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Robust control technique in power converter with linear induction motor

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ABSTRACT

Induction motors are widely used in industrial applications as actuators, thanks to their simplicity of construction, which is subsequently reflected in low-cost maintenance. This paper shows the behavior of a three-phase power converter with a linear induction motor (LIM) as load, using a quasi-sliding control technique for output voltage regulation and a new control technique to control chaos. Digital pulse width modulation (DPWM) techniques are widely used to control electronic power converters. The controller proposed in this paper was designed using zero average dynamic (ZAD) and fixed point inducting control (FPIC) techniques. The ZAD-FPIC control strategy was designed and applied to a three-phase converter with linear induction motor load. Since it is not possible to measure the secondary currents, a secondary current observer was included in the system. Finally, bifurcation diagrams are shown as a technique for tuning controller parameters in ZAD-FPIC controllers. For the illustration of numerical results a simulation of the linear induction motor drive controlled was made by MATLAB/Simulink. The designs were tested in a rapid control prototyping (RCP) system based on digital signal processing (DSP) for dSPACE platform, using the 1103 controller card and control desk interface.

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1. INTRODUCTION

Essentially there are two types of asynchronous motors: the rotary induction motor (RIM) and linear induction motor (LIM). These are widely used in industrial applications as actuators, thanks to their simplicity of construction, which is subsequently reflected in low-cost maintenance [1], [2]. When the topological characteristics of an asynchronous motor, as in the case of developing the LIM from a rotating electrical machine, its operating conditions and design criteria differ, as has been presented in previous publications [3]–[7].

This paper shows the behavior of a three-phase power converter with a LIM motor as load, using a quasi-sliding control technique for output voltage regulation and a new control technique to control chaos. The controller was designed using the following techniques: zero average dynamic (ZAD) and fixed point inducting control (FPIC) [8]–[17]. The designs were tested in a rapid control prototyping (RCP) system based on digital signal processing (DSP) for dSPACE platform.

Power converters have special interest since it is estimated that 90% of the electrical energy is processed by these devices before end use [18] and additionally this interest has been increased thanks to the use of removable energy sources [19], [20], using power electronics for the efficient transformation and rational use of electricity from generation sources to industrial and commercial use. Power converters must provide a certain output voltage level, either in regulating or tracking tasks, and be able to accept load changes and variations in the primary supply voltage level. Mohan *et al*. [21], [22] present a complete and detailed analysis on the operation and configuration of different power converters. By using switching devices that generate a desired output with low power consumption, it is possible to obtain one of the most desirable qualities of power converters and that is efficiency in performance.

On the other hand, the digital pulse-width modulation technique (DPWM) is widely used to control electronic power converters [23], [24], thanks to advantages such as: low power consumption, immunity to variations of analog components, potentially faster design process, lower sensitivity to parameter variations, programmability, reduction or elimination of external passive components, calibration or protection algorithms, ability to interface with digital systems, possibility to implement nonlinear control techniques, and advanced control algorithms, such as parameter estimation, are much easier to implement, as mentioned in [25]–[27].

2. RESEARCH METHOD

2.1. Proposed system

The proposed controller designed in this paper combines the strategies of zero averaging dynamics (ZAD) and fixed point induction controller (FPIC), presented in [8]–[15]. The design corresponds to the load of a linear induction motor with three-phase low power inverter (1500 W) which uses a dSPACE platform. The system is divided into hardware and software. In software, the control and signal acquisition techniques were implemented. The hardware is composed of a three-phase converter with a linear induction motor LIM motor as load with a rated power of 1500 W, rated voltage of 600 VDC and rated current of 20 ADC. To obtain the measurements of v_c a series resistor was used and for the measurement of i_L the current sensor HX10P/SP2 was used. The converter switches were driven by PWM outputs of the controller card, these signals are coupled via fast optocouplers (6N137). The controllers were implemented in simulink and downloaded to a DPS.

