Demo-Track using a Linear Induction Motor

Strubin J.-M., Veenstra M., Rufer A.
Laboratoire d'Electronique Industrielle, STI-ISE
Ecole Polytechnique Fédérale de Lausanne,
CH-1015 Lausanne, Switzerland
Phone: +41 21 693 2651/ Fax: +41 21 693 2600
e-mail: alfred.rufer@epfl.ch,
URL: leiwww.epfl.ch

Keywords

demonstration drive, linear asynchronous motor, sensorless.

Abstract

Technical education in classical fields like electrical engineering is confronted in western countries with on one side a high demand for engineers coming from industry and on the other side by the reduced interest from younger generation, whose interest is highly polarized by information and communication technologies. A linear motor demo-track has been set up, in order to reinforce the demonstrative aspects of modern technology as a contribution to the motivation of students for the industrial world. It is also an alternative example to the too classical rotating asynchronous motor in the field of education on variable speed drive.

1 Introduction

As Electrical engineering is not really popular for the new students, revisited methods and tools for renewed motivation are currently a discussion theme in many technical universities [1].
As simulations and computers are intensively used in the classes and labs in relation with teaching activities, most faculties now omit to demonstrate, with visible and moving attractive high technology devices, what can be realized using recent research and development.
At EPFL, an existing linear induction motor (LIM) has been reused, on a newly installed V-shaped test track, as training and demo feature for students in the department of electrical engineering. Asymmetries and other non-typical behavior specifics to the LIM can now be studied and presented.
As field oriented, sensorless or direct torque control of asynchronous motors have been in the center of research during the past twenty years in many universities and industries, the characteristic properties of linear motors due to asymmetries lead to complex modelisation and complex control strategies [2]. Simpler approaches are easily possible, because the asynchronous linear induction machine with massive rail is highly tolerant regarding orientation because of its dissipative rotor characteristics.
In this paper the power and control systems are first described. Then two different control strategies that have been used on this drive are presented. The first of these strategies is running using a speed sensor, the second one without.

2 Variable voltage and variable frequency LIM system

2.1 Introduction

Early developments in LIM have been done at EPFL during the 60's and 70's. [3]. Practical results have been verified without use of power electronics converters and control. Similarly to the newer LIM applications [4], the existing motor is reused with variable voltage and variable frequency, this achieved with a modern IGBT PWM-Inverter fed through a diode rectifier from the AC Network. The scheme of the power circuitry is given in Fig. 1.

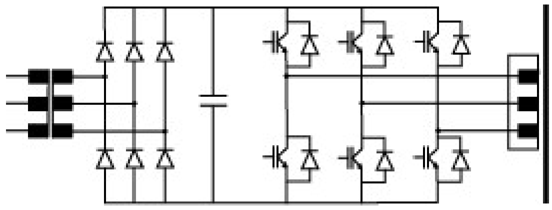

Figure 1 : Supply of the LIM

Depending on the control strategy implemented, the regulation algorithm may need to precisely know the stator voltage. Instead of measuring each output phase voltage the complete alimentation circuit is modelled in function of the DC-link voltage. This way, the output of the PWM-Inverter can be controlled measuring only the DC voltage, which needs only one voltage sensor.

2.2 Motor (stator)

The used LIM is a three-phase Linear Induction Motor with double inductor. The windings and connections on the stator are represented on Fig. 2.

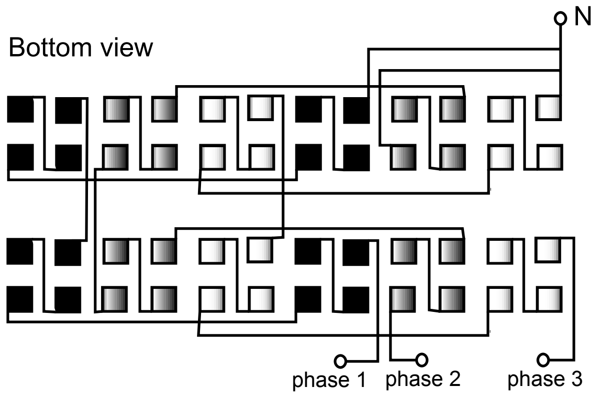

Figure 2 : Windings of the LIM

In this utilisation, the neutral point isn't connected, but a connector exists so it can be done if desired in the future.
Its main characteristics are:

