Design an Exact Linearization Controller for Permanent Stimulation Synchronous Linear Motor Polysolenoid

Quang H. Nguyen[1] , Nam P. Dao[2], Hung M. Nguyen[3] , Hien N. Nguyen[4] , Ty T. Nguyen[5], Chi P. Nguyen[6]
[1,4,6] Thai Nguyen University of Technology
[2,3,5] Hanoi University of Science and Technology

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Abstract

Nowadays, linear motions are almost indirectly realized by rotational motors, which cause several inherent weaknesses such as mechanical complication due to intermediate modules, low accuracy and performance because of accumulating errors of all elements in the systems. Using motors able to create directly linear movements is capable of removing the above limitations. This paper presents a control solution for Polysolenoid permanent-stimulation linear motors according to the exact linearization that enable physical outputs to follow reference inputs. All of currents are mobilized to make the propulsion force of the linear motors even when there is lack of the model's parameters or under effects of disturbances. The platform of the above control solution depends on the model of objects and the extract linearization. Simulation results plotted by MATLAB – Simulink re-emphasize performance of the proposed control structure.

Keywords: *Exact linearization, Polysolenoid linear motors, SVM, direct channel separation, two-phase inverter*

Nomenclature

Symbol	Unit	Meaning
L_{sd}, L_{sq}	H	d-axis and q-axis inductance
m	Kg	mass of the primary part
$\underline{u}_s$, $\underline{i}_s$	V, A	voltage and current vector
R_s	Ω	stator resistance
v , v_e	m/s	Mechanical and electrical speed
F_m, F_c	N	repulsion force, resisting force
i_{sd}, i_{sq}	A	d-axis and q-axis current
u_{sd}, u_{sq}	V	d-axis and q-axis voltage
τ	Mm	Pole pitch
p		number of pole
ψ_p	Wb	pole flux
w_e, θ	Rad/s; Rad	Electric angular velocity and position
x_p	Mm	Motor position

Abbreviation

PMSLM	Permanent-Magnetic Synchronous Linear Motor
SVM	Space Vector Modulation

I. INTRODUCTION

Polysolenoid linear motor operates according to induction phenomenon with principles as shown in [1-4].

For the drive system of linear motors, although intermediate mechanical elements have been eliminated, the system is unstable and sensitive to friction, end effect, load changes, non-sinusoidal flux distribution and so on, which affects control quality. There have been several topics in order to tackle these problems. [5] has proposed a speed controller according to self-tuning PI and estimation algorithms at low speed in order to achieve sufficient performance in this operating range. However, a variation of load such as mass will lead friction force and other resisting forces to changing. Consequently, the PI controller loses its efficiency so a model-tracking adaptive control method associated with Lyapunov has been applied in [6]. In addition, the back-stepping measure has been undertaken to address effects of friction and a Lugrie friction model-estimating controller has been demonstrated in [7]. However, friction is a factor depending on work conditions (temperature, pressure and so on); therefore, friction-estimating models remain some differences when being applied in reality. An application of the adaptive neuron network will tackle this problem as shown in [8]. This method allows controller's parameters to be tuned according to assumptions and adaptive laws in order to guarantee convergence of outputs. Adaptive fuzzy has been introduced to minimize friction drawbacks in [9]. It is shown that these above controllers require robust microprocessors because of its enormous number of calculations. Sliding controllers enabling outputs to track reference inputs rapidly have been applied to control linear motors [10]. Notwithstanding, the method as shown in [10] has to deal with difficulty in determining sliding surface and fluctuation phenomena around sliding orbit. [11] has proposed a solution to address the variation problem with upgraded sliding mode controllers. Additionally, end effect will be executed as shown in [12]. Another means of fluctuation cancellation is to use H_∞ controllers [13].

Permanent stimulation motor Polysolenoid in Figure 1 is constructed according to electromagnetic induction. When windings are supplied, two-phase alternative currents in two windings will form a current vector in a horizontal plane. Its q-axis term will interact with the flux ψ_p of the permanent magnet. The interaction generates thrust forces in primary windings of Polysolenoid motor. According to the structure of linear motors, the proposed control system is required to isolate force and flux generators. Nonlinear control in associated with a cascade architecture and exact linearization would be a suitable solution for the above requirements.

