**FPGA-Realization of a High-Performance Controller for PMLSM Drive**

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**Abstract**—This study presents a high-performance position controller for permanent magnet linear synchronous motor (PMLSM) drives based on FPGA (Field Programmable Gate Array) technology. Firstly, a mathematic modeled for PMLSM drive is defined. Secondly, to increase the performance of the PMLSM drive system, an AFC (Adaptive Fuzzy Controller) constructed by a fuzzy basis function and a parameter adjustable mechanism is derived and applied to the position control loop of PMLSM drive system to cope with the effect of the system dynamic uncertainty and external load. Thirdly, an FSM (Finite State Machine) joined by a multiplier, an adder, a LUT (Look-up table), some comparators and registers is presented to model the overall AFC, and VHDL is adopted to describe the circuit of FSM. After that, an FPGA is used to implement the overall control algorithm for PMLSM drive. Finally, an experimental system is established to verify the effectiveness of the proposed high-performance control system and some experimental results are confirmed theoretically.

I. INTRODUCTION

The advantages of superior power density, high-performance motion control with fast speed and better accuracy, are such that permanent magnet linear synchronous motors (PMLSM) are being increasingly used in many automation control fields as actuators [1-3], including computer-controlled machining tools, X-Y driving devices, robots, semiconductor manufacturing equipment, etc. However, the PMLSM does not use conventional gears or ball screws, so the external load disturbance in the drive system greatly affects positioning performance [4]. To cope with this problem, many intelligent control techniques [5-7], such as fuzzy control, neural networks control and adaptive fuzzy control have been developed and applied to the position control of PMLSM drive to obtain high operating performance. However, the execution of a neural network or adaptive fuzzy control requires many computations, so the implementing these highly complex control algorithms depend on the PC systems in most studies [4-5]. In recent years, the fixed-point Digital Signal Processor (DSP) and Field Programmable Gate Array (FPGA) also provide a possible solution in this issue [8-9]. Comparing with FPGA, although the intelligent control technique using DSP provides a flexible skill, it suffers from a long period of development and exhausts many resources of the CPU [10]. Nowadays, the FPGA has brought more attention before. The advantages of the FPGA includes their programmable hard-wired feature, fast time-to-market, shorter design cycle, embedding processor, low power consumption and higher density for the implementation of the digital system. FPGA provides a compromise between the special-purpose ASIC (application specified integrated circuit) hardware and general-purpose processors [11]. Recently, Li, T.S. [12] utilized an FPGA to implement autonomous fuzzy behavior control on mobile robot. Lin, F.J. [13] presented a fuzzy sliding-mode control for a linear induction motor drive based on FPGA. But, due to the fuzzy inference mechanism module in [13] adopts parallel processing circuits, it consumes much more FPGA resources; therefore limited fuzzy rules are used in their proposed method. To solve this problem, a FSM [14-15] joined by a multiplier, an adder, a LUT (Look-up table), some comparators and registers are proposed in this paper to model the AFC algorithm of PMLSM drive system. Then VHDL is adopted to describe the circuit of FSM. Due to FSM belongs to the sequential processing method; the FPGA resources usage can be greatly reduced. The FPGA chip employed herein is an Altera Stratix II EP2S60F672C5 [16] with 48,352 ALUTs, maximum 492 user I/O pins, 36 DSP blocks, 2,544,192 bits of RAM, and a Nios II embedded processor. Finally, an experimental system including an FPGA experimental board, an inverter and a PMSM, is set up to verify the correctness and effectiveness of the proposed method.

II. SYSTEM DESCRIPTION OF PMLSM DRIVE AND CONTROLLER DESIGN

The internal architecture of the proposed FPGA-based controller system for the PMLSM drive is shown in Fig. 1. The AFC in the position loop, P controller in the speed loop and the current vector control scheme for PMLSM are all realized in one FPGA.

