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Input–output feedback linearizing control of linear induction motor taking into consideration the end-effects. Part II: Simulation and experimental results

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ABSTRACT

This is the second part of a paper, divided in two parts, dealing with the application of the input–output feedback linearization (FL) control technique to linear induction motors (LIMs).

The first part has treated the theoretical formulation of the input–output feedback linearization control technique as to be applied to linear induction motors. This second part describes the set of tests, both in numerical simulations and experiments, performed to assess the validity of the control technique. In particular, it addresses the issues of the sensitivity of the FL control versus the LIM electrical parameters' variations and the improvements achievable by considering the LIM dynamic end effects in the control formulation.

The proposed FL technique has been further compared, under the same closed-loop bandwidths of the flux and speed systems, with the industrial standard in terms of high performance control technique: field oriented control (FOC).

1. Introduction

This is the second part of a paper, divided in two parts, dealing with the theoretical definition and application of the input-output Feedback Linearization–>input–output feedback linearization (FL) control technique to linear induction motor (LIM) drives. The first part of this paper has illustrated the theoretical framework which leads to the development of the FL controller suitable for LIM. It has also illustrated how to manage the constraints on the electrical variables arising from the adoption of the FL. The controller design criteria have been further defined.

This second part deals with the verification of the proposed FL control in both numerical simulation and experiments. It describes the experimental setup adopted for the assessment of the proposed control law. It firstly illustrates results obtained in numerical simulation in Matlab®–Simulink® environment. It further shows results connoting the improvements achievable thanks to the exploitation of the dynamic end effects in the FL controller, instead of adopting of the classic rotating induction machine (RIM) model. It also proposes a sensitivity analysis of the FL controller versus the variation of the two most significant electrical parameters of the LIM: the inductor resistance R_s and the induced part time constant T_r.

The proposed FL control has been also compared in numerical simulation with the classic FOC, with a flux model specifically developed for LIMs (Pucci, 2012), under the same closed-loop dynamic conditions.

2. Simulation results

The proposed input–output feedback linearization (FL) control technique has been verified in numerical simulation. With this regard, the entire numerical benchmark has been implemented in Matlab®–Simulink® environment.

As far as the LIM dynamic model is concerned, which is the machine under test in the following tests, the space-vector dynamic model of the LIM taking into consideration the LIM end effects (Pucci, 2012, 2014) has been implemented: this model implements the dynamic end effects by suitable speed-varying inductance and resistance terms and including also a braking force term. It offers a very reliable representation of the LIM dynamic behavior, as confirmed by Pucci (2014). The only limits of such

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a model is that it does not take into consideration the LIM static end effects, which are however less significant than the dynamic ones as far as the control issues are concerned. The rated values and electrical parameters of the adopted LIM are given in Table 1.

To verify the improvement in the dynamic performance achievable with the adoption of the proposed input–output feedback linearization with respect to other control techniques in the literature, FL has been compared with the industrial standard in terms of high performance control: field oriented control (FOC). In particular, among the various FOC versions, the classic induced part flux oriented control has been adopted (equivalent to the rotor-flux-oriented control in RIMs, Leonhard, 2001; Vas, 1998). In particular, the version of FOC based on the induced part flux model written in the induced part flux reference frame taking into consideration the LIM dynamic end effects has been adopted (Pucci, 2012). This version of the FOC, specifically developed for LIMs, is certainly the best benchmark with respect to which the performance of the proposed input–output feedback linearization can be evaluated and inherently permits better dynamic performance than the standard FOC developed for RIMs and applied to LIMs.

2.1. Terms for the comparison between FL and FOC

Comparing two different control techniques is always a hard task. In general, to make a meaningful comparison, two control techniques must be compared trying to impose the same dynamic behavior of the closed loop system of the variable to be controlled. This assumption corresponds, in the case under study, to impose the same dynamics of the controlled induced part flux amplitude and machine linear speed loops, with both FL and FOC.

As far as flux control is concerned, in the FL case, defining the dynamics of the flux control corresponds to fix a set of reasonable values of gains $k_{\psi 1}$ and $k_{\psi 2}$ such that the dynamic of the closed loop equation of the flux error (52)-Part I has fixed specifics, i.e. bandwidth and phase margin. In this case, the values shown in Table 1-(Part I) have been assigned. The dynamic of the inductor current i_{sx}, in FL, is indirectly controlled. In fact the current i_{sx} is proportional to ν_ψ as is shown in Section 5-(Part I), so only the flux dynamic is imposed, since the current dynamic results are indirectly fixed such that the closed loop flux has the imposed dynamic.

