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Inductances and force computation using Multiple model approach to nonlinear modeling and control of a pm linear synchronous actuator

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ABSTRACT

Multiple-model approach is an interesting alternative and a powerful tool for modelling complex process. This paper presents the analysis and modeling of nonlinear coupling functions using multiple model approach. Based on a 2D axisymmetric finite element model, a multi-physical model of a pm linear synchronous actuator is built, interpolated and computed over one pole pitch and for different current densities.

Each linearized model is a local representation of the electromagnetic and the electro-mechanic coupling functions under or over saturation conditions. These models are then combined to describe the nonlinear behavior of the actuator. The proposed method conserves all the properties of this system against the reduction order methods. We use an uncoupled state multiple-model in opposition to the classically used coupled state multiple model (Takagi-Sugeno). We demonstrate performance and computational efficiency of the modeling and control scheme using Matlab simulations.

Keywords: synchronous actuator, multiple model approach, coupling functions.

1. INTRODUCTION

There are many nonlinear commands applied to synchronous permanent magnet motors. These control strategies are characterized by their robustness but also by their implementation complexity. Associated with the actuator model which is multi-physical and nonlinear with an electromagnetic and a mechanical coupling of their functions, the work required to achieve a good result is tedious.

In contrast, multiple model and multiple control offers the possibility of keeping the nonlinear system performance and transform the problem into a simpler set of sub-linear models to order [1;2].

The Multiple model approach (MMA) is a modeling technique of nonlinear systems. It can enable to reach a good compromise between accuracy and complexity of the model. According to many works in this area [4], the MMA is renewed interest, particularly to control the nonlinear and complex systems.

This approach is based on the reduction of the system complexity by the decomposition of its operation space in a finished number of operation zones. Multiple models approach is a set of sub-models aggregated by an interpolation mechanism for characterizing the overall dynamic behavior of systems.

This approach can be seen as some kind of fuzzy modeling [4-5], according to Takagi and Sugeno (TS) method. The TS model is composed with a limited number of linear models interconnected due to nonlinear functions. Then, it can be used to solve problems in fields as diverse as control, observation or diagnosis of nonlinear systems, but with linear techniques.

To control these systems, an associated approach is generally applied as the Parallel Distributed Compensation (PDC) [7]. This method is based on linear controllers and is built for each interconnected linear model. The closed loop stability system is guarantee using the Lyapunov common function to all the sub-models.

Much work on analysis and synthesis problems relating to the multiple model approach has already been undertaken.

This has been motivated by the desire to establish problems of control law synthesis and full state estimation in numerical terms [8;9]. In recent years, a general approach based on multiple LTI models around various function points have been proposed. This so-called multiple model approach is a convex poly-topic representation, which can be obtained either directly from a nonlinear mathematical model, through mathematical transformation or through linearization around various function points.

In this work, the studied actuator is a pm linear synchronous one. It is applied to control a power steering system. Based on 2D axisymmetric finite element approach, the multi-physical model of this actuator is built using finite element method [3;6]. So, three-dimensional coupling functions are obtained according to the stator current and the plunger position and they are taking into account the magnetic saturation.

The dynamic model of the actuator is built under MATLAB environment and coupled to the steering system. The complexity to resolve this dynamic system and to control his behavior under nonlinear conditions, claim the necessity to linearize the coupling functions using the multiple model approach.

This paper concentrates on the analysis and the synthesis of multiple models of the electromagnetic coupling functions. There are computed over one pole pitch and for different current densities using the polytypic transformation method. These results are used to perform the dynamic behavior of the studied actuator and provide the same performances as the initial nonlinear FE model.

This paper is organized on four sections. Firstly, an overview of the multiple model approach is presented. Secondly, the multi-physical model of the actuator is developed and the interpolated functions are deduced. Thirdly, the analysis and synthesis of multiple models of the coupling functions is presented. Fourthly, the simulation results are exposed and compared to the previous finite element results.

2. Overview Of The Multiple Model Approach

The multiple model approach presents three structures: with coupled states, T-S, with decoupled states [11-13] and structure hierarchized. The T-S structure is the almost used on analysis and on the multiple model synthesis. In continuous case, it is expressed as the following form:

$$\begin{cases} \dot{x}(t) = \sum_{i=1}^{n} \mu_i(\xi(t))(A_i x(t) + B_i u(t) + D_i) \\ Y_m(t) = \sum_{i=1}^{n} \mu_i(\xi(t))(C_i x(t) + E_i u(t) + N_i) \end{cases} \quad (1)$$

With: $x(t) \in \Re^n$, $x(t)$ is the common state vector of the sub-models.