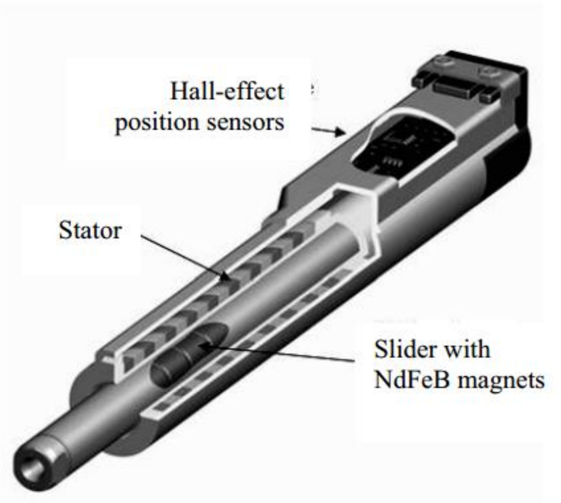


Figure 1. Polysolenoid motor

II. ACCURATE LINEARIZATION METHOD

Given a non-linear MIMO described as follows:

$$\begin{cases} \dot{\underline{x}} = \underline{f}\ \underline{x} + H\ \underline{x}\ \underline{u} = \underline{f}\ \underline{x} + \sum_{i=1}^{m} \underline{h}_i\ \underline{x}\, u_i \\ \underline{y} = \underline{g}\ \underline{x} \end{cases} \quad (1)$$

where:

$$\underline{x} = \ x_1,\dots,x_n\ ^T, \underline{g}\ \underline{x}\ = \left[g_1\ \underline{x}\ ,\dots,g_m\ \underline{x}\right]^T$$

$$\underline{u} = \ u_1,\dots,u_m\ ^T, H\ \underline{x}\ =\ \underline{h}_1\ \underline{x}\ ,\underline{h}_2\ \underline{x}\ ,\dots,\underline{h}_m\ \underline{x}$$

If the above system in (1) has a minimum relative order vector $r_1, r_2, \dots, r_m$ satisfies:

$$r = r_1 + \dots + r_m = n \quad (2)$$

The system can be accurately linearized into a linear system.

$$\begin{cases} \dot{\underline{z}} = A\underline{z} + B\underline{w} \\ \underline{y} = C\underline{z} \end{cases} \quad (3)$$

via coordinate system transformation:

$$\underline{z} = \underline{m}\ \underline{x} \quad (4)$$

Exact linearization is applied to determine the structure and coefficents of the following state feedback controller as follows:

$$\begin{aligned} \underline{u} &= -L^{-1}\ \underline{x}\ \underline{p}\ \underline{x}\ + L^{-1}\ \underline{x}\ \underline{w} \\ &= \underline{a}\ \underline{x}\ + L^{-1}\ \underline{x}\ \underline{w} \end{aligned} \quad (5)$$

The controller turns the nonlinear close loop system into linear in the new state space as shown in figure 2 with

$$\underline{p}\ \underline{x}\ = \left[L_f^{r_1} g_1\ \underline{x}\ \ \dots\ \ L_f^{r_m} g_1\ \underline{x}\right]^T \quad (6)$$

$$L\ \underline{x}\ = \begin{bmatrix} L_{h_1} L_f^{r_1-1} g_1(\underline{x}) & \dots & L_{h_m} L_f^{r_1-1} g_1\ x \\ \vdots & \ddots & \vdots \\ L_{h_1} L_f^{r_m-1} g_m(\underline{x}) & \dots & L_{h_m} L_f^{r_m-1} g_m(\underline{x}) \end{bmatrix} \quad (7)$$

where: $L_f g\ \underline{x}\ = \partial g / \partial \underline{x}\ \underline{f}\ \underline{x}$ (8)

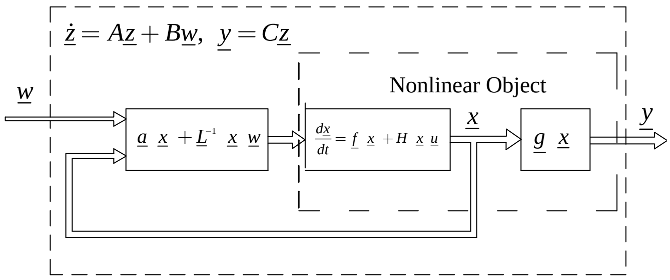


Figure 2. Structure of nonlinear object after linearization (state transformation)

After exact linearization of the nonlinear object in (1), the close loop linear system is capable of being separated into m channels. Therefore, the controller can be called as a direct channel-separating controller.

