DIRECT TORQUE CONTROL OF A SINGLE-SIDED LINEAR INDUCTION MOTOR BASED ON SLIDING MODE

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Abstract **- A single-sided linear induction motor with reaction plates is introduced into a doubly fed long stator linear drive railway system in order to solve the switch problem and can be also applied in little-used areas of the railway. Due to the irregularity and incontinuity of the reaction plate in the switch area, a robust drive controller is required. As a result, a direct torque control based on sliding mode is applied, since it has shown superior dynamic performance and can react to critical environmental conditions fast and flexibly.**

Key words **- Direct torque control, Single-sided linear induction motor, Sliding mode, Doubly fed linear motor**

1. INTRODUCTION

Since 1997, a novel mechatronic railway system, which integrates linear drives into the conventional railway system based on a modular design, has been developed within the research project NBP-„Neue Bahntechnik Paderborn“[1].

This new system is based on the operation of shuttles instead of trains, which are guided by wheels and rails and driven via a doubly fed long stator linear motor. The primary (stator) is installed between the rails, and the secondary (rotor) is fixed below the undercarriage. The primaries are divided into segments supplied by different power supply substations. Both the primary and the secondary are fitted with three phase windings, so that they can generate the respective magnetic field completely independent from each other. Due to double feeding, energy can be transmitted from the primary to the on-board supply system. Hence, neither overhead wires nor contact rails are required in this railway system. In addition, a relative movement between two shuttles on the same primary segment becomes possible [4].

For long stator linear drive railway system, a problem arises with a switch. It is very difficult to install normal primaries through the switch, a special design on the primary would be required. For example, a bending switch is applied to long stator maglev railway systems: Transrapid in Germany and Yamanashi in Japan. Unfortunately, this solution cannot be practicable for NBP railway system due to full traffic of the shuttles and flexible convoy operation.

In order to generate the thrust force successively, a simple reaction plate composed of copper and iron is applied in the switch area. Certainly, the reaction plate can be also utilized in little-used areas of the railway to reduce the cost of the track. Then, the secondary and the reaction plate form a single-sided short stator linear induction motor. This requires a proper control strategy for drive control, especially in the transition area between long and short stator drive.

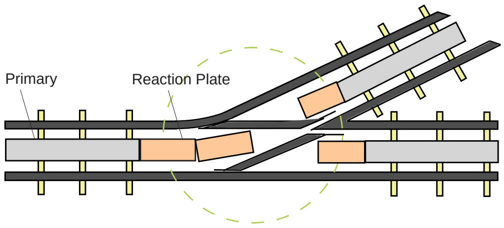

Fig 1. Sketch of a Switch

As well known, the induction motor seems to be the most complicated in terms of controllability. Furthermore, the switch crossing even puts forward a bigger challenge because of irregularity and incontinuity of reaction plates (Fig.1). Consequently a direct torque control (DTC) based on sliding mode is taken into consideration ([2],[3]), since DTC provides fast and precise torque response. Sliding mode control theory is one of the prospective control approaches for electrical machines, due to its order reduction, disturbance rejection, strong robustness and simple implementation [2].

2. CONTROL DESIGN

2.1 Sliding Mode Direct Torque Control

The induction machine model, with the stator currents (secondary) and rotor flux (reaction plate flux) as state variables, in the stationary reference frame is described by:

$$\begin{cases} \dot{i}_{S\alpha} = -\gamma_1 i_{S\alpha} + \dfrac{\beta}{T_R}\psi_{R\alpha} + \beta p\omega_m\psi_{R\beta} + \gamma_2 u_{S\alpha} \\ \dot{i}_{S\beta} = -\gamma_1 i_{S\beta} + \dfrac{\beta}{T_R}\psi_{R\beta} - \beta p\omega_m\psi_{R\alpha} + \gamma_2 u_{S\beta} \\ \dot{\psi}_{R\alpha} = \dfrac{M}{T_R} i_{S\alpha} - \dfrac{1}{T_R}\psi_{R\alpha} - p\omega_m\psi_{R\beta} \\ \dot{\psi}_{R\beta} = \dfrac{M}{T_R} i_{S\beta} - \dfrac{1}{T_R}\psi_{R\beta} + p\omega_m\psi_{R\alpha} \end{cases} \tag{1}$$