2.2. Mathematical model

The system implemented for the switched-mode power converter and the linear induction motor LIM coupled system that takes into account the end effects [4], is shown in the Figure 1. To perform a time domain analysis of such a system, it is usually assumed that magnetic saturation, hysteresis and eddy current effects are negligible, yielding in (1) that is the state space model, detailed in (2).

$$\dot{x} = \mathrm{A}(x)\mathrm{x} + \mathrm{BU} + \mathrm{D} \tag{1}$$

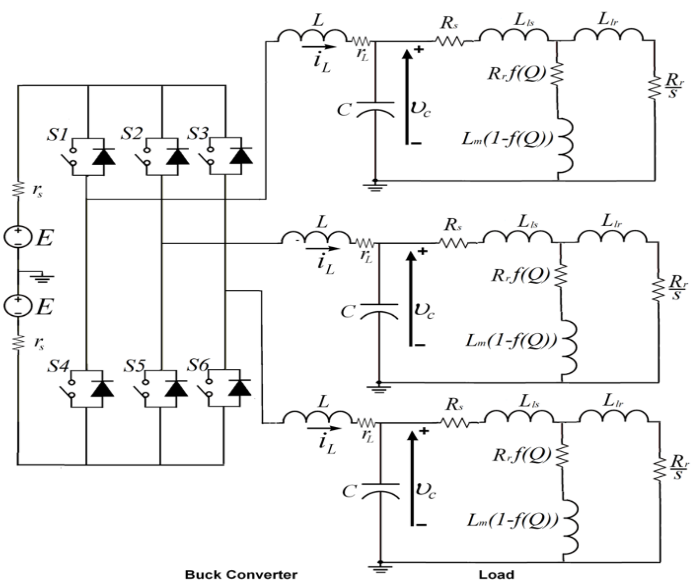


Figure 1. Electric circuit for the converter-motor system

$$\begin{bmatrix} i_{L_a} \\ \dot{v}_{c_a} \\ i_{s_a} \\ i_{r_a} \\ i_{L_b} \\ \dot{v}_{c_b} \\ i_{s_b} \\ i_{r_b} \\ i_{L_c} \\ \dot{v}_{c_c} \\ i_{s_c} \\ i_{r_c} \\ \dot{v}_m \end{bmatrix} = \begin{bmatrix} a_{11_a} & a_{12_a} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ a_{21_a} & 0 & a_{23_a} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & a_{32_a} & a_{33_a} & a_{34_a} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & a_{42_a} & a_{43_a} & a_{44_a} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & a_{11_b} & a_{12_b} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & a_{21_b} & 0 & a_{23_b} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & a_{32_b} & a_{33_b} & a_{34_b} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & a_{42_b} & a_{43_b} & a_{44_b} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & a_{11_c} & a_{12_c} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & a_{21_c} & 0 & a_{23_c} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & a_{32_c} & a_{33_c} & a_{34_c} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & a_{42_c} & a_{43_c} & a_{44_c} & 0 \\ 0 & 0 & 0 & a_{51} & 0 & 0 & 0 & a_{52} & 0 & 0 & 0 & a_{53} & -\frac{B}{M} \end{bmatrix} \begin{bmatrix} i_{L_a} \\ v_{c_a} \\ i_{s_a} \\ i_{r_a} \\ i_{L_b} \\ v_{c_b} \\ i_{s_b} \\ i_{r_b} \\ i_{L_c} \\ v_{c_c} \\ i_{s_c} \\ i_{r_c} \\ v_m \end{bmatrix} + \begin{bmatrix} \frac{E}{L_a} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & \frac{E}{L_b} & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \frac{E}{L_c} \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} S_1 - S_4 \\ S_2 - S_5 \\ S_3 - S_6 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ -\frac{F_L}{M} \end{bmatrix} \quad (2)$$

The system is made up of 3 subsystems where each phase can be treated independently. The model per phase, considering $F_L = 0$ (in 1), can be seen in the (3),

$$\begin{bmatrix} i_L \\ \dot{v}_c \\ i_s \\ i_r \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & 0 & 0 \\ a_{21} & 0 & a_{23} & 0 \\ 0 & a_{32} & a_{33} & a_{34} \\ 0 & a_{42} & a_{43} & a_{44} \end{bmatrix} \begin{bmatrix} i_L \\ v_c \\ i_s \\ i_r \end{bmatrix} + \begin{bmatrix} \frac{E}{L} \\ 0 \\ 0 \\ 0 \end{bmatrix} U_c \quad (3)$$

with $U_c = -1,1$ according to switch control.
Where:

$$a_{11} = -\frac{r_s + r_L}{L}$$

$$a_{12} = -\frac{1}{L}$$

$$a_{21} = \frac{1}{C}$$

$$a_{23} = -\frac{1}{C}$$

$$a_{32} = \frac{L_m(1 - f(Q)) + L_{lr}}{L_{ls}L_m(1 - f(Q)) + L_{lr}L_m(1 - f(Q)) + L_{lr}L_{ls}}$$

