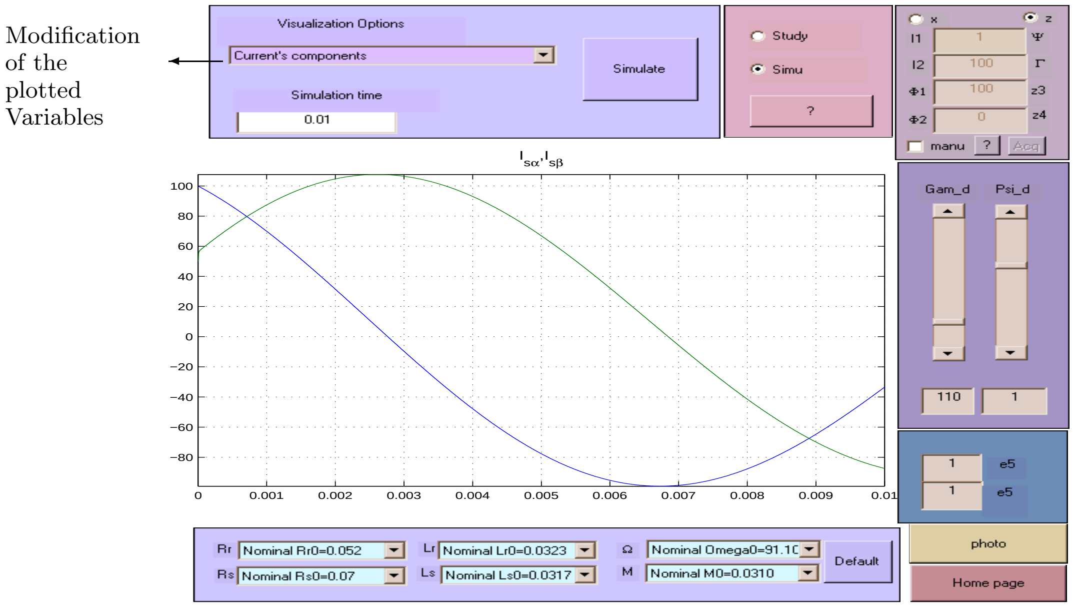

Fig. 9: Example of simulation mode's graphical plots. Scenario of Figure 7 with different visualization option.

✓ Time simulation may also be chosen using the edit text of ZONE 5. Figure 10 shows the same scenario than that of Figure 9 with a longer time simulation.

3.3 illustrating that steady state analysis is not sufficient

According to the discussion of section 2, a rigourous study of the zero dynamics stability amounts to study the stability of the time-varying non linear dynamic given by (13)-(15). Since this is an extremely complex task, the study of the steady state zero dynamics given by (16)-(17) enables a partial (but computable) result to be obtained.

More rigourously, if the steady state zero dynamics (16)-(17) is unstable, instability of the zero dynamic (13)-(15) can be inferred. If however, the former is stable, nothing can be said about the later. The aim of this section is to exhibit a scenario where such situations occur.

The following steps exhibits such scenario :

- Use ZONE 2 (see Figure 2) to define the following set-point: $\Gamma_d = 400$, $\Psi_d = 1$.
- Use ZONE 4 to choose the *study* mode in order to evaluate the stability of the steady-state zero dynamics. The corresponding behaviour of ZERODYN is then depicted on Figure 11 where it comes that the maximal value of possible initial values of z_3 that corresponds to stability is ≈ 390.
- Use the *manu* option of ZONE 1 to define the following initial condition :

$$\Psi = 1 \quad ; \quad \Gamma = 400 \quad ; \quad z_3 = 380 \quad ; \quad z_4 = 0$$