where

$$\sigma = 1 - M^2/(L_S L_R)\,,\ T_R = L_R/R_R$$

$$\beta = \frac{M}{\sigma L_S L_R}\,,\ \gamma_2 = \frac{1}{\sigma L_S}\,,\ \gamma_1 = \gamma_2\left(R_S + \frac{M^2}{L_R T_R}\right)$$

T_R is the rotor time constant, ω_m is the rotor mechanical speed, which is proportional to the linear speed of the carriage v_m. M, L_R, R_R, L_S and R_S represent mutual inductance, rotor inductance, rotor resistance, stator inductance and stator resistance respectively.

The thrust force between the stator and the rotor, i.e., between the secondary and the reaction plate is given by

$$F_x = \frac{3\pi p}{2\tau}\frac{M}{L_R}(i_{S\beta}\psi_{R\alpha} - i_{S\alpha}\psi_{R\beta})\,. \tag{2}$$

As far as linear induction motor is concerned, DTC means to control the thrust force by setting the stator voltage. Hence, the thrust force F_x, or rather the active part of the force, is a control variable. Clearly, the flux of the reaction plate plays an important role to the thrust force and must be controlled. In view of simplification, the flux square of the rotor $\psi_{R\alpha}^2 + \psi_{R\beta}^2$, instead of the flux ψ_R is set as another control variable

$$\begin{cases} T = i_{S\beta}\psi_{R\alpha} - i_{S\alpha}\psi_{R\beta} \\ \phi = \psi_{R\alpha}^2 + \psi_{R\beta}^2 \end{cases}. \tag{3}$$

Then the errors are equal to

$$e_T = T - T_{ref},\quad e_\phi = \phi - \phi_{ref}\,. \tag{4}$$

where T_{ref} and ϕ_{ref} are set values of the active thrust force and the square of the rotor flux.

An integral and a differential sliding surface functions are applied to a rotary motor in [3]. In this paper two differential sliding surface functions are adopted for the single-sided linear induction motor, namely

$$s = \begin{bmatrix} s_1 \\ s_2 \end{bmatrix} = \begin{bmatrix} \dot{e}_T + k_1 e_T \\ \dot{e}_\phi + k_2 e_\phi \end{bmatrix} \tag{5}$$

where $k_1, k_2 > 0$.

The stator voltage u can be chosen as in [3]:

$$u = \begin{bmatrix} u_{S\alpha} \\ u_{S\beta} \end{bmatrix} = -D^{-1}(b + k_c s) + u_i\,, \tag{6}$$

where k_c is a positive control gain and

$$u_i = -D^{-1}\begin{bmatrix} \mu_{c1}sign(s_1) \\ \mu_{c2}sign(s_2) \end{bmatrix} \tag{7}$$

$$D = \begin{bmatrix} d_{00} & d_{01} \\ 2\gamma_2\frac{M}{T_R}\psi_{R\alpha} & 2\gamma_2\frac{M}{T_R}\psi_{R\beta} \end{bmatrix} \tag{8}$$

comprising two auxiliary variables:

$$\begin{aligned} d_{00} &= (\gamma_1 - k_1)\gamma_2\psi_{R\beta} + \frac{\gamma_2\psi_{R\beta}}{T_R} - 2\gamma_2 p\omega_m\psi_{R\alpha} - \frac{\gamma_2 M i_{S\beta}}{T_R} \\ d_{01} &= (k_1 - \gamma_1)\gamma_2\psi_{R\alpha} - \frac{\gamma_2\psi_{R\alpha}}{T_R} - 2\gamma_2 p\omega_m\psi_{R\beta} + \frac{\gamma_2 M i_{S\alpha}}{T_R} \end{aligned} \tag{9}$$

