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Research Article

Full-order Luenberger observer based on fuzzy-logic control for sensorless field-oriented control of a single-sided linear induction motor

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ABSTRACT

This paper investigates sensorless indirect field oriented control (IFOC) of SLIM with full-order Luenberger observer. The dynamic equations of SLIM are first elaborated to draw full-order Luenberger observer with some simplifying assumption. The observer gain matrix is derived from conventional procedure so that observer poles are proportional to SLIM poles to ensure the stability of system for wide range of linear speed. The operation of observer is significantly impressed by adaptive scheme. A fuzzy logic control (FLC) is proposed as adaptive scheme to estimate linear speed using speed tuning signal. The parameters of FLC are tuned using an off-line method through chaotic optimization algorithm (COA). The performance of the proposed observer is verified by both numerical simulation and real-time hardware-in-the-loop (HIL) implementation. Moreover, a detailed comparative study among proposed and other speed observers is obtained under different operation conditions.

1. Introduction

Single-sided linear induction motor (SLIM) provides linear motion without any mechanical interface. Compared with conventional method to produce linear motion, i.e. using rotary electric motor and gear box, SLIMs possess the advantage of simple structure, lower mechanical losses and wide range of linear speed and acceleration [1].

From the viewpoint of modeling, the technical literatures can be organized into four sections: (1) modified mechanical models [2,3], (2) winding function based models [4,5], (3) field theory based models [6–8], (4) Duncan's approach based models [9,10]. In the first approach, the mechanical equations of the SLIM are modified to consider the longitudinal end effect. The winding function approach is based on defining some suitable winding functions for both primary and secondary, and then calculating the SLIM inductances, terminal voltages and flux linkages. Field theory based models utilize one-dimensional (1-D), two-dimensional (2-D) or three-dimensional (3-D) field theory to obtain equivalent circuit of the SLIM. Duncan's approach based models describe the longitudinal end effect as a coefficient related to the linear speed. This coefficient is used to modify the magnetizing branch of the SLIM equivalent circuit. More details about this approach are presented in the following section.

In order to obtain a proper controller for the SLIM, the equivalent circuit must consider undesirable phenomena such as longitudinal end effect. To address the mentioned subject, indirect field-oriented control (IFOC) strategies have been developed based on Duncan's model [11]. Moreover, the idea of total sliding-mode control integrated with an indirect field-oriented mechanism has been presented in [12]. The direct field-oriented control (DFOC), direct torque control (DTC) and model predictive control (MPC) methods have been discussed in [13–15], respectively. For aforementioned control strategies with the speed loop, the speed/position is measured by a linear encoder. Obtaining a high-performance sensorless control of the SLIM is very challenging work, while due to complexity of the machine model, very few investigations have been proposed in this way. In particular, model reference adaptive system (MRAS) based speed estimator has been introduced [16]. A fuzzy observer has been presented to estimate the linear speed and secondary flux [3]. Full-order Luenberger observer has also been investigated to estimate all state-space variables of the SLIM [17].

Providing a sensorless variable-speed drive system is a challenging work for both SLIM and rotary induction motor (RIM), however it is more important in the case of SLIM because the cost

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of linear encoder is increased in accordance with motor length. This paper proposes a full-order Luenberger observer to eliminate linear encoder from the structure of SLIM drive system. After elaborating the equations of observer with some simplifying assumptions, the observer gain matrix is provided using the conventional stability criterion. An FLC adaptive scheme is proposed to estimate linear speed from speed tuning signal depending on estimated primary current and secondary flux as state-variables. Optimum parameters of FLC are determined using an off-line method through COA. The FLC full order Luenberger observer is combined with an IFOC strategy that precisely described in [11], to control of magnetic flux and linear speed. Briefly, the main original contributions of this paper are:

- Complete design of a full-order Luenberger observer using novel simplified state-space model of SLIM.
- Applying a proper adaptive scheme based on FLC strategy in the structure of this observer to improve both dynamic and steady-state speed estimation in different operation conditions.
- The verification of introduced drive system (based on IFOC strategy including proposed FLC full-order Luenberger observer) using advanced real-time HIL simulation.

The rest of this paper is organized as follows. Section 2 introduces the dynamic model of SLIM. Section 3 describes a detailed procedure to design full-order Luenberger observer for SLIM, which includes state-space variables of the SLIM, simplifying assumptions, state-space model of the SLIM, mathematical model of full-order Luenberger observer, observer gain matrix determination, adaptive scheme based on PI controller and adaptive scheme based on FLC. Section 4 presents COA to determine the optimum values of FLC coefficients. Simulation and real-time HIL results are presented in Sections 5 and 6, respectively. Finally, Section 7 summarizes the findings and concludes the paper.