$u(t) \in \Re^m$ is the control vector,

$y(t) \in \Re^p$ presents the output vector,

$\mu_i(\xi(t)),\ i \in \{1,...,M\}$ are the activation functions that respect the property (2).

$\xi(t)$ is the decision variable vector depending on the variable measurable states and the control function $u(t)$.

The $\mu(\xi(t))$ is the activation function, that follows the activation degree of the associate local model. It authorizes the progressive passage of this model with the local nearest models.

These functions depend, for example, on the measurable variables system like the input or output signal system. They depend also on non-measurable variables like the state system. They have a triangular, sigmoidal or Gaussian form and satisfy the convex sum properties as:

$$\begin{cases} \sum_{i=1}^{n} \mu_i(\xi(t)) = 1 \\ 0 \le \mu_i(\xi(t)) \le 1 \end{cases} \quad (2)$$

The multiple models constitute the interest of universal approximation. For any nonlinear system approximation, an imposed precision can growth the number of the sub-models. On practice, a reduced sub-model can be sufficient to obtain a satisfied approximation. In the linear sub-model's case, the analysis tools of linear systems can be used.

Three approaches can be cited and allow obtaining a TS model by identification, by linearization, or by nonlinear sectors transformation [1].

3. THE CONVEX POLY-TOPIC TRANSFORMATION

The presented work is based on the convex poly-topic transformation of a nonlinear system. The main advantage of this method is to not provide an approximation error and to reduce the model number like using the linearization method. This method is based on the boundary of the nonlinear terms and is applied for analytical model. Considering the case of continuous and nonlinear system (3):

$$\dot{x}(t) = f(x(t)) + B.u(t) \qquad (3)$$

With $x(t) \in \Re^n$, $u(t) \in \Re^m$ $f(t) \in \Re^n$ and $B \in \Re^{n.m}$.

Basing on this result: ***Lemma1:*** *h(x(t))* is a burned function into *[a,b]*→ *R* with $(a,b) \in \Re^{+2}$. There exist two functions:

$$\begin{aligned} & h_i(.):[a,b] \to [0,1]; \quad i = 1,2 \\ & \qquad x(t) \to h_i(x(t)) \end{aligned} \qquad (4)$$

With $$\begin{cases} h(x(t)) = \alpha.h_1(x) + \beta.h_2(x) \\ h_1(x) + h_2(x) = 1, & \forall(\alpha,\beta) \end{cases} \qquad (5)$$

The decomposition of *h* into *[a, b]* is not unique. It can be therefore, obtained using*:*

$$\begin{cases} \beta = \min\limits_{x\in[a,b]}(h(x)) \\ \alpha = \max\limits_{x\in[a,b]}(h(x)) \end{cases} \quad \text{With : } \beta \le h(x(t)) \le \alpha \qquad (6)$$

And $$\begin{cases} h_1(x) = \dfrac{h(x(t)) - \beta}{\alpha - \beta} \\ h_2(x) = \dfrac{\alpha - h(x(t))}{\alpha - \beta} \end{cases} \qquad (7)$$

Using the hypothesis of the function continuity and boundary *f(x(t))* in the model (3) with *f(0)=0.* This function can be written as following:

$$f(x((t)) = \sum_{i=1}^{2} h_i(x(t)) A_i x(t) \qquad (8)$$

$$\dot{x}(t) = \sum_{i=1}^{2} h_i(x(t))(A_i x(t) + B_i x(t)) \qquad (9)$$

In this case, the multiple model presentation corresponds exactly to a nonlinear model into a small interval. In the context of the regulators synthesis by convex analysis, the multiple model can achieve control law by simultaneously solving Linear Matrix Inequality (LMI). In this case, the number of LMI constraints is polynomial over the number of local models. Thus, it should minimize the number of local models to limit the conservatism of the method. Either continuous T-S model given by (1), a control law synthesis will be the combination of laws for each sub model of the form:

$$u(t) = -\sum_{i=1}^{m} \mu_i(z(t)) h_i x(t) \qquad (10)$$

So, by applying it to the closed-loop model, expression (1) takes the following form:

$$\begin{cases} \dot{x}(t) = (A_z - B_z F_z) x(t) \\ y(t) = C_z x(t) \end{cases} \tag{11}$$