According to electric equivalent relationship, the object could be expressed in the following equations:

$$w_e = \frac{2\pi}{\tau} v \quad (9)$$

$$\underline{u}_s^s = R_s \underline{i}_s^s + \frac{d\underline{\psi}_s^s}{dt} \quad (10)$$

$$F = \frac{2p\pi}{\tau}\left(\psi_p + \left(L_{sd} - L_{sq}\right) i_{sd}\right) i_{sq} \quad (11)$$

$$F_m - F_c = \frac{m}{p}\frac{dv_e}{dt} \quad (12)$$

The model of the permanent-stimulation linear synchronous motor consists of non-linear characteristics as follows:

$$\begin{cases} \dfrac{di_{sd}}{dt} = -\dfrac{1}{T_{sd}} i_{sd} + \dfrac{2\pi}{\tau}\dfrac{L_{sq}}{L_{sd}} v i_{sq} + \dfrac{1}{L_{sd}} u_{sd} \\ \dfrac{di_{sq}}{dt} = -\dfrac{2\pi}{\tau} v \dfrac{L_{sd}}{L_{sq}} i_{sd} - \dfrac{i_{sq}}{T_{sq}} + \dfrac{u_{sq}}{L_{sq}} - \dfrac{2\pi}{\tau} v \dfrac{\psi_p}{L_{sq}} \\ \dfrac{dx_p}{dt} = v \end{cases} \quad (13)$$

where $x = \begin{bmatrix} i_{sd} & i_{sq} & x_p \end{bmatrix}^T$ is a state variable and $u = \begin{bmatrix} u_{sd} & u_{sq} & v \end{bmatrix}^T$ is a control signal.

Implementation of exact linearization of equations (13) according to criteria (1-4) results in a state feedback controller as shown in (14). Unit of w1 and w2 is [A/s] and that of w3 is [m/s]. Consequently, a new model able to be divided into 3 separate channels via state feedback structure has been designed (Figure 3).

$$\begin{bmatrix} u_1 \\ u_2 \\ u_3 \end{bmatrix} = \begin{bmatrix} \dfrac{L_{sd}}{T_{sd}} x_1 \\ \dfrac{L_{sq}}{T_{sq}} x_2 \\ 0 \end{bmatrix} + \begin{pmatrix} L_{sd} & 0 & -\dfrac{2\pi}{\tau} L_{sq} x_2 \\ 0 & L_{sq} & \dfrac{2\pi}{\tau} L_{sd} x_1 + \psi_p \\ 0 & 0 & 1 \end{pmatrix} \begin{bmatrix} w_1 \\ w_2 \\ w_3 \end{bmatrix} \quad (14)$$

Substitue (14) for (13) then we have:

$$\begin{cases} \dfrac{dx_1}{dt} = w_1 \\ \dfrac{dx_2}{dt} = w_2 \\ \dfrac{dx_3}{dt} = w_3 \end{cases} \quad (15)$$

The MIMO system has become the channel-separated system (15). It is thanks to this separation that control design becomes simpler. There are several methods to make state variable x track desired values. Feedforward and error compensation can be designed by a PI or sliding controller. In this study, a simple controller has been designed according to Lyapunov theory.

Current loop control:

(15) can be re-written as follows:

$$\begin{cases} \dfrac{di_{sd}}{dt} = w_1 \\ \dfrac{di_{sq}}{dt} = w_2 \end{cases} \quad (16)$$

The above system needs to guarantee that vector $\underline{i}_s$ is vertical to the flux of the magnetic pole. Therefore, magnetizing current i_{sd} equals zero and only thrust force generator i_{sq} differs from zero. Then, an outer loop for the speed control is necessary but that for flux can be ignored.