- S_n = 36 [kVA] : nominal apparent power
- I_n = 41 [A] : nominal current
- U_n = 165 [V] : nominal phase voltage
- p = 1 : number of pole pairs
- τ_p = 129 [mm] : pole length
- v_s = 12 [m/s] : synchronous speed
- N_s = 58 [turns/inductor]
- Z_n = 12: number of slots
- Star coupling, free neutral point
- δ = 2 [mm] : air gap

2.3 Rail (rotor)

The motor rail, corresponding to the massive rotor of a conventional induction machine, is a simple V-shaped aluminium I-profile, carrying and guiding the moving stator by rolls. In Fig. 3, the picture represents the track mounted on the wall of a high power laboratory at EPFL. Steep and reduced power climbing segments simulate conditions similar to a roller coaster, allowing high accelerations and fast movements but also stand-still under load conditions, as test-conditions for the control performances.

Figure 3 : Rail of the LIM (rotor)

2.4 Control system

The control system (Fig. 4) is made of a floating-point architecture Digital Signal Processor, which facilitates the practical implementation of functionality by students without any needed experience in assembler programming. The DSP is completed by devices like FPGA for digital modulation of the PWM Inverter, and by fast AD converters for fast real time data acquisition.

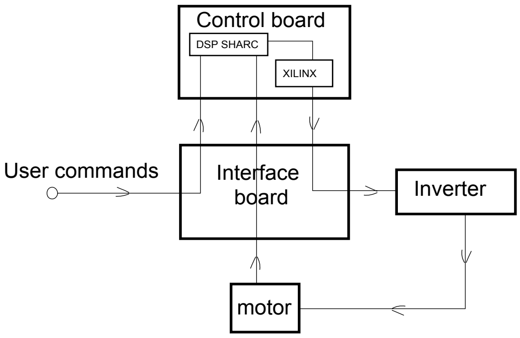

Figure 4 : Control system

Because of its quickness, its large number of AD's (14) and its multiple graphical tools, this dedicated card developed at EPFL/LEI is a very powerful and efficient development tool [5]. Especially the easy up-and download facilities for parameter setting and representation of records are particularly suited for education purpose.

2.5 Complete system

Fig. 5 shows the complete system. Depending on the control strategy implemented, each of the sensors may or not be used. But they are anyway useful to dimension all the regulation parameters because they give interesting informations on the system behavior.

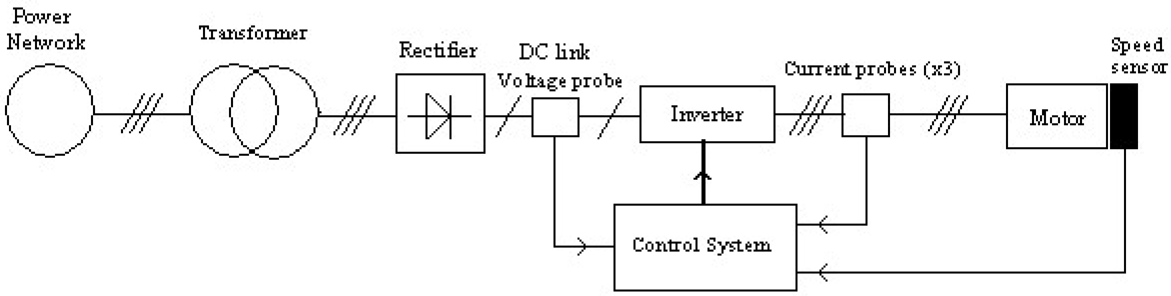

Figure 5 : Complete system

2.6 Characteristic curves

Fig. 6 shows the characteristic curves of the regulation. They are the same for the both regulation strategies described next. These curves characterize the motor when it is operated with constant stator flux. To assure this, the stator frequency must rise with the stator voltage [6]. Along with these curves, the nominal stator voltage is set to 165 [V] corresponding to the nominal stator frequency of 50 [Hz].

