Control Strategy for a Novel Combined Operation of Long Stator and Short Stator Linear Drive System

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Abstract

To realize a highly flexible propulsion system, a combined drive of long stator and short stator linear motors is applied to operate vehicles of the NBP (Neue Bahntechnik Paderborn, i.e. New Rail Technology of Paderborn in English) railway system. The control strategy of this combination is described. The presented experimental results, which show the control performance, are based on extensive theoretical investigations.

Keywords: Control, Linear drives, Field oriented control, Motion control, Sliding mode control, Test bench

1. Introduction

A novel mechatronic railway system has been developed within the research project NBP since 1997, which integrates linear drive technology into existing conventional railway system on a modular design base. The main principle of this new system is based on the operation of small trains, so-called shuttles, for transportation of both passengers and cargo. The shuttles drive to the destination directly and automatically without transferring procedures [1].
The shuttle is guided by ordinary wheels and rails and is driven via a linear motor. The primary (long stator) is installed between the rails, and the secondary (rotor) is fixed below the undercarriage.
In order to realize the flexible driving in two directions, the shuttles should be accelerated and decelerated arbitrarily. Both the primary and the secondary are equipped with three phase windings in order to generate their magnetic fields independently from each other. Due to doubly feeding, energy can be transmitted from the primary to the on board supply system and in other words, neither overhead wires nor contact rails are required in this railway system. In addition, the relative movement between two shuttles on the same primary segment becomes possible.
In view of saving energy and improving efficiency, the primaries are divided into segments, which are supplied by different power supply substations. Depending on the shuttle position they are switched on or off accordingly. The emerging tangential magnetic forces (thrust) between the primary and the secondary accelerate or decelerate the shuttle. As a result, the wheels are used only for steering and guidance, the wear will be reduced to a large degree.

2. Combined Linear Drives

As well known, a conventional railway is equipped with switches. Unfortunately, it is very difficult to install normal primaries through the switch, a special design of primary would be required. In fact, the switch problem is existent for all long stator linear drive system. For example, a bending switch is applied to long stator maglev trains: Transrapid in Germany and Yamanashi in Japan. Unfortunately, this solution cannot be practicable for NBP railway system because of flexible operation concept.

In order to generate the thrust force successively, reaction plates are implemented between the rails, which are composed of two layers: copper and iron. Hence, there is no active primary under secondary windings in the switch area temporarily. The secondary and the reaction plate form a single-sided short stator linear induction motor with the secondary being the short stator of this linear induction motor. This requires a suitable strategy in drive control, especially in the transition area between long and short stator operation.

Certainly, the reaction plates can be applied not only in the switch, but also in little-used areas of the railway to reduce the cost of the track.

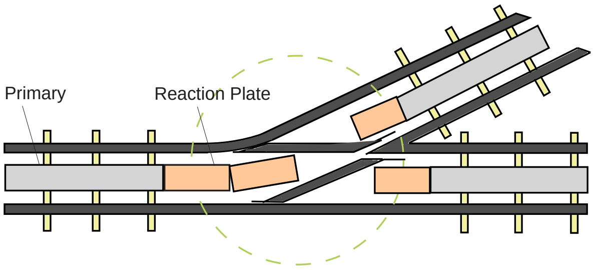

Fig. 1 Switch

2.1 Control of Long Stator Linear Drive

Considering the drive control, the system modelling and the control structure are based on a primary current oriented reference frame, which is the same for all secondaries. The reference q-axis primary current I_{Sq} [1] is set to zero by definition, then the electrical orientation of the primary current was chosen as the reference d-axis. Therefore, the secondary current in the orthogonal q-axis results in buildup of thrust force because of the interaction of primary flux linkage and the orthogonal secondary current.

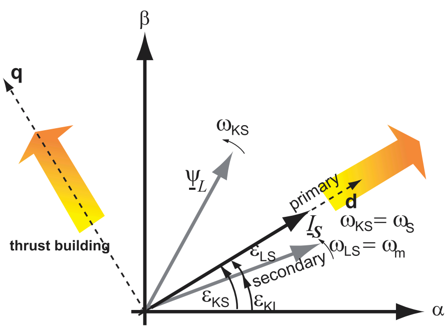

Fig. 2 Reference frame of long stator drive

The orientation on the primary current is applied, so that the reference frame moves along with the electrical position of the primary magnetic field. The drive control is designed on the basis of given drive profiles for the references in acceleration, velocity and position of the linear motor.

1. All variables with subscript 'S' are used for Primary, with subscript 'L' for secondary, with subscript 'RS' for reaction plate. 'S', 'L' and 'RS' are abbreviations for Stator (in English, Stator), Laeufer (in English, Rotor) and Reaktionsschiene (in English, Reaction Plate), respectively.