Or more explicitly:

$$\dot{x}(t) = \sum_{i=1}^{m} \sum_{j=1}^{m} \mu_i(z(t)) \mu_j(z(t)) (A_i - B_i h_j) x(t) \tag{12}$$

The stability conditions of the closed-loop system are equivalent to find the control gains h_j such that the derivative of a quadratic candidate function of Lyapunov is negative. Stabilize the model is therefore to solve the following problem: Finding a positive definite matrix P and matrices h_i, with $i=1,..,M$, such that:

$$(A_z - B_z F_z)^T P + P(A_z - B_z F_z) < 0 \tag{13}$$

Note that inequality is nonlinear (P and h_i).
Using the matching property with the symmetric matrix of full rank (14), we get expression (15).

$$X = P^{-1} \tag{14}$$

$$XA_z^T + A_z X - XF_z^T B_z^T - B_z F_z X) < 0 \tag{15}$$

By making the change of variables bijective:

$$M_i = F_i X \quad for \quad i = 1, \ldots, M. \tag{16}$$

The problem becomes (LMI) in the variables X and M_i.

$$\gamma_{ij} = XA_i^T + A_i X - M_j^T B_i^T - B_i M_j) < 0 \tag{17}$$

So we end up with the quantities:

$$\sum_{i=1}^{M} \sum_{j=1}^{M} \mu_i(z(t)) \mu_j(z(t)) \gamma_{ij} \tag{18}$$

Results can then be deducted. Subsequently, it's stated:

$$E(x(t)) = \begin{pmatrix} A(x(t)) & B(x(t)) \\ C(x(t)) & D(x(t)) \end{pmatrix} \tag{19}$$

Assuming that $E(x(t))$ is continuous and bounded, *Lemma 1* allows to limit each non-constant term of the matrix $E(x(t))$ and turn as follows:

$$E(x(t)) = \sum_{i=1}^{n} \mu_i(x(t)) E_i \tag{20}$$

$$\text{With :} \quad E_i = \begin{pmatrix} A_i & B_i \\ C_i & D_i \end{pmatrix} \tag{21}$$

The global structure of the multiple model is presented by fig.1.

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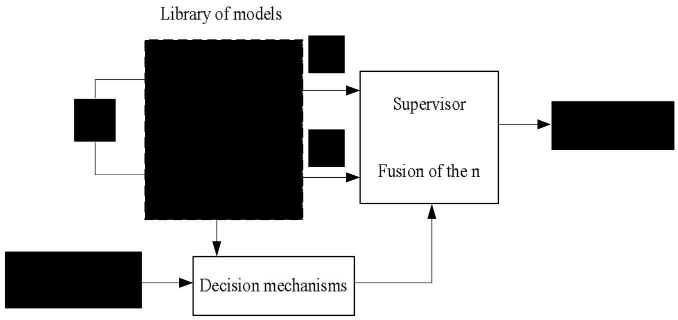

Figure 1. Global Structure of a multiple model [7]

4. Multi-physical Model Of The Linear Pm Synchronous Actuator

The studied actuator is a pm tubular linear synchronous one (PMTLSA). It is required to a high precision and heavy loads as a rack steering system.

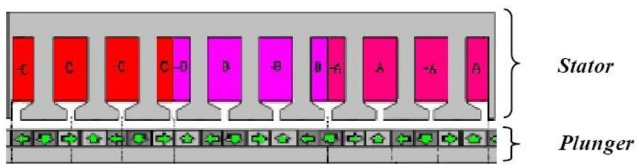

Figure 2. Half cross section of a PMTLSA structure

The multi-physical model of this actuator is built using a finite element method taking into account the magnetic saturation and the end effects. This saturation can have two origins: either a too high current in a phase or a powerful magnet too close to a magnetic structure.