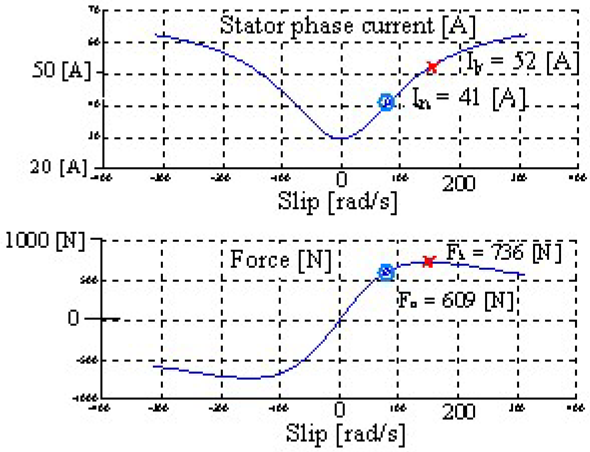

Figure 6 : Characteristic curves of the LIM

The two important points on these curves are the nominal point (ω_{rn} = 80 [rad/s], I_n = 41 [A]) and the breakdown point (ω_{rk} = 151 [rad/s], I_k = 52 [A])). In comparison with classical rotating induction motors, the values of the slip during operation may be very high. They illustrate also the specific characteristics of a pioneer development of a LIM

Another particularity is the value of the magnetising current (ω_r = 0) which is quite important (I_0 = 29 [A]) and is due to the adapted geometry and the ironless rail.

3 Position regulation using a speed sensor

3.1 Regulation strategy

Fig. 7 shows the regulation strategy. Even if sophisticated control for the LIM is currently under way [2], a simpler strategy is followed for the set up of the test track, which is particularly easy to implement and simple to be understood by younger college students [6]. First the drive is regulated in speed, then an additional loop for regulating the position will be added.

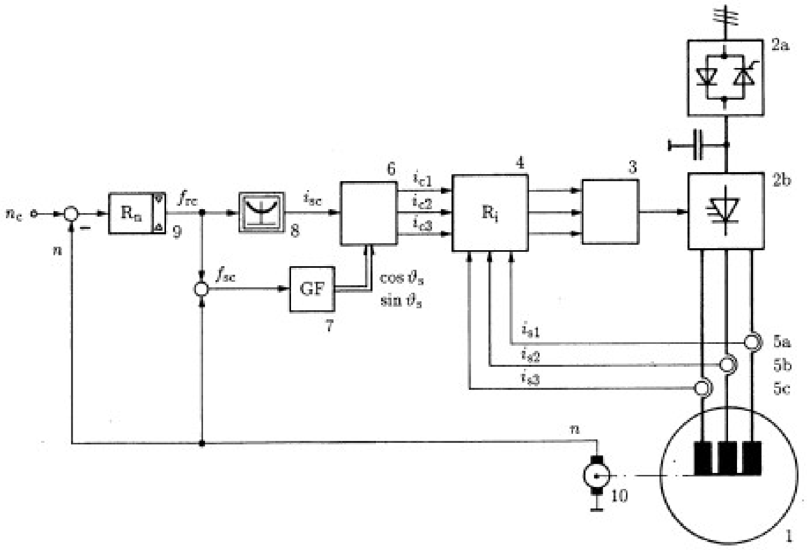

Figure 7 : Regulation strategy

The external loop is a speed regulation. Depending on the speed error, the regulation system sets the motor force by acting on the slip frequency (block 9).
The stator frequency is obtained by summing the desired slip frequency and the measured mechanical speed (converted in electrical Hertz). In this field, the motor parameters and especially the high slip frequency simplifies strongly the implementation of this addition.
Each phase current, corresponding to the slip frequency as in Fig. 6, is then set (block 8) and regulated with a PI regulator (block 4). The instantaneous phase of each current (block 6) is obtained by integrating the stator frequency (block 7). The phase difference between the three phase currents is 2π/3.