The synchronous speed of the primary v_S can be expressed by the mechanical speed v_m and the speed of secondary magnetic field relative to the secondary

$$v_S = v_m + v_L \tag{1}$$

and the angular frequency of primary and secondary current are given by

$$\omega_S = \omega_m + \omega_L = \pi\frac{v_m}{\tau} + \omega_L \tag{2}$$

with pole pitch τ.
If equation (2) can be met, with a constant air gap, the thrust force between the primary and the secondary is proportional to the product of primary current and secondary current. The thrust force of secondary is controlled by using the q-axis current i_{Lq}, and the orthogonal d-axis primary current is kept constant, in other words, there is a fixed phase relation between primary current and secondary current, which are controlled separately [2][3].
Contrary to conventional linear drive system, the amplitude of primary current is controlled to keep constant. Its frequency could be either a constant or varied based on eqn. (2).
For the drive control of long stator linear drives, there are thus four remaining variables to be controlled besides the primary current: q-axis secondary current and, superimposed, the acceleration, the velocity and the position of the motor.
The reference value of mechanical velocity of the secondary v_m (ω_m) is given by a profile generator. Due to doubly fed motor, the angular frequency of the primary current ω_S can be orientate to that of the secondary current ω_L, and vice versa. This flexibility offers a degree of freedom for the control strategy of combined operation of long stator and short stator linear drive systems.

2.2 Control of Short Stator Linear Drives

During long stator linear drive mode, most of the required energy is supplied by the primary, whereas the energy is completely provided by the secondary during short stator linear drive mode.
However, the secondary of NBP linear motor is designed as a doubly fed linear motor and relatively inappropriate to be operated as a short stator of a linear induction motor. As a result, the thrust force between the secondary and the reaction plate is smaller than that between the primary and the secondary. The ratio of the thrust force amounts to

$$F_{x\_}\text{Long Stator}/F_{x\_}\text{Short Stator} \approx 4 \tag{3}$$

According to the principle of induction motors, the thrust force between the secondary and the reaction plate is generated by raising the secondary frequency. The magnetic field of secondary must move faster than the secondary, i.e. the mechanical speed, so that the maximal thrust force can be achieved.
The angular frequencies of secondary current and current of reaction plate are given as follows:

$$\omega_L = \omega_m + \omega_{RS} \tag{4}$$

A linear induction motor model is introduced in the rotor-flux-oriented reference frame (reaction plate flux in this case).
Two different methods are investigated in order to achieve the optimal control results. One approach is the rotor-flux-oriented control, which lacks robustness to parameter uncertainties. It is obviously, the motor parameters are changing strongly in switch area. As a result, a direct torque control based on sliding mode is also applied, since it has shown superior dynamic performance and can react to the critical environmental conditions very fast and flexibly.

2.2.1 Rotor-flux-oriented Control

The classical block diagram of field-oriented control is illustrated in Fig.3. It is well known that the rotor flux is required for the implementation of thrust force or speed control. It is estimated instead of being measured [8].

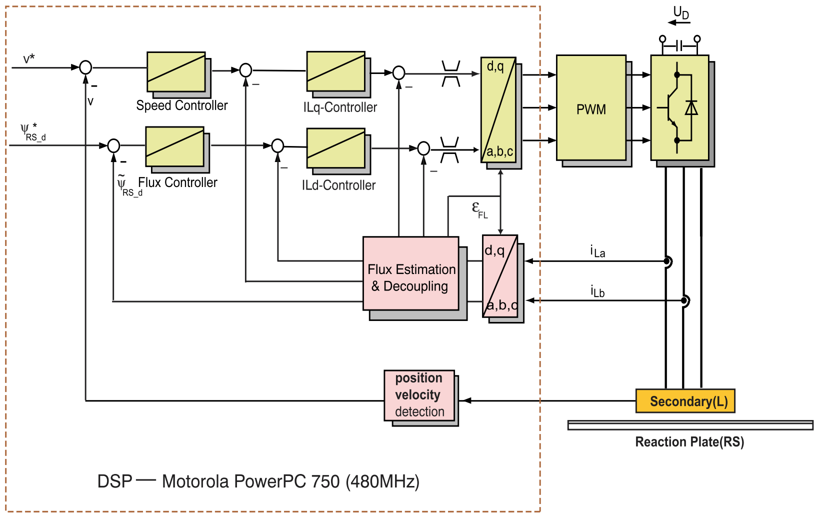

Fig. 3 Block diagram of field oriented control for short stator linear drives

2.2.2 Direct Torque Control based on Sliding Mode

Direct torque control (DTC) allows very fast torque responses and flexible control of an induction machine. As far as linear induction motor are concerned, DTC is to generate the secondary reference voltages from the thrust force error and flux error of reaction plate, and there is no inner current regulation loop compared with the field oriented control [4][6].
Because of reasons of order reduction, disturbance rejection, insensitivity to parameter variations and simple implementation of sliding mode control, DTC is carried out based on this principle. Moreover, a sliding mode flux observer to estimate the flux of the reaction plate is developed and implemented.