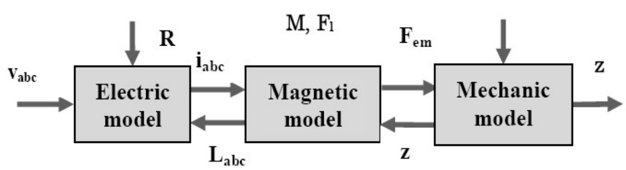

Figure 3. Synoptic diagram of the actuator model coupling

The electrical model of the actuator is expressed for three phases *j (a, b, c)* and is given by the expression (22):

$$v_j = R_s\, i_j + \left[L_s + \frac{\partial L_s}{\partial i_j} i_j\right]\frac{\partial i_j}{\partial t} + \left[\frac{\partial \psi_{pmj}}{\partial z} + \frac{\partial L_s}{\partial z} i_j\right]\frac{\partial z}{\partial t} \qquad (22)$$

The dynamic behavior of this linear actuator is expressed as:

$$M\frac{d^2 z}{dt^2} + f_v \frac{dz}{dt} = F_{em} - f_s sign(\frac{dz}{dt}) - F_{ch} \qquad (23)$$

$$F_{em} = \sum_{k=a,b,c} \frac{u_{fem_k} i_k}{v}\Big|_{i_k=cte} = \sum_{k=a,b,c} f_k(z).i_{k=cte} \qquad (24)$$

with: $u_{fem3} = -v.N_p\hat{\phi}_{fm}\begin{cases}\sin(N_p z)\\ \sin(N_p z+\frac{2\pi}{3})\\ \sin(N_p z+\frac{4\pi}{3})\end{cases}$ (25)

5. POLY-TOPIC TRANSFORMATION OF THE COUPLING FUNCTIONS

The Finite Element results of the coupling functions are stored on 2D look-up tables and represented as surface responses according to current densities and plunger positions and taking into account the magnetic saturation effects [3].

Comparing the evolution of these functions depend of the position of the magnets before the corresponding phase. The mutual inductances are neglected saw its low amplitude relative to self-inductances.

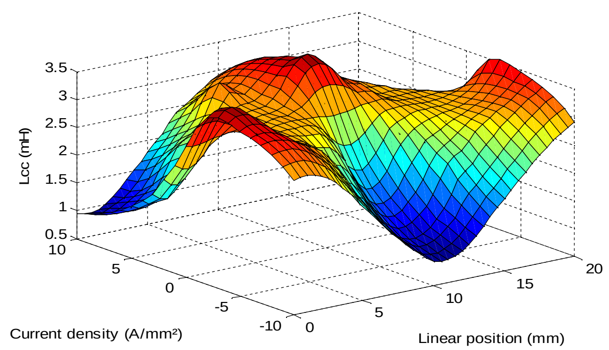

Figure 4. FE results of the self-inductance L_{cc}

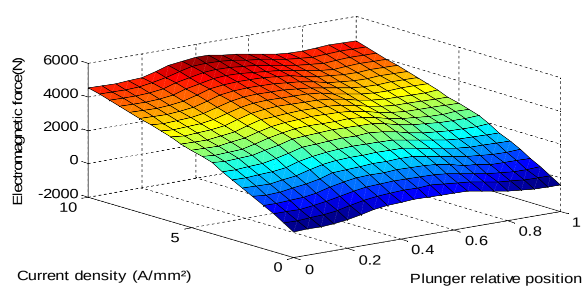

Figure 5. FE results of the electromagnetic force F_{em}

The evolution analysis of the coupling functions like the self-inductances L_s (fig.4) and the electromechanical force F_{em} (fig.5) shows that a mathematical interpolation is possible for different current density intervals.

a. Interpolation functions of the self-inductances

Following a detailed modeling of the stator inductances, a mathematical interpolation is carried out to achieve an analytical model of the self-inductances.

The self-inductances *[Ls]* form a three-degree's square matrix. It contains constant terms grouped in $[L_{S0}]$ and variable terms that are grouped in $[L_{S2}]$.

$$[L_s]=[L_{S0}]+[L_{S2}(z,i)] \qquad (26)$$

$$[L_s] = \begin{pmatrix} L_a \\ L_b \\ L_c \end{pmatrix} = L_o + \begin{bmatrix} L_{ma}(J_a) \\ L_{mb}(J_b) \\ L_{mc}(J_c) \end{bmatrix}$$

$$with \begin{bmatrix} L_{ma}(J_a) \\ L_{mb}(J_b) \\ L_{mc}(J_c) \end{bmatrix} = L_m \begin{pmatrix} J_a \sin(N_p z) \\ J_b \sin(N_p z + \frac{2\tau_p}{3}) \\ J_c \sin(N_p z + \frac{4\tau_p}{3}) \end{pmatrix} \text{ and } L_m = \begin{cases} 0.14 & if \ J \in [0;6] A/mm^2 \\ 0.12 & if \ J \in [6;8] A/mm^2 \\ 0.1 & if \ J \in [8;10] A/mm^2 \end{cases} \quad (27)$$