For i_{sd} is set to be zero, the following control rule has been selected to make i_{sd} converge to 0 :

$$w_1 = -k_3 i_{sd} \quad (17)$$

In order that i_{sq} follows the reference input i_{sq}^r, control rules have been chosen as follows:

$$w_2 = \frac{di_{sq}^r}{dt} - k_4\left(i_{sq} - i_{sq}^r\right) \quad (18)$$

From (17) and (18), we have:

$$\begin{cases} \dfrac{di_{sd}}{dt} + k_3 i_{sd} = 0 \\ \dfrac{d}{dt}\left(i_{sq} - i_{sq}^r\right) + k_4\left(i_{sq} - i_{sq}^r\right) = 0 \end{cases} \quad (19)$$

where k_3, k_4 are positive constants so the system in (19) is stable. Then we have $i_{sd} \to 0$ và $i_{sq} \to i_{sq}^r$.

In the direct channel-separating control structure in Figure 3, SVM element could work as 1/1 transfer function with the meaning: output values repeat the input ones in terms of moudle, frequency and phase. Hence, it is acceptable that this element could not be considered in the synthesis of the system. Notwithstanding, in a simulation system, this part should be integrated into the model as shown in [13-14] so that the model matchs the real system.

Position control loop:

The system model is shown as follows:

$$\begin{cases} \dfrac{dv}{dt} = \dfrac{p}{m}\left(F - F_c\right) \\ F = \dfrac{2\pi}{\tau}\left[\psi_p i_{sq} + \left(L_{sd} - L_{sq}\right) i_{sd} i_{sq}\right] \\ \dfrac{dx}{dt} = v \end{cases} \quad (20)$$

There are inner and outer control loops in which the former aims at making v follow v_c and the latter controls x to track x_r. Control laws could be written as follows:

$$\begin{cases} v_c = \dot{x}_r - k_1\left(x - x_r\right) \\ i_{sq}^r = \dfrac{\hat{F}_c + \dfrac{m}{p}\dot{v}_c - k_2\left(v - v_c\right)}{\dfrac{2\pi}{\tau}\left[\psi_p + \left(L_{sd} - L_{sq}\right) i_{sd}\right]} \end{cases} \quad (21)$$

where $\hat{F}_c$ is estimated by the load estimator as shown in (21)

$$\hat{F}_c = \frac{2\pi}{\tau}\left[\psi_p i_{sq} + \left(L_{sd} - L_{sq}\right) i_{sd} i_{sq}\right] - \frac{m}{p}\dot{v} \quad (21)$$

Consider $\hat{F}_c \approx F_c$ and combine (21) and the model in (20) then we have:

$$\begin{cases} \frac{d}{dt}(x-x_r)+k_1(x-x_r)=0 \\ \frac{d}{dt}(v-v_c)+k_2(v-v_c)=0 \end{cases} \quad (22)$$

where k_1, k_2 are selected to be positive constants so the system in (22) is stable; therefore, we have $v \to v_c$ and $x \to x_r$.

Consequently, proposed controllers stablize the system; therefore, position x approaches the reference one x_r.

