Control Engineering Practice 36 (2015) 133–141

Contents lists available at ScienceDirect

Control Engineering Practice

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

Input–output feedback linearizing control of linear induction motor taking into consideration the end-effects. Part I: Theoretical analysis

Francesco Alonge [a], Maurizio Cirrincione [b], Marcello Pucci [c,*], Antonino Sferlazza [a,c]

[a] D.E.I.M. (Department of Energy Information Engineering and Mathematical Models) of the National Research Council (CNR) of Italy, University of Palermo, Viale delle Scienze, 90128 Palermo, Italy
[b] The School of Engineering and Physics, The 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 21 October 2013
Accepted 18 August 2014
Available online 5 December 2014

Keywords:
Linear induction motor (LIM)
Feedback linearization
End-effects

ABSTRACT

This first part of a paper, divided into two parts, deals with the theoretical formulation of the input–output feedback linearization (FL) control technique as to be applied to linear induction motors (LIMs). Linear induction motors, differently from rotating induction motors (RIMs), present other strong non-linearities caused by the so-called dynamic end effects, leading to a space-vector model with time-varying inductance and resistance terms and an additional braking force term. This paper, starting from a dynamic model of the LIM taking into consideration its dynamic end effects, previously developed by the same authors, defines a feedback linearization (FL) technique suited for LIMs, since it inherently considers its end effects. It further emphasizes the role of the LIM dynamic end effects in the LIM control formulation, highlighting the differences with respect to the corresponding technique for RIMs. It describes the control design criteria, taking also into consideration the constraints on the control and controlled variables, arising from the application of such control technique in a real scenario.

The second part of this paper describes the set of tests, both in numerical simulations and experiments, performed to assess the correctness of the proposed control technique.

1. Introduction

Linear induction motors (LIM) have been largely studied for several years (Boldea & Nasar, 1997, 1999; Laithwaite, 1975; Nasar & Boldea, 1987; Poloujadoff, 1980; Yamamura, 1979). Among the main reasons of their interest there is the opportunity to develop a direct linear motion without the need of any gear-box for the motion transformation (from rotating to linear). This advantage presents, as counterpart, the disadvantage of an increase of complexity of the machine model, presenting the so-called end effects and border effects. In particular, end effects are to be divided into two categories: (a) static and (b) dynamic end effects. Static end effects are due to asymmetries in the inductor structure in the longitudinal direction causing different reluctances of the magnetic paths of the three inductor phases. Dynamic end effects are caused by the relative motion between the short inductor and the induced part track and can be defined on the basis of the spatial representation, on the longitudinal direction of the LIM, of the root mean square (RMS) value of inductor MMF (magnetomotive force) profile. They are caused by the sudden growth of new currents in the induced part track. As a result, starting from the assumption that the rotating induction machine (RIM) presents a dynamic space-vector model which is non-linear (Leonhard, 2001; Vas, 1998), the dynamic model of the LIM presents further additional significant non-linearities, caused by the dynamic end effects.

The definition of a space-vector dynamic model of the LIM, taking into consideration the end effects, with a representation suitable for control purposes is not an easy task. Gentile, Rotondale, and Scarano (1987, 1988) propose a complete dynamic model of the LIM, taking into consideration both the static and dynamic end effects. It is, however, not adoptable for control purposes because of its complexity and strong dependence on the constructional aspects of the machine (pole pitch, air-gap length, thickness of the induced part track, slots width and depth, number of turns for phases etc.). Recently, a space-vector dynamic model of the LIM taking into consideration its dynamic end effects (not the static ones) has been developed and experimentally validated (Pucci, 2014). This last model has been expressed in a state-space form and is therefore particularly suitable for control purposes, in particular for the definition of state estimators, observers or novel control techniques taking into consideration the additional non-linearities arising from the presence of the dynamic end effects. If the space-vector state

---

* Corresponding author.
E-mail addresses: francesco.alonge@unipa.it (F. Alonge), m.cirrincione@ieee.org (M. Cirrincione), pucci@pa.issia.cnr.it (M. Pucci), antonino.sferlazza@unipa.it, sferlazza@pa.issia.cnr.it (A. Sferlazza).

http://dx.doi.org/10.1016/j.conengprac.2014.08.009

List of 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
ω_{mr}	electrical angular speed of the induced part flux
v	mechanical linear speed
a	mechanical linear acceleration
p	pole-pairs
τ_p	pole-pitch
τ_m	inductor length
M	inductor mass

model of the LIM in Pucci (2014) is considered, the additional strong non-linearities caused by the dynamic end effects are twofold:

(1) the presence of electric parameters of the model (inductances and resistance), which vary non-linearly with the machine speed;
(2) the presence of a braking force, whose terms depend on the square of induced part flux amplitude as well as on the product between the induced part flux amplitude and the inductor current components.