It will be shown by using the Lyapunov function, if the sliding mode occurs on the surface $s = 0$ in a finite time, in other words, if the sliding surface s is attractive.

$$V = \frac{1}{2}s^T s \tag{10}$$

And its time derivative is $\dot{V} = s^T\dot{s}$ with

$$\begin{aligned} \dot{s}_1 &= \ddot{e}_T + k_1\dot{e}_T = (\ddot{T} - \ddot{T}_{ref}) + k_1\dot{e}_T = b_1 + (Du)(1,1) \\ \dot{s}_2 &= \ddot{e}_\phi + k_2\dot{e}_\phi = \ddot{\phi}_{ref} + k_2\dot{e}_\phi = b_2 + (Du)(2,1) \end{aligned} \tag{11}$$

$$\begin{aligned} b_1 = {} & \left(\gamma_1^2 - k_1\gamma_1 + \frac{\gamma_1 - k_1}{T_R} + p^2\omega_m^2\right)T + \left(-k_1\beta p\omega_m + \gamma_1\beta p\omega_m - \frac{\beta p\omega_m}{T_R}\right)\phi \\ & + \left(\frac{p\omega_m}{T_R} + 2\gamma_1 p\omega_m - k_1 p\omega_m\right)\phi_d + \gamma_2\psi_{R\alpha}\dot{u}_{S\beta} - \gamma_2\psi_{R\beta}\dot{u}_{S\alpha} - \frac{p\omega_m M m_i}{T_R} \\ & - \beta p\omega_m\dot{\phi} - \ddot{T}_{ref} - k_1\dot{T}_{ref} \end{aligned} \tag{12}$$

$$\begin{aligned} b_2 = {} & 2\frac{M}{T_R}\left(\frac{M}{T_R}m_i - \left(\frac{1}{T_R} + \gamma_1\right)\phi_d + \frac{\beta}{T_R}\phi + p\omega_m T\right) \\ & + \left(k_2 - \frac{2}{T_R}\right)\dot{\phi} - k_2\dot{\phi}_{ref} - \ddot{\phi}_{ref} \end{aligned} \tag{13}$$

with

$$\begin{aligned} \phi_d &= i_{S\alpha}\psi_{R\alpha} + i_{S\beta}\psi_{R\beta} \\ m_i &= i_{S\alpha}^2 + i_{S\beta}^2 \end{aligned} \tag{14}$$

The time derivative of the sliding surface functions should take the parameter variation $(\Delta b, \Delta D)$ into account. In view of parameter uncertainty of the linear motor, the time derivative of the sliding functions are modified as

$$\dot{s} = (b + \Delta b) + (D + \Delta D)u = b + Du + z \tag{15}$$

$$z = \Delta b + \Delta D u \tag{16}$$

$$\begin{aligned} \dot{V} = s^T\dot{s} &= s^T\left(b - b - k_c s - \begin{bmatrix} \mu_{c1}sign(s_1) \\ \mu_{c2}sign(s_2) \end{bmatrix} + z\right) \\ &= -k_c s^T s - \mu_{c1}|s_1| - \mu_{c2}|s_2| + s_1 z_1 + s_2 z_2 \le -k_c s^T s < 0 \end{aligned} \tag{17}$$

Clearly, the time derivative is definitively negative as long as μ_{c1} and μ_{c2} are assigned as the upper limits of z_1 and z_2.

To moderate the chattering problem, a smoothing factor is introduced in the sliding surface functions.

$$Sat(s_i) = \frac{s_i}{|s_i| + \lambda_i} \tag{18}$$

with $\lambda_i > 0$.

When the control error trajectories reach the sliding surface i.e. $s_1 = s_2 = \dot{s}_1 = \dot{s}_2 = 0$, it is obvious that the actual thrust force and rotor flux will converge to the set values.

