Control Engineering Practice 55 (2016) 116–126

Contents lists available at ScienceDirect

Control Engineering Practice

journal homepage: www.elsevier.com/locate/conengprac

Adaptive feedback linearizing control of linear induction motor considering the end-effects

Francesco Alonge [a], Maurizio Cirrincione [b], Filippo D'Ippolito [a], Marcello Pucci [c], Antonino Sferlazza [a,c,*]

[a] D.E.I.M. (Department of Energy Information Engineering and Mathematical Models), Viale delle Scienze, 90128 Palermo, Italy
[b] School of Engineering, University of the South Pacific, Laucala Campus, Suva, Fiji Islands
[c] I.S.S.I.A. C.N.R. Section of Palermo (Institute on Intelligent Systems for Automation), via Dante 12, Palermo 90128, Italy

ARTICLE INFO

Article history:
Received 3 December 2015
Received in revised form
25 June 2016
Accepted 27 June 2016
Available online 21 July 2016

Keywords:
Linear induction motor
Adaptive systems
Feedback linearization
End-effects
Parameters' estimation

ABSTRACT

This paper proposes an input–output feedback linearization techniques for linear induction motors, taking into consideration the dynamic end-effects. As a main original content, this work proposes a new control law based on the on-line estimation of the induced-part time constant. The estimation law is obtained thanks to a Lyapunov based analysis and thus the stability of the entire control system, including the estimation algorithm, is intrinsically guaranteed. Moreover, with such an approach even the on-line variation of the induced-part time constant with the speed is retrieved, thus improving the behavior of previously developed approaches where such a variation vs. speed is considered a priori known. The proposed control technique, integrating the on-line induced-part time constant estimation, is tested by means of simulations and experiments carried out on a suitably developed test set-up.

1. Introduction

A significant amount of research activity has been carried out on Linear Induction Motors (LIMs) since seventies (Boldea & Nasar, 1997, 1999; Laithwaite, 1975; Nasar & Boldea, 1987; Poloujadoff, 1980; Yamamura, 1979). Although they do not require any mechanical apparatus which transform rotating motion in a linear one, a significant increasing of the complexity of their dynamic models occurs, due to the so-called end-effects. These end-effects cause additional significant non-linearities in the LIM dynamic model with that of the Rotating Induction Machine (RIM) (Leonhard, 2001; Vas, 1998).

Since the goal of this work is to propose a high performance control system for the LIM, the dynamic model considered in this paper is that described in Pucci (2014), which takes into account the end-effects. As described in Pucci (2014), these effects produce variations of the electric parameters of the model with the machine speed, and the presence of an additional braking force.

From the other side, the control system theory offers several control techniques to cope with non-linear systems (Isidori, 1995; Khalil, 2002; Slotine & Li, 1991). Among such techniques, the input–output Feedback Linearization (FL) is that of interests for this work.

A restricted number of works in the literature face up to the input–output feedback linearization of LIMs (Huang & Fu, 2003; Lin & Wai, 2001, 2002; Wai & Chu, 2007). All these papers, however, are based on the classic RIM model, as far as the controller design is concerned (De Luca & Ulivi, 1989; Kim, Ha, & Ko, 1990; Krzeminski, 1987; Marino, Peresada, & Valigi, 1993, 2010). It can be thus concluded that the state of the art of the application of FL to LIMs is the same as that of the applications of FL to RIMs, whose current state of the art is described in Marino et al. (2010).

Recently, Alonge, Cirrincione, Pucci, and Sferlazza (2015a, 2015b, 2016) deal with the issue of the input–output FL control of LIM, taking into consideration the LIM additional nonlinearities due to the end-effects in the control action. In particular, in Alonge et al. (2015a, 2015b) it is described by the conventional FL technique that assumes all the known parameters of the motor-load system. However, it is well known that eventual variations of the model parameters can cause deterioration of the behavior of the control system. A first adaptive version of FL is proposed in Alonge et al. (2016), where an adaptation law for the stator resistance is given. In particular an MRAS (Model Reference Adaptive System)

* Corresponding author at: D.E.I.M. (Department of Energy Information Engineering and Mathematical Models), Viale delle Scienze, 90128 Palermo, Italy.
E-mail addresses: francesco.alonge@unipa.it (F. Alonge), m.cirrincione@ieee.org (M. Cirrincione), filippo.dippolito@unipa.it (F. D'Ippolito), pucci@pa.issia.cnr.it (M. Pucci), sferlazza@pa.issia.cnr.it, antonino.sferlazza@unipa.it (A. Sferlazza).

http://dx.doi.org/10.1016/j.conengprac.2016.06.018
0967-0661/

observer for the stator resistance using a PI-based adaptation law is used. However among all the electrical parameter variations, the induced part time constant variation is certainly one of the most important, since from its correct knowledge depends on the correct field orientation, and to the best Authors' knowledge it has not never been considered in other works in the literature. It should be noted that, while in the RIM, such rotor time constant depends on both the heating/cooling of the rotor and the magnetization level inside the machine (field weakening, optimal efficiency algorithms), in the LIM it also varies with the speed, due to the end-effects.

Starting from these considerations, this paper proposes an adaptive input–output feedback linearization technique for LIMs, taking into consideration the dynamic end-effects. More precisely, as a main original content this work proposes a control law based on the on-line estimation of the induced part time constant. The estimation law is derived from a Lyapunov based approach so as to intrinsically guarantee the stability of the entire control system, including the estimation algorithm. Moreover, with such an approach even the on-line variation of the induced part time constant with the speed is retrieved, with the aim of improving the behavior of the system controlled by the FL described in Alonge et al. (2015a, 2015b, 2016), where the function of the induced part time constant vs. speed is considered a priori known.