$$a_{33} = -\frac{R_s(L_m(1 - f(Q)) + L_{lr}) + R_r f(Q) L_{lr}}{L_{ls}L_m(1 - f(Q)) + L_{lr}L_m(1 - f(Q)) + L_{lr}L_{ls}}$$

$$a_{34} = -\frac{R_r L_m(1 - f(Q)) + sL_{lr}R_r f(Q)}{s(L_{ls}L_m(1 - f(Q)) + L_{lr}L_m(1 - f(Q)) + L_{lr}L_{ls})}$$

$$a_{42} = \frac{L_m(1 - f(Q))}{L_{ls}L_m(1 - f(Q)) + L_{lr}L_m(1 - f(Q)) + L_{lr}L_{ls}}$$

$$a_{43} = -\frac{R_s L_m(1 - f(Q)) + R_r f(Q) L_{ls}}{L_{ls}L_m(1 - f(Q)) + L_{lr}L_m(1 - f(Q)) + L_{lr}L_{ls}}$$

$$a_{44} = -\frac{R_r\big(L_m(1-f(Q)) + L_{ls} + sf(Q)L_{ls}\big)}{s\big(L_{ls}L_m(1-f(Q)) + L_{lr}L_m(1-f(Q)) + L_{lr}L_{ls}\big)}$$

$$\text{s} = (v_s - v_m)/v_s,$$

s is the motor slip, v_m is the mover speed and v_s is the synchronous speed. The mechanical equation is given by (4).

$$\dot{v_m} = \frac{i_{r_a}^2 R_{r_a}}{Msv_s} + \frac{i_{r_b}^2 R_{r_b}}{Msv_s} + \frac{i_{r_c}^2 R_{r_c}}{Msw_s} - \frac{B}{M} v_m - \frac{F_L}{M} \quad (4)$$

Then:

$$a_{51} = \frac{i_{r_a} R_{r_a}}{Msv_s}$$
$$a_{52} = \frac{i_{r_b} R_{r_b}}{Msv_s}$$
$$a_{53} = \frac{i_{r_c} R_{r_c}}{Msw_s}$$

2.3. ZAD-FPIC control strategy

The ZAD-FPIC control strategy was applied by equivalent phase circuit for the linear induction motor LIM. In the case of a three-phase system, the control must be applied independently in each phase, taking into account that the reference voltage will be shifted according to the phase of the corresponding circuit. Since the mechanical dynamics is very slow compared to the electrical dynamics, the motor speed is considered constant in each sample period.

In order to apply the linear induction motor and fixed point inducting control ZAD-FPIC control strategy, it was necessary to obtain the secondary current in the equivalent circuit of each phase, which is the current through L_{lr} in Figure 1. The original secondary current equation can be used directly as the observer equation. The implementation of such a current observer is the on-line simulation of a controlled linear induction motor. This observer is stable with the convergence rate depending on the secondary time constant, in this case the dynamic observer equation is given by (5).

$$\begin{aligned}\frac{d\hat{\imath}_r}{dt} = {} & \frac{L_m(1-f(Q))}{L_{ls}L_m(1-f(Q))+L_{lr}L_m(1-f(Q))+L_{lr}L_{ls}} v_c \\ & - \frac{R_s L_m(1-f(Q))+R_r f(Q)L_{ls}}{L_{ls}L_m(1-f(Q))+L_{lr}L_m(1-f(Q))+L_{lr}L_{ls}} i_s \\ & - \frac{R_r\big(L_m(1-f(Q))+L_{ls}+sf(Q)L_{ls}\big)}{s\big(L_{ls}L_m(1-f(Q))+L_{lr}L_m(1-f(Q))+L_{lr}L_{ls}\big)} \hat{\imath}_r\end{aligned} \quad (5)$$

Where $s = (v_s - v_m)/v_s$ and $\hat{\imath_r}$ is the estimate of the per phase secondary current and the error is calculated as $\tilde{\imath_r} = \hat{\imath_r} - i_r$, obtaining the following error dynamic:

$$\frac{d\tilde{\imath_r}}{dt} = -\frac{R_r\big(L_m(1-f(Q))+L_{ls}+sf(Q)L_{ls}\big)}{s\big(L_{ls}L_m(1-f(Q))+L_{lr}L_m(1-f(Q))+L_{lr}L_{ls}\big)} \tilde{\imath_r} \quad (6)$$

A Lyapunov function is selected as:

$$V = \frac{1}{2}\tilde{\imath_r}^2 > 0$$

And calculate the time derivative of V along the solution of (6) to yield,

$$\dot{V} = -\frac{R_r\big(L_m(1-f(Q))+L_{ls}+sf(Q)L_{ls}\big)}{s\big(L_{ls}L_m(1-f(Q))+L_{lr}L_m(1-f(Q))+L_{lr}L_{ls}\big)} \tilde{\imath_r}^2 < 0 \quad (7)$$

This means that if we simply integrate in (5), the mismatch between the real and estimated secondary current tends to zero asymptotically. The rate of convergence may be improved if properly designed observer gain is introduced.