3.2 Realization

Current regulation (block 4) is one of the key point of this strategy. Especially when the frequency is high, the regulation must be very efficient. The regulation sampling period is set to 150 [µs].
The output voltage command signal is represented on the top of Fig. 8.

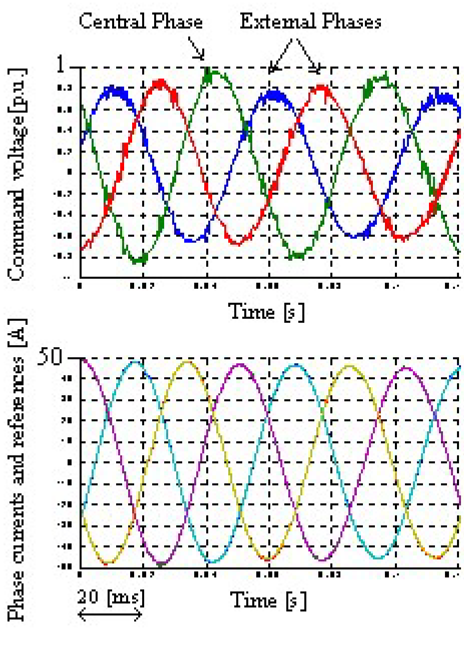

Figure 8 : Command voltage and phase currents

If symmetric current is imposed, more voltage is needed in the central phase. The reason is that the others phases surround this one. This confers to it a greater self-inductance.
To be able to present impressive demonstrations like stopping a few centimeters before the end of the rail, we make sure that there will not be any overshot.
Fig. 9 shows the chosen speed profile depending on the position error. It means that as long as the motor is far enough from the desired position (>1.2 [m]), the regulation sets the speed reference to a constant value of 3 [m/s] towards the desired position. As soon as the motor is within 1.2 meter from the final position, the speed reference is diminishing linearly with the position error.

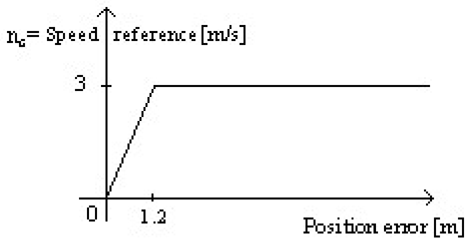

Figure 9 : Speed profile

Several strategies for the position regulation are admissible. In fact the chosen strategy is a proportional regulation with limitation. The main concern is that we do not want any overshot. Because the system behavior is good an integrator is not added for the position regulation. If it is done in the future, an antireset windup is mandatory to avoid integrator over saturation and overshoots.
Fig. 10 shows the results recorded on the real track. Position 0 corresponds to the lowest part of the track in the hollow of the rail in V (Fig. 3). The speed reference is ramped. In fact, an infinite acceleration can of course not be obtained. Ramping the reference avoids the integrator regulating the slip frequency to saturate and disturb the dynamic.

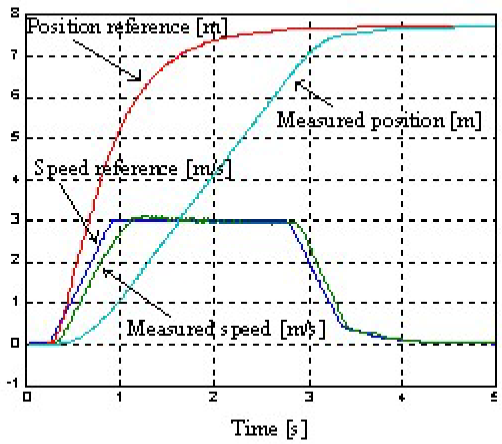

Figure 10 : Speed and position regulation

4 Sensorless speed regulation

4.1 Control strategy

Because the motor model is not accurate in every case, speed estimation will not be perfect, especially during transient behavior. Consequently the same strategy than above will not be used because its efficiency and its stability depend on a precise measuring of the instantaneous speed.
Rather than setting the currents, the regulation sets the voltage and always imposes constant and rated stator flux. This way the motor constantly has a maximum of force. To achieve that, the magnitude of