A. Mathematical modeling of PMLSM drive

The dynamic model of a typical PMLSM can be described as follows

\[
\frac{d}{dt} i_d = -\frac{R}{L_d} i_d + \frac{\pi}{\tau} \frac{L_a}{L_d} \dot{x}_q i_q + \frac{1}{L_d} v_d \tag{1}
\]

\[
\frac{d}{dt} i_q = -\frac{\pi}{\tau} L_q \ddot{x}_q i_d - \frac{R}{L_q} i_q + \frac{\pi}{\tau} \frac{\rho}{L_q} \dot{x}_p + \frac{1}{L_q} v_q \tag{2}
\]

where \(v_d, v_q\) are the d and q axis voltages; \(i_d, i_q\) are the d and q axis currents, \(R\) is the phase winding resistance; \(L_d, L_q\) are the d and q axis inductance; \(\dot{x}_p\) is the translator speed; \(\lambda_f\) is the permanent magnet flux linkage; \(\tau\) is the pole pitch. The developed electromagnetic thrust force is given by [3].
The current control of a PMLSM drive is based on a vector control approach. That is, if we control \( i_d \) to 0 in Fig. 1, the PMLSM will be decoupled, so that control a PMLSM will become easy as to control a DC linear motor. After simplification and considering the mechanical load, the model of a PMLSM can be written as the following equations,

\[
F_e = \frac{3\pi}{2}\lambda_j i_y \Delta K_i i_q \tag{3}
\]

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\[
F_e = \frac{3\pi}{2}\lambda_j i_y \Delta K_i i_q \tag{4}
\]

with

\[
K_i = \frac{3\pi}{2}\lambda_j \tag{5}
\]

and the mechanical dynamic equation of PMLSM is

\[
F_e - F_L = M_a \frac{d^2x_r}{dt^2} + B_a \frac{dx_r}{dt} \tag{6}
\]

where \( F_e \) is the motor thrust force, \( K_i \) is force constant, \( M_a \) is the total mass of the moving element, \( B_a \) is viscous friction coefficient and \( F_L \) is the external force.

### B. Adaptive fuzzy controller (AFC) in position control loop

The dash-dot rectangular area in Fig. 1 presents the architecture of an AFC for PMLSM drive. It consists of a fuzzy controller, a reference model and a parameter adjusting mechanism. Detailed description of these is as follows.

1. **Fuzzy controller (FC):**

   In Fig. 1, the tracking error and the change of the error, \( e, \Delta e \) are defined as

   \[
e(k) = x_m(k) - x_r(k) \tag{7}
\]

   \[
\Delta e(k) = e(k) - e(k-1) \tag{8}
\]

   and \( e, \Delta e \) and \( u_f \) are input and output variables of FC, respectively.

   **FPGA-based position control IC**

### The design procedure of the FC is as follows:

(a) Take \( e, \Delta e \) as the input variables of FC, and define their linguistic variables as \( E \) and \( \Delta E \). The linguistic value of \( E \) and \( \Delta E \) are \{\( A_0, A_1, A_2, A_3, A_4, A_5, A_6 \)\} and \{\( B_0, B_1, B_2, B_3, B_4, B_5, B_6 \)\}, respectively. Each linguistic value of \( E \) and \( \Delta E \) is based on the symmetrical triangular membership function which is shown in Fig. 2. The symmetrical triangular membership function are determined uniquely by three real numbers \( \xi_1 \leq \xi_2 \leq \xi_3 \), if one fixes \( f(\xi_1) = f(\xi_3) = 0 \) and \( f(\xi_2) = 1 \). With respect to the universe of discourse of \([-6,6]\], the numbers for these linguistic values are selected as follows:

\[
A_0 = B_0; [-6, -6, -4], A_1 = B_1; [-6, -4, -2], A_2 = B_2; [-4, -2, 0], A_3 = B_3; [-2, 0, 2], A_4 = B_4; [0, 2, 4], A_5 = B_5; [2, 4, 6], A_6 = B_6; [4, 6, 6] \tag{9}
\]