Although the LIM presents a far more non-linear model than the RIM, the approach adopted in the literature for its control has been usually to straightforwardly extend the classic control technologies developed for RIMs to LIMs.

The control system theory, however, offers an important corpus (Isidori, 1995; Khalil, 2002; Slotine & Li, 1991) of non-linear control methodologies for dealing with highly non-linear system. Among all, one of the most promising is the so-called input–output feedback linearization. Nevertheless, very few applications of non-linear control methods to electrical drives are provided by the scientific literature. Among these few applications, a very limited number of papers deal with the input–output feedback linearization of linear induction motors (Huang & Fu, 2003; Lin & Wai, 2001, 2002; Wai & Chu, 2007). All these papers approach the FL control of the LIM, adopting for the controller synthesis a dynamic model of the LIM which neglects both the static and the dynamic end effects. This corresponds to adopt the dynamic model of the equivalent rotating induction machine (RIM). From the controller design point of view, therefore, Lin and Wai (2001, 2002), Huang and Fu (2003), and Wai and Chu (2007) present exactly the same approach of Krzeminski et al. (1987), De Luca and Ulivi (1989), Kim, Ha, and Ko (1990), and Marino, Peresada, and Valigi (1993, 2010), which specifically propose the application of FL to RIM control. On the basis of the above, the state-of-the-art of the application of FL to LIMs corresponds to the state-of-the-art of the applications of FL to RIMs. For this reason, the main contributions of application of FL to RIMs should be briefly highlighted in the following. In particular, De Luca and Ulivi (1989) present an approach to the control of induction motors based on differential-geometric concepts, while, Marino et al. (1993) present a nonlinear adaptive state feedback input–output linearizing control. The current state-of-the-art is described by Marino et al. (2010).

This paper proposes an input–output feedback linearization (FL) technique for linear induction motors. The methodology is inspired from Marino et al. (2010), just as theoretical framework. The starting point of the proposed FL technique is, however, the space-vector dynamic model of the LIM taking into consideration its dynamic end effects recently developed by Pucci (2014). This model is particularly suitable for the application of the FL technique, since it is expressed in a state form. Starting from this dynamic space-vector model, a control system has been designed which, on the basis of the estimated induced part flux linkage and measured linear speed, outputs two suitably defined additional control variables. The control system is designed in such a way that the adoption of these control variables corresponds to deal with an equivalent LIM model which is linear and expressed in canonical control form. Finally, the real control variables of the machine, corresponding to the direct and quadrature components of the inductor voltages expressed in the inductor reference frame, are obtained from the additional ones after a set of suitably defined non-linear functions, depending on both these additional control inputs and the LIM electric variables (inductor currents, induced part flux linkage).

The proposed FL approach is thus able to take into consideration, besides the classic non-linearities of the RIM, even the further non-linearities caused by the dynamic end effects.

This paper is divided into two parts. The first part deals with the theoretical formulation of the input–output feedback linearization control technique as to be applied to linear induction motors. The second part describes the set of tests, both in numerical simulation and experimental, performed to assess the correctness of the control technique, and to verify the related dynamic performance.

2. Space-vector equivalent circuit of the LIM including end effects (Pucci, 2014)

In a LIM, differently from a RIM, the secondary (induced part), consists of a sheet of aluminum with a back core of iron. During the motion of the inductor, a continuous variation of the aluminum sheet happens, while the inductor presents a limited length. This causes a variation of the induced currents in the sheet and corresponding magnetic flux density in the air-gap, in proximity to the entrance (front of the motion) and exit (back of the motion) of the inductor. The amounts and signs of the flux modifications at the two ending parts of the inductor, meaning its entrance (in the direction of the motion) and its end (terminal part of the inductor in the direction of the motion), are different. When the moving inductor faces a new part of aluminum sheet, new induced currents are generated starting from a null value. The induced current, suddenly growing in a region of the induced part track where there was not insisting any magnetic flux, for the Faraday law arises trying to oppose to the magnetic flux increase. The effect is a deep reduction of the resulting flux in proximity to the entrance. At the same time, at the exit the induced current opposes to a sudden flux reduction from the inducer, creating an overall flux increase. The higher the speed of the inductor, the higher the end effect phenomenon. This last has been taken into consideration in the literature by the so-called end effect factor Q (da Silva, dos Santos, Machado, & De Oliveira, 2003; Duncan, 1983),