the phase voltage must vary proportionally with the frequency [6]. The phase difference between the 3 phase voltages is constant and equals $2\pi/3$. The regulation strategy is represented on Fig. 11.
The stator currents are measured to evaluate the field loss due to the stator resistance. This loss is compensated by acting on the voltage (designated by comp. R_s).
To obtain a given mechanical speed ω_m the slip ω_r is estimated. Adding this two results in the necessary stator frequency ($\omega_s = \omega_m + \omega_r$). This operation is designated by comp. slip on Fig. 11. This is then a regulation with positive feedback. We then must be cautious to avoid destructive behavior of the drive. In fact the currents have to be kept under rated values in any case.

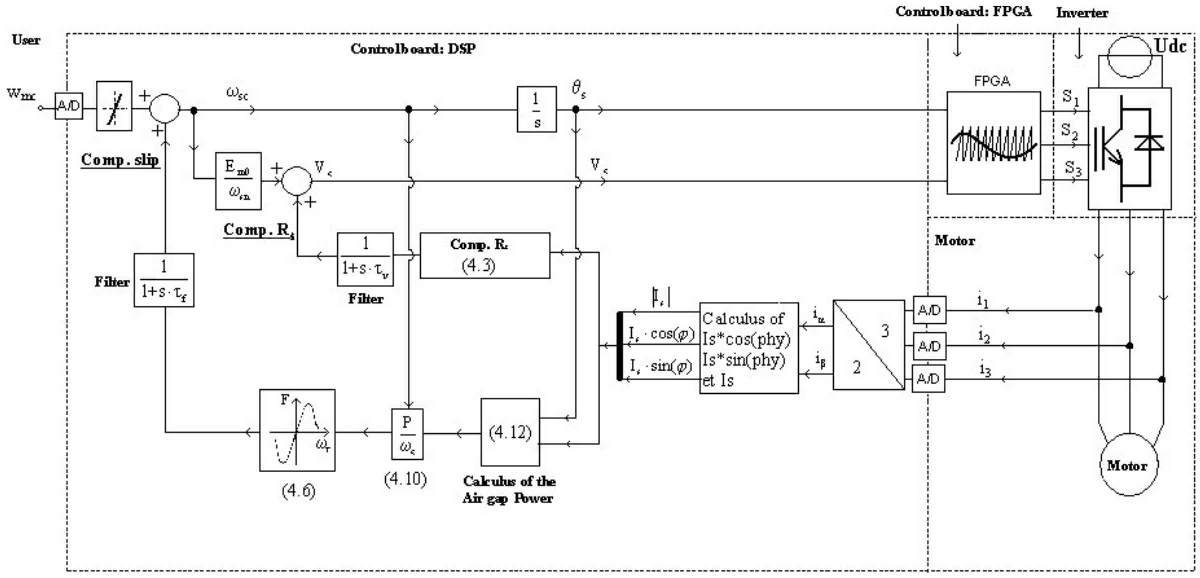

Figure 11 : Control strategy

Because of the positive feedback, it is mandatory to filter the slip estimation. Consequently, the user must not expect immediate reaction of the regulation system in case of load or speed transient.

4.2 Resistive Field losses compensation

To ensure constant and rated stator flux (E_{m0}) despite the varying phase current (I_s), the stator phase voltage (U_s) must be equal to:

$$U_S = I_S \cdot R_S \cdot \cos(\Phi) + \sqrt{\left(\frac{E_{m0} \cdot f_s}{f_{sn}}\right)^2 - (I_S \cdot R_S \cdot \sin(\Phi))^2} \quad (1)$$

As visible on figure 11, only the compensation is filtered.