The term L_o is constant and represent average value of these inductors. The terms $L_{am}(J_a)$, $L_{bm}(J_b), L_{cm}(J_c)$ represent the magnetizing part of these inductances. They are proportional to the current density J of the corresponding phase *(a,b,c).* There are non-linear and symmetric functions according to the current phase.

b. Interpolation function of the thrust force

To analyze the thrust force characteristic, a mathematical interpolation is applied for the three sub-defined templates interval [10].

$$F_{em} = K_f J \qquad with \ K_f = \begin{cases} 675 & if \ J \in [0;6] A/mm^2 \\ 587 & if \ J \in [6;8] A/mm^2 \\ 500 & if \ J \in [8;10] A/mm^2 \end{cases} \quad (28)$$

A second solution is to determine a polynomial model of the 3rd order of force. In this case, it is considered that the force varies as a function of the current density and that the force undulations due to the magnets position are neglected [10].

$$F_{em}(kN) = -0.0245 J^3 - 0.02 J^2 - 1.351 J - 0.0719 \quad (29)$$

The interpolated functions of the coupling functions are represented using their analytical expressions. So, the best method to obtain the multiple models of the coupling functions is the convex polytypic transformation up this statement by *Lemma 1*.

c. Multiple Models of the self-inductances

Taking the case of the inductance *[Ls]* expressed by the model (29). Considering μ_1, μ_2 *and* μ_3 as three weighting functions of the system and expressed by (30).

$$\begin{cases} \mu_1 = \frac{1-d_1}{2} \\ \mu_2 = \frac{d_1-d_2}{2} \\ \mu_3 = \frac{1+d_2}{2} \qquad with \ d_i \cong \tanh(J-a_i) \ ; a_i \in \{6,8\} \end{cases} \quad (30)$$

Three local models are obtained:

$$if \ J_a \in [0,6[\ => \begin{cases} L_{a1} = L_0 + 0.14.J_a.\sin(N_p.z) \\ \mu_1 = \frac{1}{2}[1-\tanh(J_a-6)] \end{cases}$$

$$if\ \ J_a \in [6,8[\ => \begin{cases} L_{a2} = L_0 + 0.12.J_a.\sin(N_p.z) \\ \mu_2 = \frac{1}{2}[\tanh(J_a - 6) - \tanh(J_a - 8)] \end{cases}$$

$$if\ \ J_a \in [8,10] => \begin{cases} L_{a3} = L_0 + 0.1.J_a.\sin(N_p.z) \\ \mu_3 = \frac{1}{2}[1 + \tanh(J_a - 8)] \end{cases} \quad (31)$$

The overall inductance multiple models L_a is obtained as follows:

$$L_a = \sum_{i=1}^{3} \mu_i L_{ai} \quad (32)$$

By applying the multiple model approach to L_b and L_c inductors, the following results are obtained:

$$L_b = \sum_{i=1}^{3} \mu_i L_{bi} \qquad and \quad L_c = \sum_{i=1}^{3} \mu_i L_{ci} \quad (33)$$

d. Electromagnetic force Multiple Models

The multiple model approach is applied to the expression (28) of the electromagnetic force, according to the poly-topic transformation method. It gives the following results:

$$\text{If } J \in [0,6[\ => \begin{cases} F_{em1} = 675.J \\ \mu_1 = (\frac{1 - \tanh(J-6)}{2}) \end{cases}$$

$$\text{If } J \in [6,8[\ => \begin{cases} F_{em2} = 587.J \\ \mu_2 = (\frac{\tanh(J-6) - \tanh(J-8)}{2}) \end{cases}$$

$$\text{If } J \in [8,10[\ => \begin{cases} F_{em3} = 500.J \\ \mu_3 = (\frac{1 + \tanh(J-8)}{2}) \end{cases} \quad (34)$$

With μ_1, μ_2 and μ_3 corresponding weighting functions.