2.2 Sliding Mode Flux Observer

The above mentioned control strategy can be implemented under the assumption that all the states are measured and known. However, the rotor (reaction plate) flux is not measurable easily, especially for the linear motor. Consequently, a sliding mode observer is developed to estimate the rotor flux.

The differential equations of the observer are proposed as

$$\begin{cases} \dot{\tilde{i}}_{S\alpha} = -\gamma_1 \tilde{i}_{S\alpha} + \dfrac{\beta}{T_R}\tilde{\psi}_{R\alpha} + \beta p \omega_m \tilde{\psi}_{R\beta} + \gamma_2 u_{S\alpha} + \Lambda_1 \\ \dot{\tilde{i}}_{S\beta} = -\gamma_1 \tilde{i}_{S\beta} + \dfrac{\beta}{T_R}\tilde{\psi}_{R\beta} - \beta p \omega_m \tilde{\psi}_{R\alpha} + \gamma_2 u_{S\beta} + \Lambda_2 \\ \dot{\tilde{\psi}}_{R\alpha} = \dfrac{L_m}{T_R}\tilde{i}_{S\alpha} - \dfrac{1}{T_R}\tilde{\psi}_{R\alpha} - p\omega_m \tilde{\psi}_{R\beta} + \Lambda_3 \\ \dot{\tilde{\psi}}_{R\beta} = \dfrac{L_m}{T_R}\tilde{i}_{S\beta} - \dfrac{1}{T_R}\tilde{\psi}_{R\beta} + p\omega_m \tilde{\psi}_{R\alpha} + \Lambda_4 \end{cases} \tag{19}$$

$\tilde{i}_{S\alpha}$, $\tilde{i}_{S\beta}$, $\tilde{\psi}_{R\alpha}$ and $\tilde{\psi}_{R\beta}$ are the estimated values of $i_{S\alpha}$, $i_{S\beta}$, $\psi_{R\alpha}$, $\psi_{R\beta}$. Λ_1 to Λ_4 represent the inputs of the observer, which should be determined yet.

The estimate errors are equal to

$$e = \begin{bmatrix} e_1 \\ e_2 \\ e_3 \\ e_4 \end{bmatrix} = \begin{bmatrix} \tilde{i}_{S\alpha} - i_{S\alpha} \\ \tilde{i}_{S\beta} - i_{S\beta} \\ \tilde{\psi}_{R\alpha} - \psi_{R\alpha} \\ \tilde{\psi}_{R\beta} - \psi_{R\beta} \end{bmatrix} \tag{20}$$

and their time derivatives are

$$\dot{e} = \begin{bmatrix} \dot{e}_1 \\ \dot{e}_2 \\ \dot{e}_3 \\ \dot{e}_4 \end{bmatrix} = \begin{bmatrix} \dfrac{\beta}{T_R}e_3 + \beta p \omega_m e_4 + \Lambda_1 \\ \dfrac{\beta}{T_R}e_4 - \beta p \omega_m e_3 + \Lambda_2 \\ -\dfrac{1}{T_R}e_3 - p\omega_m e_4 + \Lambda_3 \\ -\dfrac{1}{T_R}e_4 + p\omega_m e_3 + \Lambda_4 \end{bmatrix}. \tag{21}$$

The input variables of the flux observer can be chosen as:

$$\begin{bmatrix} \Lambda_1 \\ \Lambda_2 \\ \Lambda_3 \\ \Lambda_4 \end{bmatrix} = -\begin{bmatrix} \rho_1 sign(e_1) \\ \rho_2 sign(e_2) \\ \rho_3 sign(e_3) \\ \rho_4 sign(e_4) \end{bmatrix} \tag{22}$$

Obviously, not only the rotor flux but also the stator currents are estimated. Because the stator currents are measurable, the estimate errors of stator currents can be obtained in an easy way. If the sliding surface for the stator currents are attractive, the current convergence of the estimated currents is guaranteed, regardless of the estimate errors of rotor flux e_3 and e_4. Then, the estimate error of rotor flux can be fixed in terms of Λ_1 and Λ_2.