4.3 Slip compensation

Because the speed is not measured, the slip frequency can not be precisely known. The following strategy estimates the slip by measuring only the currents.

Using the relation between slip and force:

$$F_L = \frac{2 \cdot F_k}{\frac{s}{s_k} + \frac{s_k}{s}} \quad (2)$$

We can obtain for the slip frequency ω_r :

$$\omega_r = \frac{F_L}{F_k + \sqrt{F_k^2 - F_L^2}} \cdot \omega_{rk} \tag{3}$$

The load force can be expressed:

$$F_L = \frac{\pi \cdot P_\sigma}{\tau_p \cdot \omega_s} \tag{4}$$

Where P_σ is the air gap Power, which can be evaluated using the following representation:

P_{EL} [W]	= Stator electric Power
P_{CUS} [W]	= Stator resistive losses
P_m [W]	= Iron losses
P_{CUR} [W]	= Rotor resistive losses
P_σ [W]	= Air gap power
P_{MEC} [W]	= Mechanical power
P_{F+V} [W]	= Friction + fanning losses
P_{SHAFT} [W]	= Power at the shaft

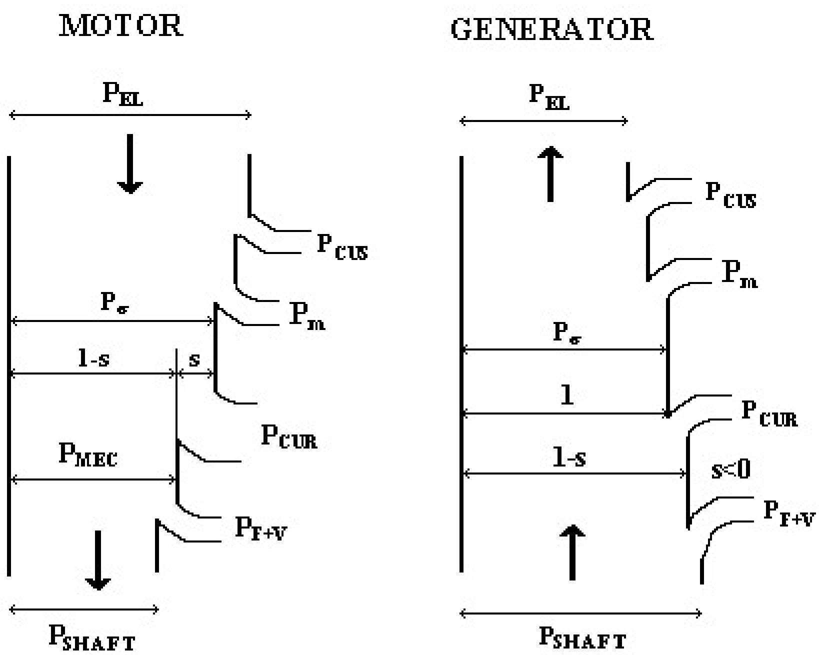

Figure 12 : Power flux in the motor

In the motor case, P_σ can then be written:

$$P_\sigma = P_{el} - P_{cus} - P_m = 3 \cdot U_s \cdot I_s \cdot \cos(j) - 3 \cdot R_s \cdot I_s^2 - \frac{\|U_m\|^2}{R_m} \tag{5}$$

with

$$U_m = U_s - \left(R_s + j \cdot \omega_s \cdot L_{fs}\right) \cdot I_s \tag{6}$$

By looking at (1), (3), (4) and (5), it appears that the only necessary machine parameters are R_s, R_m, L_{fs}, F_k and ω_{rk}.

If the parameters of the motor are unknown, the model can be simplified by choosing $R_m = 0$, which is equivalent to not consider any iron losses. In this case $P_m = 0$. The parameters still needed for the estimation algorithm are then R_s, F_k et ω_{rk}. These three parameters can be directly measured. Of course the estimation is then less precise, but still gives good results.