Correspondingly, in the FOC case, the induced part flux amplitude is controlled by a PI controller (see block diagram of the FOC in Fig. 5 of Pucci, 2012). The hierarchy of the control is organized so that the output of the flux controller is the reference of the direct component of the inductor current i_{sx} in the induced part flux reference frame. The PI regulating i_{sx} has been tuned so to impose the best dynamic performance of its control loop, taking into consideration that:

(1) The transient inductance value of LIM is a speed varying quantity, differently from that of the RIM, which can be assumed to be constant. The design of the controller has been thus made for one value of the speed (the rated one typically), and then further verified at lower speeds.
(2) In the LIM case, differently from the RIM one, the dynamics of the inductor current is slower than that of the induced part flux, because of the big air-gap and thin aluminium track (Pucci, 2014). It makes flux control more critical for the LIM than for the RIM.

The entire flux loop has been then tuned, in the FOC case, so that the dynamic is equal to that imposed with the FL (see Table 1-(Part I) for the values of the proportional and integral gains given to all the controllers in the FOC case). This is confirmed by comparing the Bode diagrams of the closed loop transfer functions of the controlled induced part flux in the FL and FOC cases (Fig. 4-(Part I)). It can be easily observed that the 3 dB bandwidths and the phase margins (shown in Table 2-(Part I)) of the induced part flux in both cases are almost equal ($B_{-3db} = 455$ rad/s and $m_\Phi = 40^\circ$). Finally, even the maximum values of the acceptable inductor current amplitudes, above which the control presents a saturation action, have been set equal for FL and FOC, to make a reliable comparison.

Table 1
Parameters of the LIM.

Rated power, P_{rated} (W)	425
Rated voltage, U_{rated} (V)	380
Rated frequency, f_{rated} (Hz)	60
Pole-pairs	3
Inductor resistance, R_s (Ω)	11
Inductor inductance, L_s (mH)	637.6
Induced part resistance, R_r (Ω)	32.57
Induced part inductance, L_r (mH)	757.8
3-phase magnetizing inductance, L_m (mH)	517.5
Rated thrust, F_n (N)	62
Rated speed (m/s)	685
Mass (kg)	20

As far as speed control is concerned, in the FL case, defining the dynamics of the speed control corresponds to fix a set of reasonable values of gains k_{v1} and k_{v2} such that the dynamic of the closed loop equation of the speed error (53)-(Part I) has fixed specifics, i.e. bandwidth and phase margin. In this case, the values shown in Table 1-(Part I) have been assigned. The dynamic of the inductor current i_{sy}, in FL, is indirectly controlled. In fact the current i_{sy} is function of a as is shown in Section 5-(Part I), so only the speed dynamic is imposed, since the current dynamic results indirectly fixed such that the closed loop speed have the imposed dynamic.

Correspondingly, in the FOC case, the speed is controlled by a PI controller (see block diagram of the FOC in Fig. 5 of Pucci, 2012). The hierarchy of the control is organized so that the output of the speed controller is reference of the quadrature component of the inductor current i_{sy} in the induced part flux reference frame. The parameters of the PI regulating i_{sy} have been tuned equal to those of i_{sx}.

The entire speed loop has been then tuned, in the FOC case, so that the dynamic is equal to that imposed with the FL (see Table 1-(Part I) for the values of the proportional and integral gains given to all the controllers in both the FL and FOC cases). This is confirmed by comparing the Bode diagrams of the closed loop transfer function of the speed loops in the FL and FOC cases (Fig. 5-(Part I)). It can be easily observed that the 3 dB bandwidths and the phase margins (shown in Table 2-(Part I)) of the speed in both cases are almost equal ($B_{-3db} = 37$ rad/s and $m_\Phi = 128^\circ$).

It should be however borne in mind that, while the FL ensures that the poles of the induced part flux and speed are always those imposed by the designer, independently from the working speed of the LIM, in the FOC case their dynamics are imposed by the designer for one working condition (rated speed where the end effects are more visible), while they then vary with the speed of the machine. This results in the degradation of the performance of FOC with respect to FL, as shown in the following.

2.2. Comparative tests

Even the choice of the tests under which the FL has to be compared to the FOC is not straightforward. As clearly demonstrated in Marino, Peresada, and Valigi (1993) and Marino, Tomei, and Verrelli (2010) for the RIM case, and verified theoretically in the Part I of this paper for the LIM case, the major differences between FOC and FL control appear when the machine is