The sliding surface of the flux observer are defined as $s_{i_S} = \begin{bmatrix} s_1 & s_2 \end{bmatrix}^T = \begin{bmatrix} e_1 & e_2 \end{bmatrix}^T$, $s_{\psi_R} = \begin{bmatrix} s_3 & s_4 \end{bmatrix}^T = \begin{bmatrix} e_3 & e_4 \end{bmatrix}^T$.

Consider the sliding surface, if

$$\begin{cases} \rho_1 > \dfrac{\beta}{T_R}(\eta_1 + |\tilde{\psi}_{R\alpha}|) + \beta p |\omega_m| (\eta_2 + |\tilde{\psi}_{R\beta}|) \\ \rho_2 > \dfrac{\beta}{T_R}(\eta_2 + |\tilde{\psi}_{R\beta}|) + \beta p |\omega_m| (\eta_1 + |\tilde{\psi}_{R\alpha}|) \\ \rho_3, \rho_4 > 0 \end{cases}, \tag{23}$$

where η_1 and η_2 describe the upper limits of $|\psi_{R\alpha}|$ and $|\psi_{R\beta}|$, then the sliding surface for the current and the flux is attractive.

In order to prove the stability of the sliding surface, the Lyapunov function is utilized:

$$\begin{aligned} \dot{V} &= s_{i_S}{}^T \dot{s}_{i_S} = [e_1 \quad e_2][\dot{e}_1 \quad \dot{e}_2]^T \\ &< e_1\Big(\frac{\beta}{T_R}(e_3 - (\eta_1 + |\tilde{\psi}_{R\alpha}|)) + \beta p(\omega_m e_4 - |\omega_m|(\eta_2 + |\tilde{\psi}_{R\beta}|))\Big) + \\ &\quad e_2\Big(\frac{\beta}{T_R}(e_4 - (\eta_2 + |\tilde{\psi}_{R\beta}|)) + \beta p(\omega_m e_3 - |\omega_m|(\eta_1 + |\tilde{\psi}_{R\alpha}|))\Big) < 0 \end{aligned}$$

$$\begin{aligned} \dot{V} &= s_{\psi_R}{}^T \dot{s}_{\psi_R} = [e_3 \quad e_4][\dot{e}_3 \quad \dot{e}_4]^T \\ &= -\frac{e_3^2}{T_R} - \rho_3|e_3| - \frac{e_4^2}{T_R} - \rho_4|e_4| < 0 \end{aligned} \tag{24}$$

Clearly, the time derivative of the sliding surface for currents and flux are clearly negative.

A smoothing factor is also applied to the sliding surface of the observer in order to reduce the chattering.

$$Sat(s_j) = \frac{s_j}{|s_j| + \lambda_j} \tag{25}$$

with $\lambda_j > 0$.

3. EXPERIMENTAL RESULTS

The proposed control scheme was implemented at the test bed in the above mentioned Electrical Drives and Power Electronics Laboratory. An 8-m test bed was built for a linear drive module with 8 primaries and 2 secondaries. For the purpose of testing the proposed drive control a 2.4-m bilayer reaction plate is mounted at the test bed.

All the controls for the linear drive module are executed on a DSP (Motorola PowerPC 750, 480MHz) platform in this system.