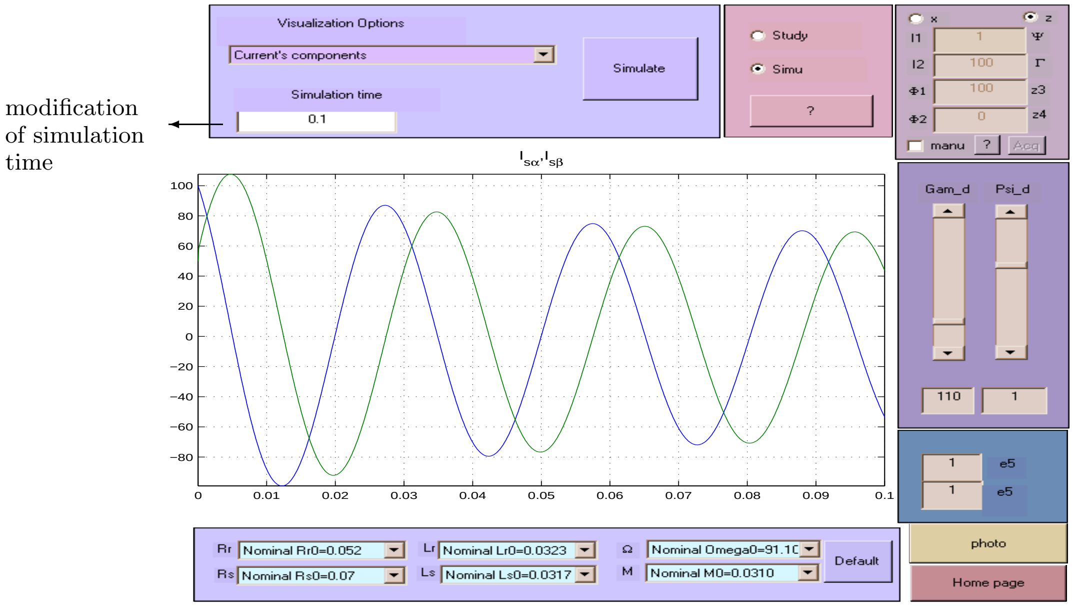

Fig. 10: Example of simulation mode's graphical plots. Scenario of Figure 7 with different visualization option.

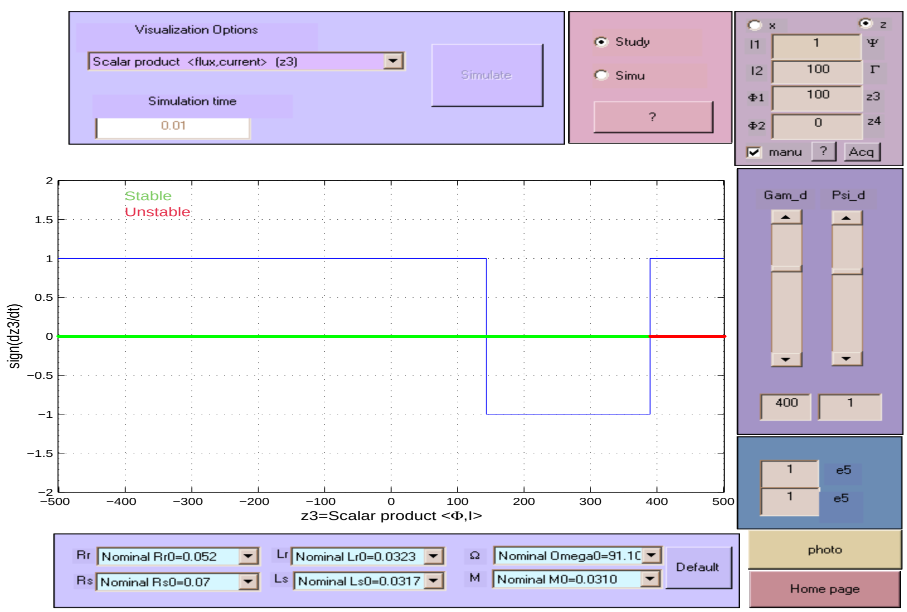

Fig. 11: Study of the stability of the steady state zero dynamics with $\Gamma_d = 400$, $\Psi_d = 1$. Maximum value of initial z_3 is ≈ 390.

Note that this initial condition is such that $\Gamma = \Gamma_d$ and $\Psi = \Psi_d$. Therefore, for all $z_3 < 390$ the stability of the whole zero dynamics (13)-(15) can be deduced from the stability of teh steady state zero dynamics (16)-(17). This can be verified on Figures 12 and 13 where times simulation results are plotted for all variables and for the only z_3 respectively. Note also that when only the z_3 plot options is chosen in ZONE 5, the limit stability bound $z_3^{max} \approx 390$ is also displayed (see Figure 13).