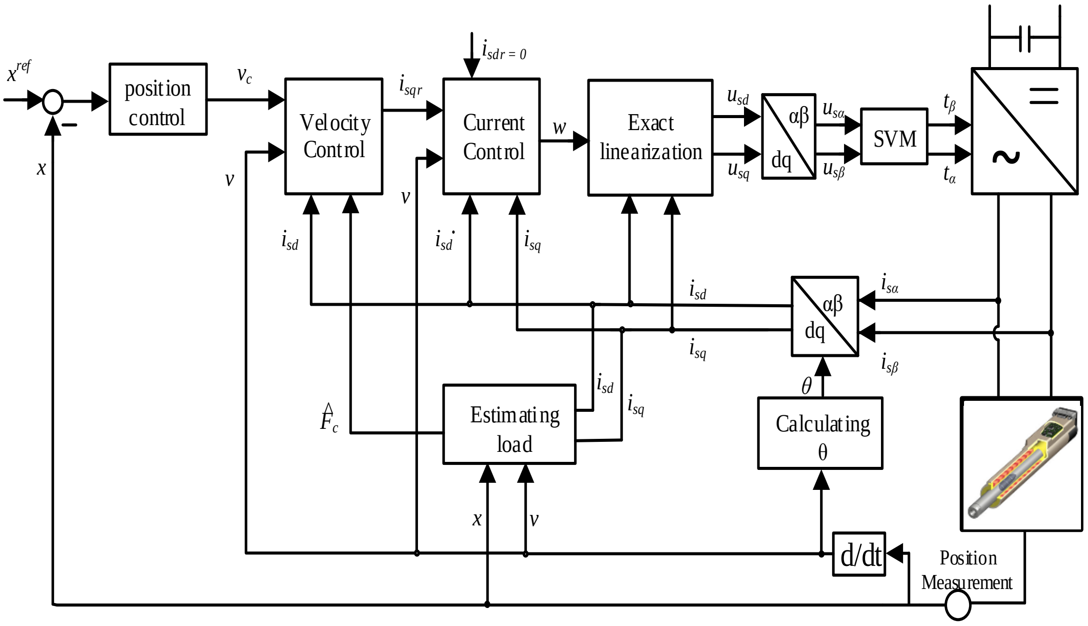


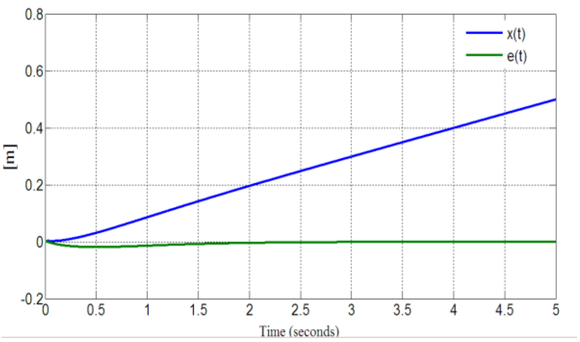
Figure 3. Permanent stimulation linear motor control structure using exact linearization

III. SIMULATION RESULTS

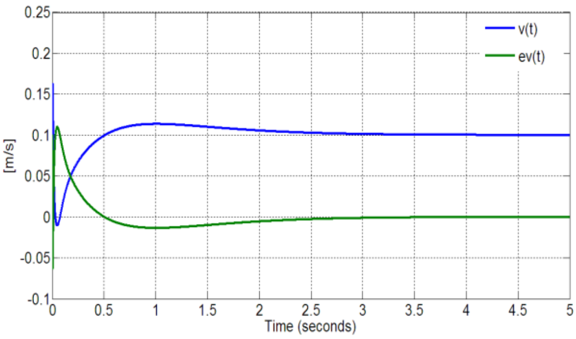
The entire system as shown in Figure 3 has been simulated in MATLAB/ Simulink. The simulation model is reasonable in comparison with reality. Indeed, the electric circuit (inverter) is designed by PowerSim (a toolbox integrated in Simulink). The software is able to describe electric and electronic circuits in principle diagrams in which elements are wired visually.

Parameters of the motor is the same as LinMot motor P01_48x240/390x540_C:

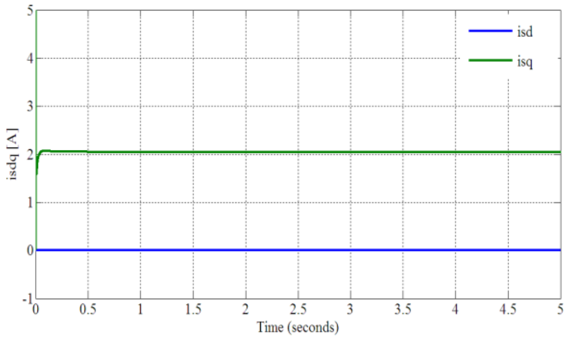
- Number of pole: 4
- Polar step: 60 *mm*
- Rotor mass: 1.5 *Kg*
- Phase coil resistor: 3.1 Ω
- d-axis inductor: 2.182 *mH*
- q-axis inductor: 2.182 *mH*
- Flux: 9.31*Wb*