4.4 Results and comments

To show the behaviour of the motor in a general case, the speed reference is varied with a potentiometer. Fig. 13 shows that when the reference is not varied to quickly and for low speeds, the response is quite good, with only little oscillations.

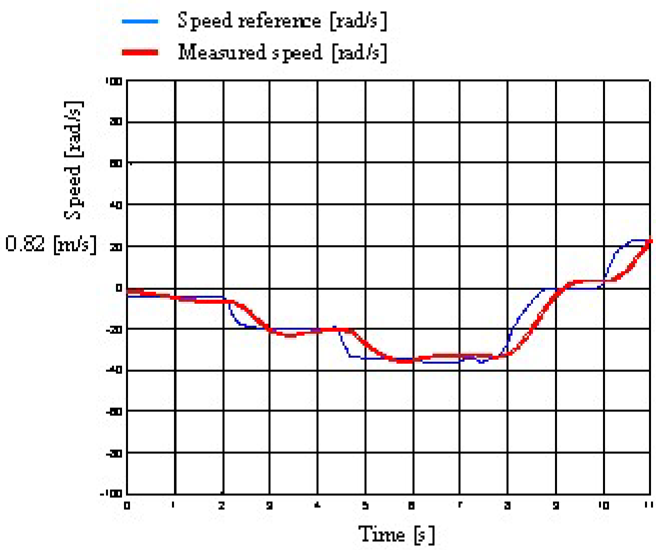

Figure 13 : Reference and measured speed

4.5 Synthesis

The thoughts and measures above make it possible to draw the following conclusions concerning a sensorless regulation.

Speed estimation and regulation algorithms are stable. This makes it possible to guaranty a stable behaviour in any operating case.

This strategy does not allow very good dynamic behaviour. Indeed the filtering of the speed estimation slows down the regulation response.

Speed estimation depends strongly of the rail temperature. Indeed the slip estimation depends strongly of the rotor resistance (R_r). If the rail temperature raises, the rotor resistance raises too. Consequently the breakdown slip (ω_{rk}) raises too (linearly with R_r). Because the strategy directly uses ω_{rk} to estimate the slip, it is quite sensitive to the variations of R_r.

Because the rotor (rail) is linear, a constant rotor resistance for every position can not be expected. In case a very precise regulation is demanded, a way of evaluating R_r has to be implemented. Some methods have been presented [7]-[9], they usually use the difference between the measured current and the modelled current.

Evaluating R_r will cause the strategy to be more complex and conduct to more precise modelling which would reduce the robustness. In the case of a sensorless drive, if a slight offset and regulation delay is tolerable, it's better not to complicate the strategy.

In other hand, the proposed regulation suits well the demonstration purposes. The motor can accelerate, run at steady speed and break in a very proper manner. It is able to climb steep segment and completely stop on them. The electrical and mechanical phenomenons can be observed using the control board facilities, making it possible to show the particular behaviours of the LIM and to compare it with conventional rotating motors.

5 Conclusion

A drive using a linear asynchronous motor has been realised. First the system is regulated in a "classical" way by using a speed sensor. The current regulation is excellent and allows using the drive in a very demonstrative manner.
In the next step, the same motor is regulated without any speed sensor. The regulation reacts well at any change of reference or resistant force and the system is stable. But the speed estimation is not perfect. Indeed the varying electrical characteristics of the rail with temperature and position have not been taken into account. In the case that a high precision is demanded, it will have to be done.
Also in case very high dynamic performances are desired, a better model will be needed in order to take care of the characteristic properties of linear motors.
In other hand, the drive can be well used as a demonstrative feature. The graphical procedures included in the control system allow showing easily the electrical and mechanical phenomenons occurring in the system. The two regulation strategies make it possible to show the advantages/inconvenients of a sensorless control, since the performances of the drive in each case can be easily compared.
Today, spectacular demos can be achieved for visitors and during information seminars for young college students. Actually and in the future, visiting students or other verification of research can also use the demo test track.

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