2. Dynamic model of the LIM

The main difference between LIMs and RIMs lies in the so-called end-effects. These effects could be divided into two categories: static and dynamic end-effects. Static end-effects are caused by the asymmetric distribution of the reluctances of the magnetic path of the three phases. This kind of effects has not been considered in this paper, even because their presence does not modify significantly the LIM dynamics. On the contrary, dynamic end-effects are caused by the motion of the limited length inductor with a certain speed over an induced part track theoretically of infinite length. Consequently the magnetic flux density in the air-gap varies.

The effect is a deep reduction of the resulting flux in proximity of the entrance and in a deep increase of the flux at the exit of the inductor. This has been taken into consideration in the literature by a so-called end-effect factor Q (Da Silva, Dos Santos, Machado, & De Oliveira, 2003; Duncan, 1983), defined as:

$$Q = \frac{\tau_m}{T_r v}. \tag{1}$$

For the symbols, see Table 1.

As highlighted in Duncan (1983) and Pucci (2014), the higher the machine speed, the higher the air-gap thickness (higher leakage inductance) and the lower the inductor length, the lower the factor Q. It means that the end-effects increase with the machine speed, with the air-gap thickness and reduce with the inductor length. For details to the mathematical modelling of the LIM refer to Pucci (2014).

To the aim of describing the proposal FL technique, the dynamic model of the LIM, taking into consideration its dynamic end-effects (Pucci, 2014), is written in the induced part flux reference frame as in Alonge et al. (2015a) where the input–output FL of LIM is carried out without adaptation of the model parameters. However the model presented in Alonge et al. (2015a) is showed here in a slightly different form in order to make possible the adaptive FL. In particular, writing the equations in the induced part flux reference frame, the following model for the LIM is used:

Table 1
List of symbols.

Symbols	
u_{sx}, u_{sy}	Inductor voltages in the induced part flux reference frame
i_{sx}, i_{sy}	Inductor currents in the induced part flux reference frame
ψ_{rx}, ψ_{ry}	Induced part fluxes in the induced part flux reference frame
f_e	Electromagnetic thrust
f_r	Load force
f_{eb}	Braking force
L_s (L_r)	Inductor (induced part) inductance
L_m	3-Phase magnetizing inductance
R_s (R_r)	Inductor (induced part) resistance
T_r	Induced part time constant
σ	Total leakage factor
ω_r	Electrical angular speed of the induced part
v	Mechanical linear speed
a	Mechanical linear acceleration
p	Pole-pairs
τ_p	Pole-pitch
τ_m	Inductor length
M	Inductor mass

$$\frac{di_{sx}}{dt} = -\frac{R_s}{\hat{\sigma}\hat{L}_s} i_{sx} - \gamma i_{sx} - \hat{L}_m \beta \alpha i_{sx} + \frac{p\pi}{\tau_p} v i_{sy} + \frac{\alpha \hat{L}_m i_{sy}^2}{\psi_r} + \beta\alpha\psi_r + \frac{u_{sx}}{\hat{\sigma}\hat{L}_s}, \tag{2}$$

$$\frac{di_{sy}}{dt} = -\frac{R_s}{\hat{\sigma}\hat{L}_s} i_{sy} - \gamma i_{sy} - \hat{L}_m \beta \alpha i_{sy} - \frac{p\pi}{\tau_p} v i_{sx} - \frac{\alpha \hat{L}_m i_{sy} i_{sx}}{\psi_r} - \beta\frac{p\pi}{\tau_p} v\psi_r + \frac{u_{sy}}{\hat{\sigma}\hat{L}_s}, \tag{3}$$

$$\frac{d\psi_r}{dt} = -(\alpha - \eta)\psi_r + \alpha \hat{L}_m i_{sx}, \tag{4}$$

$$\frac{dv}{dt} = \mu(\psi_r i_{sy}) - \frac{f_r}{M} - \frac{\vartheta}{M}\psi_r^2, \tag{5}$$

where $\psi_r = \psi_{rx}$, and the variables $\alpha, \beta, \gamma, \eta, \mu$ and ϑ are time varying parameters defined as follows:

$$\alpha = \left(\frac{1}{\hat{T}_r} - \frac{\hat{R}_r}{\hat{L}_m}\right), \quad \beta = \frac{\hat{L}_m}{\hat{\sigma}\hat{L}_s\hat{L}_r}, \quad \gamma = \frac{\hat{R}_r}{\hat{\sigma}\hat{L}_s}\left(1 - \frac{\hat{L}_m}{\hat{L}_r}\right), \quad \eta = -\frac{\hat{R}_r}{\hat{L}_m},$$

$$\mu = \frac{3}{2} p \frac{\pi}{\tau_p} \frac{\hat{L}_m}{\hat{L}_r} \frac{1}{M}, \quad \vartheta = \mathrm{sign}(v) \frac{3}{2} \frac{L_r}{\hat{L}_r^2} \frac{1 - e^{-Q}}{p\tau_p},$$

where

$$\hat{L}_m = L_m(1 - f(Q)), \quad \hat{L}_s = L_{\sigma s} + L_m(1 - f(Q)),$$

$$\hat{L}_r = L_{\sigma r} + L_m(1 - f(Q)), \quad \hat{R}_r = R_r f(Q),$$

$$\hat{T}_r = \frac{L_{\sigma r} + L_m(1 - f(Q))}{R_r(1 + f(Q))}, \quad \hat{\sigma} = 1 - \frac{\hat{L}_m^2}{\hat{L}_r\hat{L}_s},$$

with:

$$f(Q) = \frac{1 - e^{-Q}}{Q}. \tag{6}$$

The details for the derivation of model (2)–(4) are not given since it is not the aim of this paper, actually the reader is addressed to Pucci (2014) and Alonge et al. (2015a) for the modelling aspects.