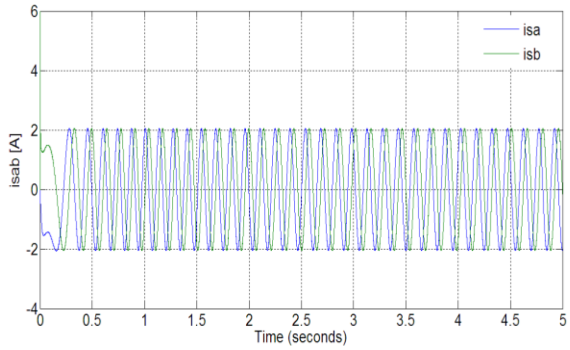
a. Trajectory and trajectory error



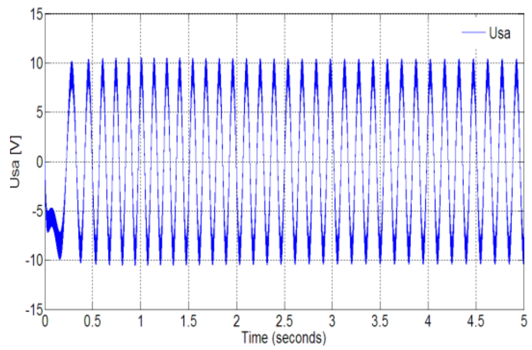
b. Velocity and velocity error



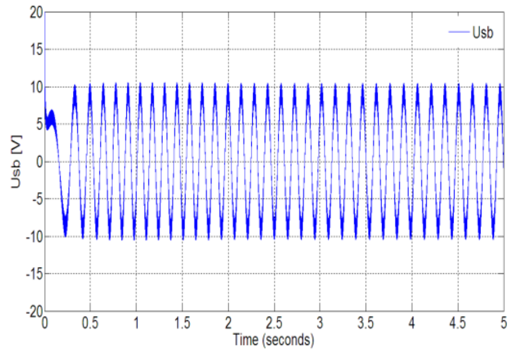
c. i_{sd} and i_{sq}



d. Stator current

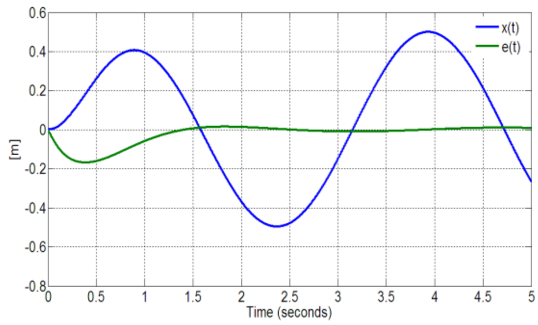


e. Voltage u_{sa}

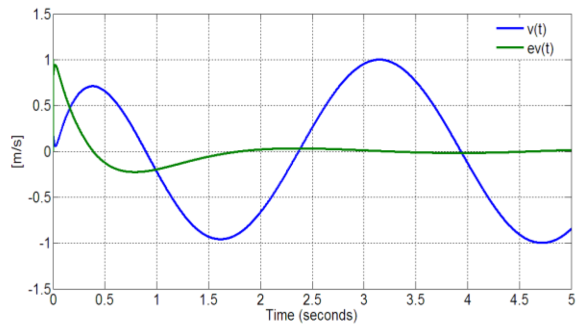


f. Voltage u_{sb}

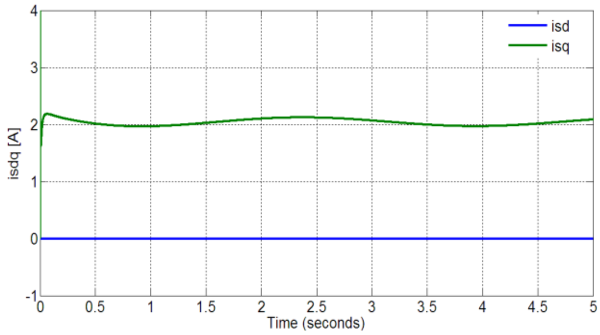
Figure 4. Simulation results with linear target trajectory $x(t) = 0.1t$