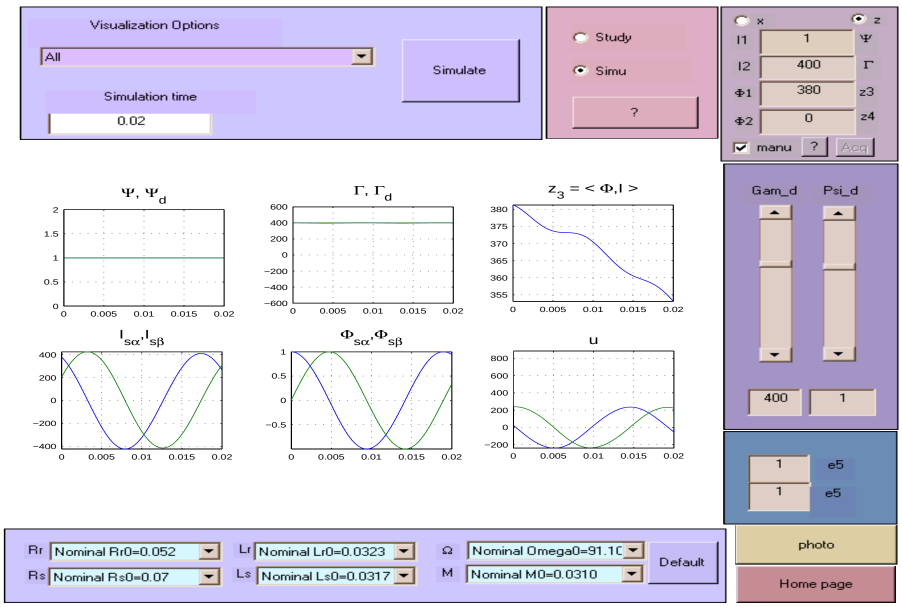

Fig. 12: Simulation results for the scenario of Figure 11

- Now, let us perturb the initial conditions in such a way that Γ differs from Γ_d. take for instance :

$$\Gamma = 380 \neq \Gamma_d = 400$$

and let us keep z_3 unchanged in the stability zone. Figures 14 and 15 show the corresponding simulation results where instability occurs. On Figure 15 in particular, it can be shown how z_3 goes extremely fast from the stability zone to the instability zone **during the very short transient phase**. This is typically what makes the study of the steady state dynamics (16)-(17) insufficient to decide whether the true zero dynamics (13)-(15) is stable or not.

3.4 The use of ZERODYN in the ENSIEG's control workshops

ZERODYN has been and still used by the students of ENSIEG, a french engineering school in the context of workshops feeding a nonlinear control course. The theoretical concepts in nonlinear control methodologies and some examples on nonlinear systems are included in a 18 hours course. A 12 hours simulation workshops are carried out in order to address concrete nonlinear systems case studies. During these sessions, a teacher supervises at most 12 students. ZERODYN is used in 4 hours simulation workshop.

A document is distributed beforehand to the students so that they can carry out a theoretical preparation at home : they have to determine the theoretical model of the AC-motor. This theoretical study is continued with the teacher help and allows students to check some of the theoretically predictable features on the system stability. In particular, the graph of figure 1 is determined. Then, the graphical environment Zerodyn is presented and a user's manual is distributed. We insisted on doing the theoretical analysis before presenting ZERODYN because otherwise, we feared that the students are naturally inclined to push on buttons without seeking a deep understanding of the subjacent theory.

At the end of the workshop, the students produce technical reports. Based on these reports, one can make some remarks :

✓ Students examined with a particular attention the effects of the motor's parameters on stability (zone 6)