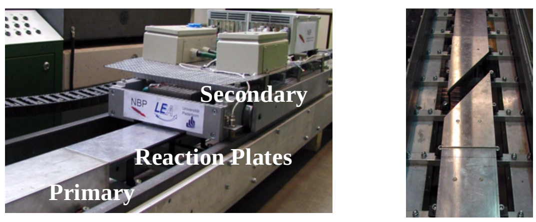

Fig 2. Test Bed and Reaction Plates with Gap

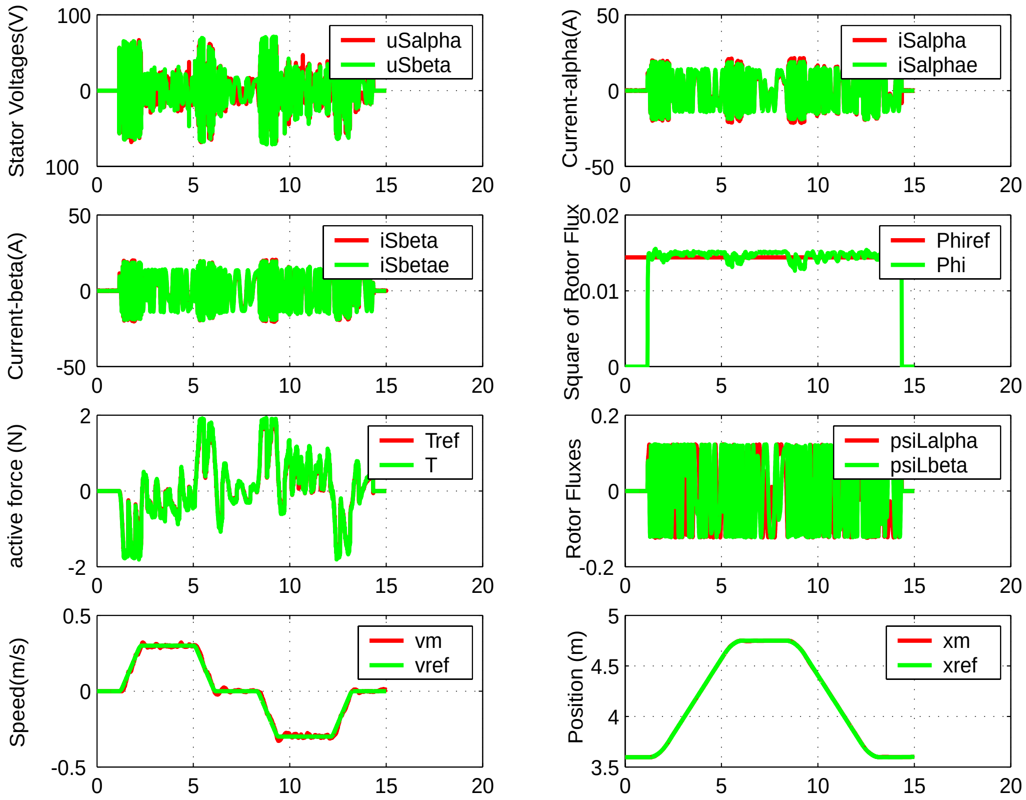

Fig 3. Experimental results of sliding mode DTC

Speed control can be achieved through the thrust force control. As a result, a trapezoidal speed reference command is applied to the linear drive module. Fig. 3 shows the experimental results with both the sliding mode controller and sliding mode observer working. The active thrust force, or rather the speed, and the square of the rotor flux are controlled to the reference values.

In order to simulate the critical condition in the switch area, a reaction plate with a gap is specially introduced into the experimental environment.

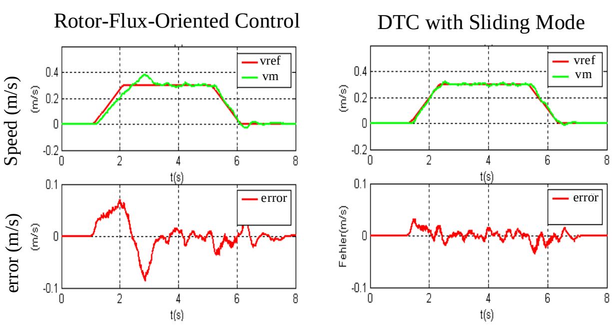

Fig 4. Comparison of field oriented control with sliding mode DTC

It is shown from the experimental results, DTC with Sliding Mode is faster and more robust to the parameter uncertainties than the conventional rotor-flux-oriented control under the same conditions.

4. Conclusion

In this paper, a new direct torque control based on sliding mode and a sliding mode flux observer are designed for a single-sided linear induction motor in a doubly fed long stator drive system. The proposed algorithm is verified by experiments.

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