(b) Compute the membership degree of \( e \) and \( \Delta e \). Figure 2(a) shows that the only two linguistic values are excited (resulting in a non-zero membership) in any input value, and the membership degree \( \mu_{A_i}(e) \) can be derived from Fig. 2(b), in which the error \( e \) is located between \( e_i \) and \( e_{i+1} \), two linguistic values of \( A_i \) and \( A_{i+1} \) are excited, and the membership degree is obtained by

\[
\mu_{A_i}(e) = \frac{e_{i+1} - e}{2} \tag{10}
\]

where \( e_{i+1} = \Delta - 6 + 2*(i+1) \). Similar results can be obtained in computing the membership degree \( \mu_{B_j}(\Delta e) \).

(c) Select the initial fuzzy control rules by referring to the dynamic response characteristics [17], such as,

\[
\text{IF} \ e \ \text{is} \ A_i \ \text{and} \ \Delta e \ \text{is} \ B_j \ \text{THEN} \ u_f \ \text{is} \ c_{ij} \tag{11}
\]

where \( i \) and \( j \) are 0~6, \( A_i \) and \( B_j \) are fuzzy number, and \( c_{ij} \) is real number. The graph of fuzzification and fuzzy rule table is shown in Fig. 3.

![Fig. 1 The architecture of the FPGA-based position control IC for PMLSM drive system](image)
is a back-shift 1 (23)

and the difference equation is written as.

\[
x_m(k) = -b_1x_m(k-1) - b_2x_m(k-2) + a_0x_p^*(k) + a_1x_p^*(k-1) + a_2x_p^*(k-2)
\]

(3) Parameter adjusting mechanism:

The gradient descent method is used to derive the AFC control law in Fig. 1. The adjusting of fuzzy controller parameters is to minimize the square error between the mover position and the output of the RM. The instantaneous cost function is defined by

\[
\lambda(k+1) = \frac{1}{2}e(k+1)^2 - \frac{1}{2}e(k)^2
\]

and the parameters of \( c_{mn} \) are adjusted according to

\[
\Delta c_{mn}(k+1) = \frac{\partial J(k+1)}{\partial c_{mn}(k)} = -\alpha \frac{\partial J(k+1)}{\partial e_{mn}(k)}
\]

with \( m = j, j+1, n = i, i+1 \) and where \( \alpha \) represents learning rate.

The formulations for the adjustment of the fuzzy controller in the fuzzy controller are derived, at initially, assume \( F_k \) to be zero in (6), and take Laplace transformation of (4) and (6). Then, the bilinear transformation is used to derive the digital transfer function of PMLSM drive system.

\[
x_p(k) = \frac{\phi z^{-1}}{(1 - \phi z^{-1})(1 - z^{-1})}
\]

where \( \phi = \exp(-B_mT/J_m) \). The \( z^{-1} \) is a back-shift operator and \( T \) is the sampling period. Additionally, in Fig. 1, the current command, \( i'_q \) is formulated by the output of fuzzy controller, \( u_f \),

\[
i'_q(k) = K_p(u_i(k-1) + (K_p + K_i \mu_f(k) - x_p(k)) + x_p(k-1))
\]

and where \( K_p, K_i \) are the PI controller gains, \( u_i \) is the output of the I controller in the position loop and \( K_p \) is the P controller gain in the speed loop. From (18) and (19),

\[
x_p(k) = (\Phi + 1 - \Psi K_p)x_p(k-1) - (1 - \Psi K_i)x_p(k-2) + \Psi K_m \mu_f(k-2) + \Psi K_c \mu_f(k-1) + K_p \mu_f(k-1)
\]

The chain rule is used and the partial differential equation for \( J(k+1) \) in (16) can be written as

\[
\frac{\partial J(k+1)}{\partial e_{mn}(k)} = -e'(k+1) \frac{\partial e'(k+1)}{\partial x_p(k)} \frac{\partial x_p(k)}{\partial \mu_f(k)} \frac{\partial \mu_f(k)}{\partial \mu_f(k)} \frac{\partial \mu_f(k)}{\partial \mu_f(k)} \frac{\partial \mu_f(k)}{\partial \mu_f(k)}
\]