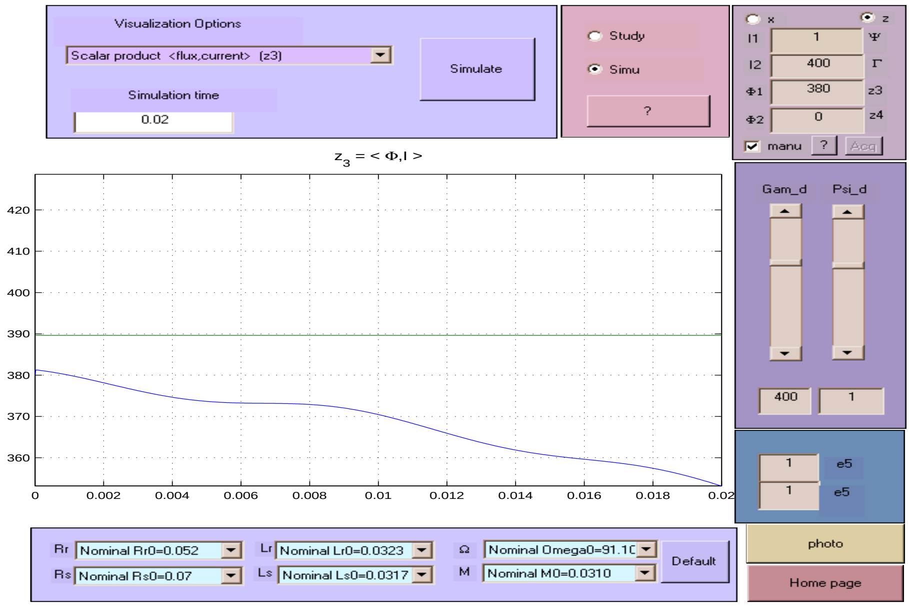

Fig. 13: Simulation results for the scenario of Figure 11. Zoom on z_3.