3. RESULTS AND DISCUSSIONS

Figure 2 shows the simulation results of the secondary currents observer (5). To show the convergence process, select as initial conditions the observed currents $i_{\widehat{r_a}} = \widehat{i_{r_b}} = \widehat{i_{r_c}} = 3A$, and the real secondary currents $i_{r_a} = i_{r_b} = i_{r_c} = 0A$. Since the observer is just on-line simulation of the linear induction motor LIM model, no observer gain is to be adjusted. The controlled linear induction motor LIM behavior with observed secondary currents was very close to behavior of controlled system feeding with the real secondary currents in numerical simulation. For the illustration of numerical results, a simulation of the linear induction motor drive controlled by zero average dynamic and fixed point inducting control ZAD–FPIC control strategies was made. The motor model used in simulation was the per phase equivalent circuit as shown in Figure 3.

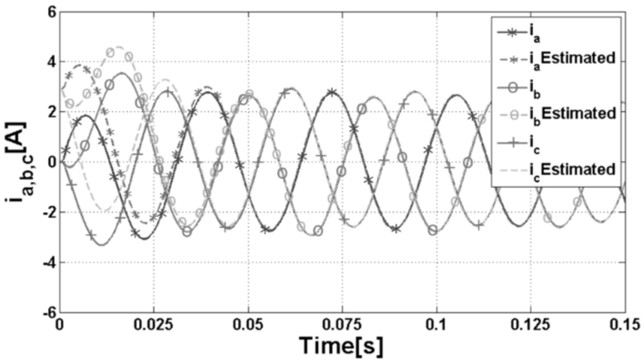


Figure 2. Response of the secondary current observer

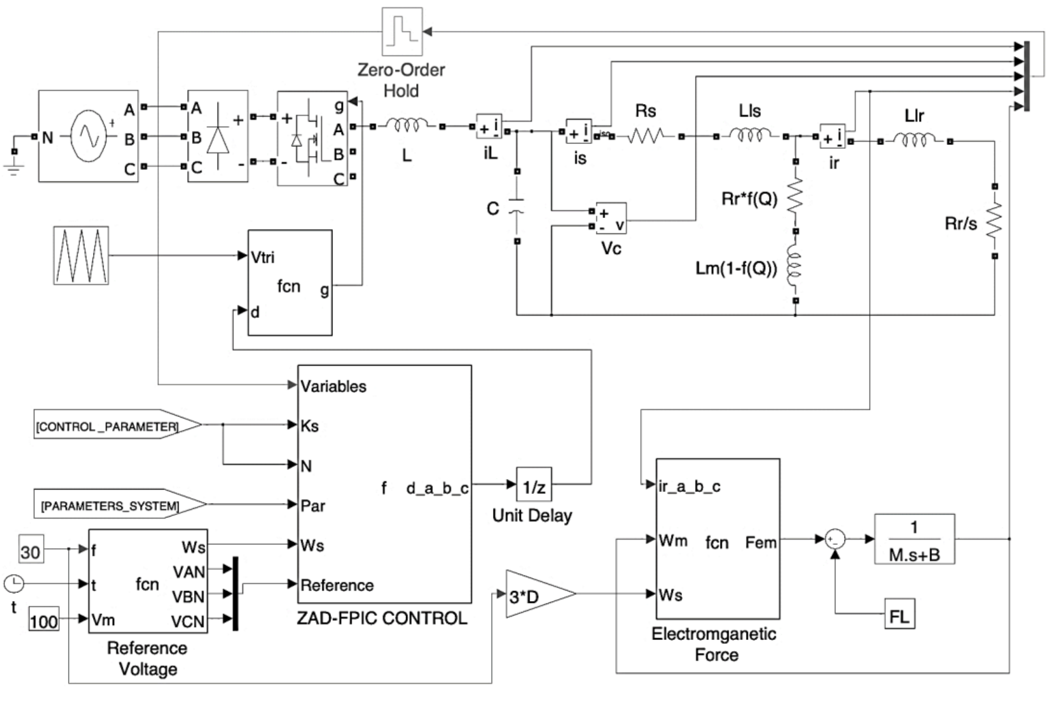
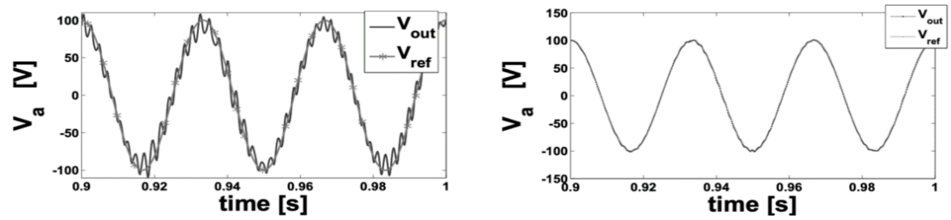