From (12) and (20), we can get

\[
\frac{\partial \mu_f(k+1)}{\partial \mu_f(k)} = d_{mn}
\]

and

\[
\frac{\partial \mu_f(k+1)}{\partial \mu_f(k)} = (K_p + K_i)K_p
\]
Therefore, (21) is substituted into (17), and then the parameters \( c_{m,n} \) of fuzzy controller described by (12) can be adjusted using the following expression.

\[
\Delta c_{m,n}(k) = \alpha (K_p + K_i)\Psi K_r e(k) d_{n,m} \tag{24}
\]

with \( m = j, j+1 \) and \( n = i,i+1 \). Because the motor parameter \( \Psi \) is not easily to determined, so the \( \text{sign}(\Psi) \) is used in (24). It is unity because \( \Psi \) is positive. The \( \text{sign}() \) represents the sign operator.

III. POSITION CONTROL IC DESIGN FOR PMLSM DRIVE

Figure 4 illustrates the internal architecture of the proposed FPGA implementation of the AFC and the current vector controller for PMLSM drive system. The FPGA chip adopted herein is Altera Stratix II EP2S60F672C5 with 48,352 ALUTs, maximum 492 user I/O pins, 36 DSP blocks, 2,544,192 bits of RAM. The Nios II embedded processor has a 32-bit configurable CPU core. The internal circuit in Fig.4 comprises a Nios II embedded processor IP (Intelligent Properties) and a position control IP. The Nios II processor is depicted to generate the position command, collect the response data and the communication with external device. The position control IP includes mainly a position AFC circuit and a circuit for current vector controller. The sampling frequency of position control loop is designed with 2kHz. The position controller are all realized by hardware in an FPGA.

The overall experimental system depicted in Fig.1 includes an FPGA (Stratix II EP2S60F672C5), a voltage source IGBT inverter and a PMLSM. The PMLSM was manufactured by the BALDOR electric company; and it is a single-axis stage with a cog-free linear motor and a stroke length with 600mm. The parameters of the motor are: \( R_s = 27 \Omega, L_s = L_q = 23.3 \) mH, \( K_t = 79.9N/A \). The input voltage, continuous current, peak current (10% duty) and continuous power of the PMLSM are 220V, 1.6A, 4.8A and 54W, respectively. The maximum speed and acceleration are 4m/s and 4 g but depend on external load. The moving mass is 2.5Kg, the maximum payload is 22.5Kg and the maximum thrust force is 73N under continuos operating conditions. A linear encoder with a resolution of 5μm is mounted on the PMLSM as the position sensor, and the pole pitch is 30.5mm (about 6100 pulses). The inverter has three sets of IGBT power transistors. The collector-emitter voltage of the IGBT is rated 600V; the gate-emitter voltage is rated ±20V, and the DC collector current is rated 25A and in short time (1ms) is 50A. The photo-IC, Toshiba TLP250, is used in the gate driving circuit of IGBT. Input signals of the inverter are PWM signals from the FPGA device.

For implementation, the control sampling frequency of the current and position loops are designed as 16kHz and 2kHz, respectively. In the proposed adaptive position control IC, the current controller, speed controller and the adaptive fuzzy position controller are all realized by hardware in an FPGA. The fuzzy controller is first used in position loop, and the parameter adjustment of the fuzzy controller is based on the gradient descent method. The transfer function of the reference model in Fig.1 is chosen by a second order system with the natural frequency of 40 rad/s and damping ratio of 1; therefore, the output response of the reference model will have the characteristics of no overshoot, 0.2sec rising time and zero steady-state. After applying the bilinear transformation with sampling frequency of 2 kHz, the parameters of the difference equation in (15) are obtained by \( a_0=0.000098, a_1=0.000196, a_2=0.000098, b_1=-1.960396, b_2=0.960788 \).