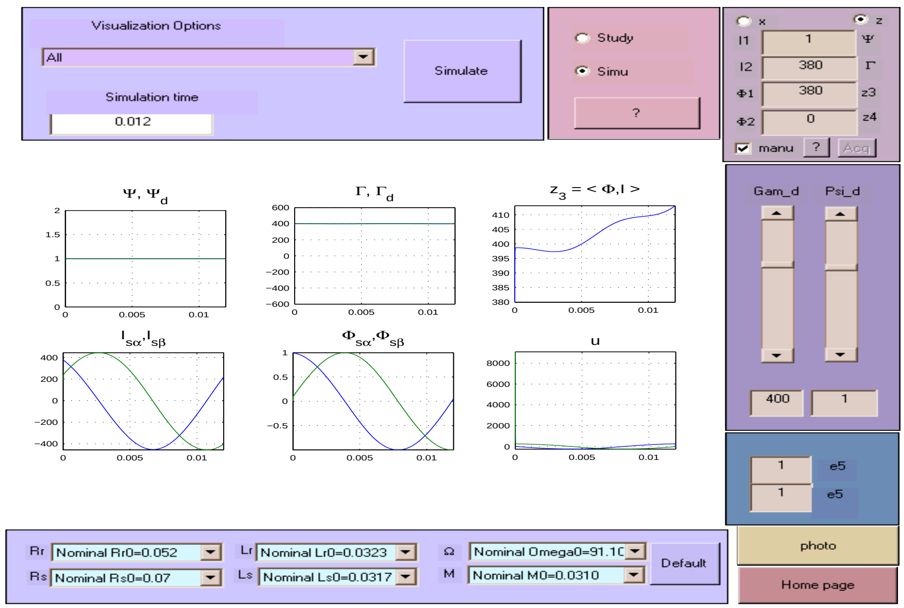

Fig. 14: Simulation results for the scenario $\Gamma \neq \Gamma_d$

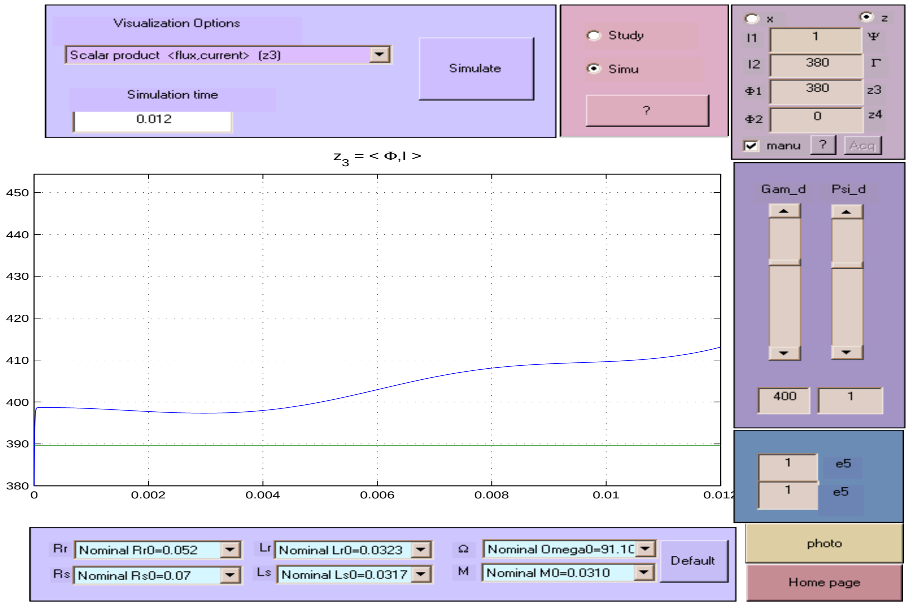

Fig. 15: Simulation results for the scenario $\Gamma \neq \Gamma_d$. z_3 goes from stability zone to instability zone during the transient phase.

- ✓ All the students visualized the graphical plots (flux, torque, z3, current, tension) when the system is in an unstable region : they could note that, in this case, the variables diverge. This adequation between a static analysis-based prediction and the corresponding temporal behaviour produced an undeniable satisfaction.
- ✓ Many students clearly established the link between stability and the desired pair (torque/flux), namely, if the desired torque is too high in comparison with the desired flux, then the system becomes unstable (zone 2).
- ✓ Roughly speaking, the theoretical analysis took about 2 hours $\frac{1}{2}$. Therefore, the use of ZERODYN lasted 90 minutes.
- ✓ As the theoretical aspects were well understood, the students really could benefit from this environment since it enabled the exploration of a larger domain of possibilities that would be cumbersome to explore by analytical computations.

To conclude, the experiment has been judged positively and will thus be renewed the next years.

3.5 Implementation issues

In this section some further details on the implementation of ZERODYN are given. ZERODYN is realized by means of MATLAB©'s graphical user interface creation facility. This results in a set of .m files. One of these files (named vue1.m) is the principal one that is to be executed in MATLAB to access ZERODYN principal view.

ZERODYN needs version 6.0 of MATLAB© to run correctly. To reduce execution time of system's integration, the integration subroutine is a (.dll) file that has been first created under FORTRAN using the integration subroutine LSODA. This is a crucial fact since interactivity is a basic feature of ZERODYN.

4 Conclusion

In this paper, the user friendly analysis and simulation environment ZERODYN has been presented. This environment enables the concept of zero dynamics appearing in nonlinear control to be studied. The AC-motor is used as an underlying example.

A key feature of ZERODYN is the high level of interactivity it offers in the sense that modifications imposed by user are automatically and instantaneously translated in graphical properties enabling an easy understanding of physical implications. This environment will soon be freely accessible at *www-hayate.ensieg.inpg.fr*

A Appendix

A.1 Expressions of A and B in (1)

$$A(\Omega) = \begin{pmatrix} -\alpha & -p\Omega & \frac{R_r}{q} & \frac{p\Omega L_r}{q} \\ p\Omega & -\alpha & -\frac{p\Omega L_r}{q} & \frac{R_r}{q} \\ -R_s & 0 & 0 & 0 \\ 0 & -R_s & 0 & 0 \end{pmatrix} \tag{20}$$

$$B = \begin{pmatrix} \frac{L_r}{q} & 0 \\ 0 & \frac{L_r}{q} \\ 1 & 0 \\ 0 & 1 \end{pmatrix} \tag{21}$$

where :

- ✓ R_r, R_s: Rotor and stator resistors respectively.
- ✓ L_r, L_s: Rotor and stator inductance respectively.
- ✓ M: Mutual inductance.
- ✓ $q := L_s L_r - M^2$.
- ✓ $\sigma := 1 - \dfrac{M^2}{L_s L_r} = \dfrac{q}{L_s L_r}$.
- ✓ $T_s := \dfrac{L_s}{R_s}$; $T_r := \dfrac{L_r}{R_r}$.
- ✓ $\alpha := (\frac{1}{\sigma T_r} + \frac{1}{\sigma T_s})$.

A.2 Expression of $\bar{\mathbf{D}}_{\mathbf{3}}(\mathrm{S}, \mathbf{y_d})$ in (18)

Straightforward (but cumbersome) computations enable to show that [2] :

$$\dot{S} = -\frac{1}{\sigma T_r} S + \frac{R_r}{q} \Psi_d + \frac{R_r L_s}{p^2} \frac{\Gamma_d^2}{L_r \Psi - qS} \tag{22}$$

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