Figure 3. Equivalent circuit model per-phase for simulation

Figure 4 (a) shows the time behavior when the bifurcation parameter K_s is 0.25. The controlled voltage has chaotic behavior and has quite difference respect to the reference voltage for phase a. In Figure 4 (b) the tracking error of controlled voltage respect to the reference voltage is more low, in this case the K_s value is 0.5. Phase portrait for i_a and v_a variables shows a one-periodic solution for $K_s = 0.5$. When $K_s = 0.25$ the qualitative behavior is quite different as shown in Figure 5.



(a) (b)

Figure 4. Time behavior for voltage motor (controlled voltage) of phase a for (a) time behavior with K_S=0.25 and (b) time behavior with K_S=0.5

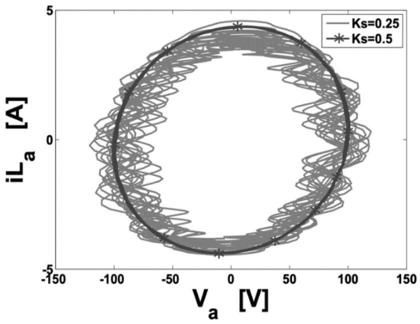
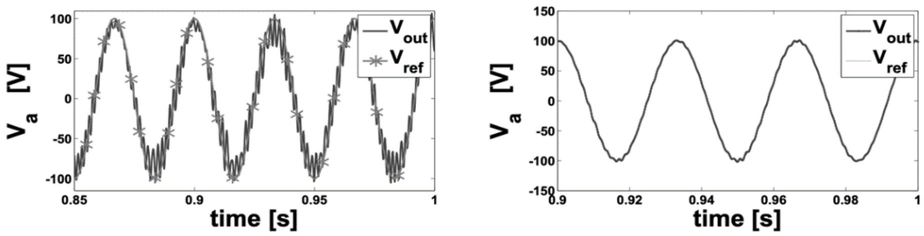


Figure 5. Phase portrait for i_a and $v_a$variables

Figure 6 (a) shows the time behavior when the bifurcation parameter N is 0.1. The controlled voltage has chaotic behavior and has quite difference respect to the reference voltage for phase a. In Figure 6 (b) the tracking error of controlled voltage respect to the reference voltage is more low, in this case the N value is 3.0. Phase portrait for i_a and v_a variables shows a one-periodic solution for $K_s = 0.5$. When $K_s = 0.25$ the qualitative behaviour is quite different as shown in Figure 7.



(a) (b)

Figure 6. Time behavior for voltage motor (controlled voltage) of phase a for (a) time behavior with *N*= 0.1 and (b) time behavior with *N*= 3.0

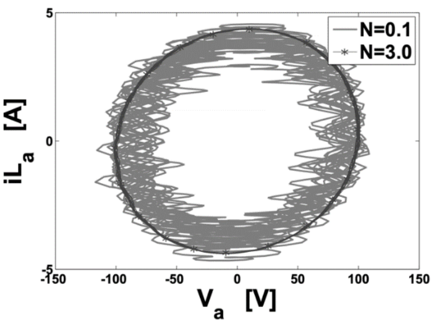


Figure 7. Phase portrait for i_a and v_a variables

4. CONCLUSION

The control strategy zero average dynamic and fixed point inducting control ZAD-FPIC was designed and applied to three phasic converter with linear induction motor load. Because is not possible to measure the secondary currents, a secondary current observer was included in the system. For this system, simulations were performed. The stability of the closed loop system was analyzed using bifurcation diagrams, and stable and transitions to chaos were observed. Due to limitation in the mover path (1.5 meters), experiments with the control system were not made. Finally, were shown the bifurcation diagrams like a technique for to adjust controller parameters in ZAD and fixed point inducting control ZAD–FPIC controllers.

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