IV. EXPERIMENTAL SYSTEM AND RESULTS

The overall experimental system depicted in Fig.1 includes an FPGA (Stratix II EP2S60F672C5), a voltage source IGBT inverter and a PMLSM. The PMLSM was manufactured by the BALDOR electric company; and it is a single-axis stage with a cog-free linear motor and a stroke length with 600mm. The parameters of the motor are: \( R_s = 27 \Omega, L_s = L_q = 23.3 \) mH, \( K_t = 79.9N/A \). The input voltage, continuous current, peak current (10% duty) and continuous power of the PMLSM are 220V, 1.6A, 4.8A and 54W, respectively. The maximum speed and acceleration are 4m/s and 4 g but depend on external load. The moving mass is 2.5Kg, the maximum payload is 22.5Kg and the maximum thrust force is 73N under continuos operating conditions. A linear encoder with a resolution of 5μm is mounted on the PMLSM as the position sensor, and the pole pitch is 30.5mm (about 6100 pulses). The inverter has three sets of IGBT power transistors. The collector-emitter voltage of the IGBT is rated 600V; the gate-emitter voltage is rated ±20V, and the DC collector current is rated 25A and in short time (1ms) is 50A. The photo-IC, Toshiba TLP250, is used in the gate driving circuit of IGBT. Input signals of the inverter are PWM signals from the FPGA device.

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To evaluate the dynamic performance of PMLSM drive while applying the AFC in Fig. 1, the step response is firstly to test. While the position command is a 4/3Hz square wave signal with amplitude be 10mm and the FC is only used in the position loop in Fig. 1, the step responses of mover under external load of 11Kg is shown in Fig. 6. Although the position loop in Fig. 1, the step responses of mover under signal with amplitude be 10mm and the FC is only used in the test. While the position command is a 4/3Hz square wave while applying the AFC in Fig. 1, the step response is firstly to exhibit an overshoot and oscillation phenomenon in Fig. 6. Accordingly, the AFC is selected by human experience in the case of only FC (learning rate=0), the step responses still exhibit an overshoot and oscillation phenomenon in Fig. 6. Accordingly, the AFC is adopted in Fig.1 to solve this problem. When the proposed AFC is used with learning rate being 0.1, its tracking results are highly improved and presented in Fig. 7. After tracking one or two square wave commands, the mover of PMLSM can closely follow the output of the reference model. Secondly, the frequency response is considered to evaluate the performance of the proposed controller. A tested input signal of the sinusoid wave with 10mm amplitude and frequency variation from initial 2 Hz to final 6 Hz is provided. In this design, the frequency tracking response and the tracking error of the PMLSM without and with adaptation are shown in Fig. 8 and Fig.9. Figure 9 reveals that the position tracking error, using the AFC (learning rate=0.1) is only 0.35~0.7 times of that obtained by using only the FC in Fig.8. Therefore, the experimental results in Figs. 6 to 9 demonstrate that the proposed FPGA-based AFC for PMLSM drive is effective and robust.

V. CONCLUSIONS

A high-performance AFC for PMLSM drive based on FPGA technology is successfully demonstrated in this paper. The contributions herein are summarized as follows.

1. An FSM joined by one multiplier, one adder, one LUT, some comparators and registers has been employed to model the overall AFC algorithm for PMLSM, such that it not only is easily implemented by VHDL but also can reduce the FPGA resources usage.

2. The use of AFC in the position control of PMLSM drive has been demonstrated good performance in uncertain environments by some experimental results.
Fig. 7 (a) Position and (b) current, response of step position command using the AFC under 11 Kg external load.

Fig. 8 Frequency response of a 2Hz to 6Hz sinusoid input signal using the FC under 11 kg external load.

Fig. 9 Frequency response of a 2Hz to 6Hz sinusoid input signal using the AFC under 11 kg external load.

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