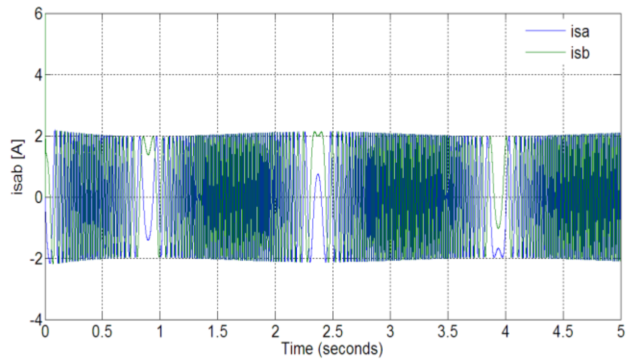
a. Trajectory and trajectory error



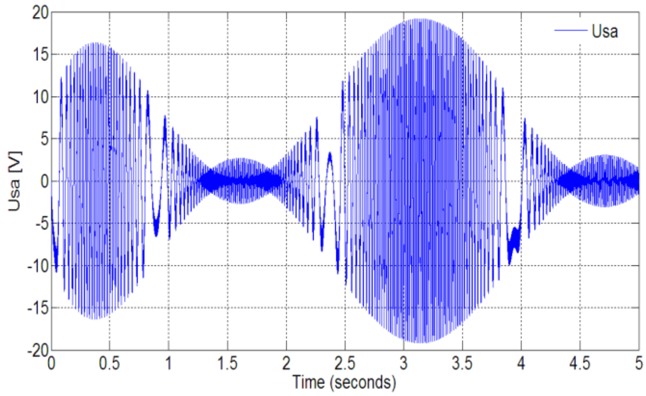
b. Velocity and velocity error



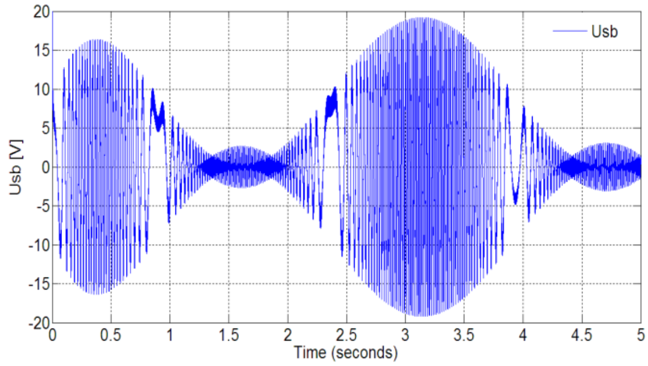
c. i_{sd} and i_{sq}



d. Stator current



e. Voltage u_{sa}



f. Voltage u_{sb}

Figure 5. Simulation results with sinusoidal target trajectory $x(t)=0.5\sin(2t)$

Responses of position, velocity and output voltage control have proved workability of the proposed system. With the constant motion *x(t)=0.1t* or sinusoidal trajectory *x(t)=0.5sin(2t),* performances in Figure 4 and 5 have shown the controllers' quality. Position and velocity of the motor approaches the reference inputs rapidly even immediately. Phase a and b voltages fluctuate with a phase difference of 90^0. It is thanks to the controller that the motor performs its efficiency when i_{sd} comes to zero quickly. The entire current vector $\underline{i}_s$ is applied to generate rotating forces for the motor.

IV. CONCLUSIONS

Simulation results have shown that the direct channel-separating controller is suitable for the permanent stimulation synchronous motor. Additionally, controllers in the structure including current controller R_{isd}, R_{isq} and speed controller are able to discrete and easy to be embedded to microprocessors. Moreover, the implementation of SVM algorithm and exact linearization controller using microprocessors is feasible because simple algebraic calculations are required.

In future, authors intend to undertake the control system using microprocessors to acquire a complete experimental system to verify the proposed algorithm's efficiency.

V. ACKOWLEDGMENTS

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