The global model of force is the following:

$$F_{em} = \sum_{i=1}^{3} \mu_i F_{emi} \quad (35)$$

The simulation results of the obtained multiple models of the coupling functions expressed by equations (32), (33) and (35) are presented by figures 6 to 9, over one pole pitch and for different current densities.

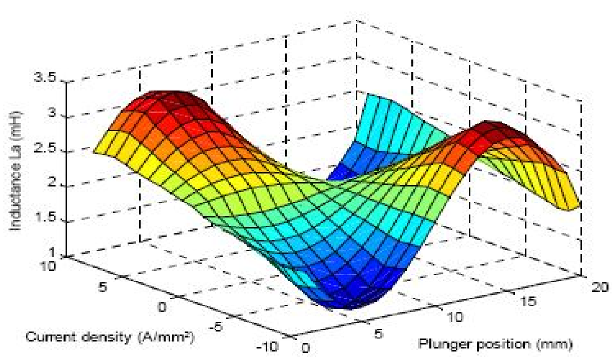

Figure 6: Self-inductance L_a

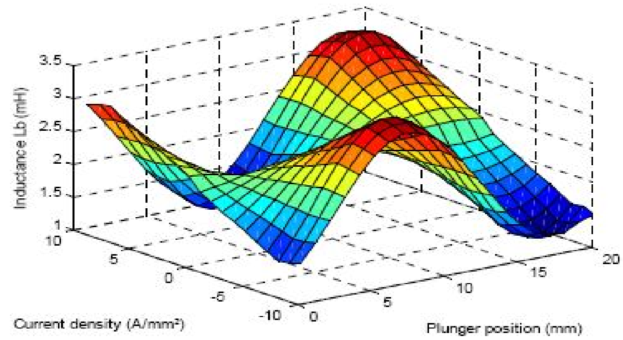

Figure 7: Self-inductance L_b

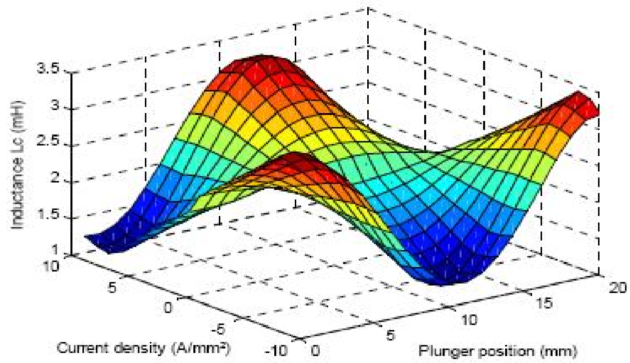

Figure 8: Self-inductance Lc

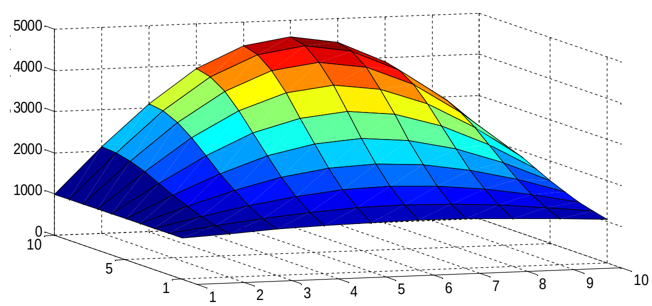

Figure 9: Electromagnetic force response area *Fem(J, z)*

The comparison between the 3D finite element results (fig. 4 and 5) and the multiple models using the poly-topic transformation method (fig. 6, 7, 8 and 9), prove the performance of this analysis. The global structure of a multi-model presented by fig.1 is applied to restructure the multi-physical model of the studied actuator and to resolve his dynamic behavior.

6. CONCLUSION

In this paper, a multiple model approach is applied, firstly, to analyze the finite element results of the electromagnetic and electro-mechanical coupling functions of a linear pm synchronous actuator, then, to synthesis multiple sub-models that conserves all the nonlinearities under saturation conditions.

The multiple model approach is a structure particularly well suited to nonlinear modeling systems over a wide operating range. It provides an analytical model that can accurately capture the complexity of the system and can provide the same performances as the finite element model of the pm synchronous actuator.

The obtained results are useful for a dynamic modeling of the actuator. They can avoid the singularity points and can reduce the simulation time.

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