2. Dynamic model of SLIM

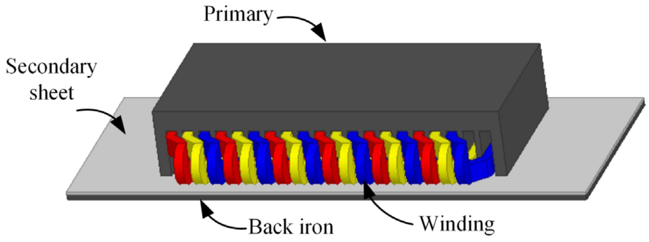

Fig. 1. The structure of SLIM.

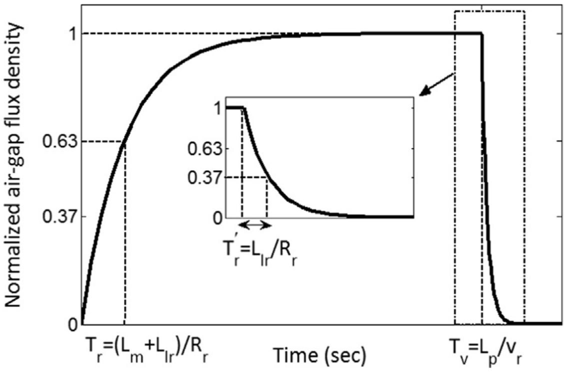

Fig. 2. Normalized air-gap flux density versus time.

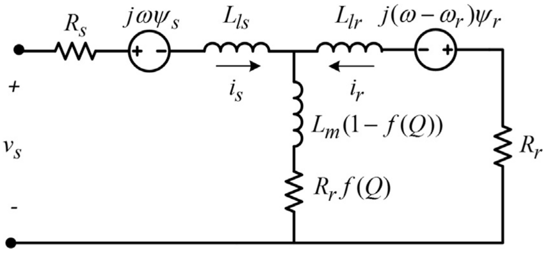

Fig. 3. Space vector model of SLIM.

The structure of SLIM is shown in Fig. 1. In the SLIM, when the primary moves along the secondary, it continuously encounters by a new material of secondary. Because of appearance of this new material, the air-gap flux density is gradually increased at the entry of primary with total secondary time constant that is described by $T_r=(L_m+L_{lr})/R_r$, where L_m, L_{lr} and R_r are magnetizing inductance, secondary leakage inductance and secondary resistance respectively. The flux density is decreased at the exit of primary with the secondary leakage time constant in the following way: $T'_r=L_{lr}/R_r$. Fig. 2 shows the gradual increasing and sudden decreasing of normalized air-gap flux density versus time. In this figure, the term $T_v=L_p/v_l$ is the time of traverse an imaginary point by the primary core, where L_p and v_l are the primary length and linear speed respectively. Increasing and decreasing of the air-gap flux density cause eddy current in the secondary sheet. The eddy current deteriorates air-gap flux density in longitudinal direction as well as increases ohmic losses. Such phenomena is so-called longitudinal end effect which can be described by end effect factor as follows [9]:

$$Q=\frac{T_v}{T_r}=\frac{L_p/v_l}{(L_m+L_{lr})/R_r} \tag{1}$$

This factor amends the magnetizing inductance in the following way:

$$M=L_m(1-f(Q)) \tag{2}$$

where

$$f(Q)=\frac{1-e^{-Q}}{Q} \tag{3}$$

The space vector model of the SLIM is shown in Fig. 3. The term $R_rf(Q)$ demonstrates the ohmic losses due to longitudinal end effect. The primary and secondary voltage vectors in the arbitrary reference frame are written as follows:

$$\boldsymbol{v}_s=R_s\boldsymbol{i}_s+j\omega\boldsymbol{\psi}_s+\frac{d}{dt}\boldsymbol{\psi}_s+R_{sh}(\boldsymbol{i}_s+\boldsymbol{i}_r) \tag{4}$$

$$\boldsymbol{v}_r=0=R_r\boldsymbol{i}_r+j(\omega-\omega_r)\boldsymbol{\psi}_r+\frac{d}{dt}\boldsymbol{\psi}_r+R_{sh}(\boldsymbol{i}_s+\boldsymbol{i}_r) \tag{5}$$

with

$$R_{sh}=R_rf(Q) \tag{6}$$

where R_s and R_r are the primary and secondary resistances, ψ_s and ψ_r are the primary and secondary flux linkages, i_s and i_r are the primary and secondary currents, ω_r is the angular electrical speed of primary and j is the imaginary unit. The flux linkages are related to the currents by

$$\boldsymbol{\psi}_s=L_s\boldsymbol{i}_s+M\boldsymbol{i}_r \tag{7}$$

$$\boldsymbol{\psi}_r=L_r\boldsymbol{i}_r+M\boldsymbol{i}_s \tag{8}$$

where L_s, L_r and M are the self and modified magnetizing inductances. The electromagnetic thrust generated by the SLIM is calculated as follows:

$$F_e=\frac{3}{2}\frac{p}{2}\frac{\pi}{\tau}Re(j\boldsymbol{\psi}_s\boldsymbol{i}_s) \tag{9}$$

where p and τ are the pole number and the pole pitch respectively.