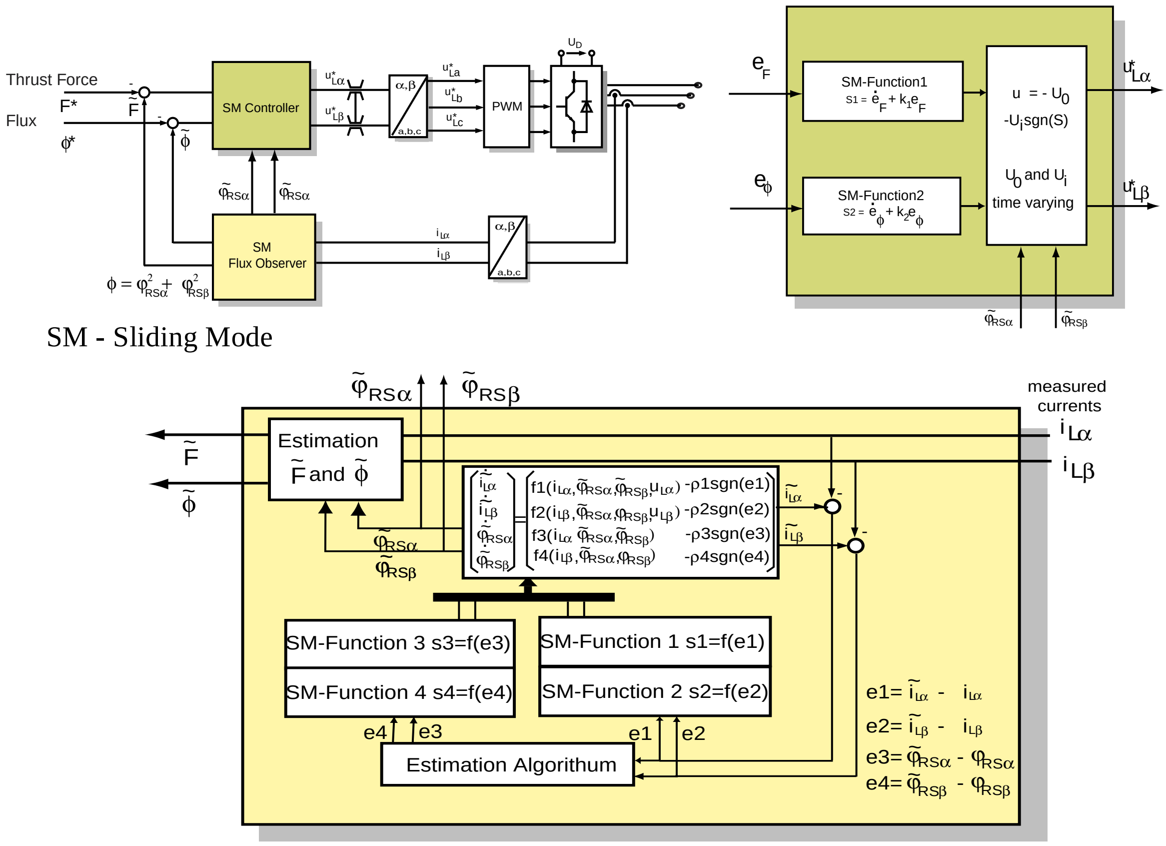

Fig. 4 Control scheme of direct torque control based on sliding mode

The thrust force of the short stator linear motor, i.e. between the secondary and the reaction plate, is expressed by

$$F_x = \frac{3\pi p}{2\tau}\frac{M}{L_{RS}}(i_{L\beta}\psi_{RS\alpha} - i_{L\alpha}\psi_{RS\beta}) \tag{5}$$

DTC for this short stator linear motor is to control the thrust force by using the secondary voltage inputs. Hence, the thrust force (F) 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 reaction plate $\psi^2_{RS\alpha} + \psi^2_{RS\beta}$, instead of the flux ψ_{RS} is set as another control variable.
Then, the control errors are equal to

$$e_F = F - F_{ref}, \qquad e_\phi = \phi - \phi_{ref} \tag{6}$$

An integral and a differential sliding mode function are applied to a rotary motor in [6]. In this paper, two differential sliding surface functions are adopted for the short stator linear motor, namely

$$\begin{cases} s_1 = \dot{e}_F + k_1 e_F \\ s_2 = \dot{e}_\phi + k_2 e_\phi \end{cases} \tag{7}$$

where k_1, k_2 are positive control gains.
The derivative of the sliding surfaces can be expressed as follows:

$$\dot{s} = b + Du \tag{8}$$

where u is the voltages vector of the secondary. $u = \begin{bmatrix} u_{L\alpha} \\ u_{L\beta} \end{bmatrix}$

If the reference voltages of the secondary are equal to

$$u = -D^{-1}(b + k_c s) - D^{-1}\begin{bmatrix} \mu_{c1} sign(s_1) \\ \mu_{c2} sign(s_2) \end{bmatrix} \tag{9}$$

then, the control errors e_F, e_ϕ converge to zero, where μ_{c1}, μ_{c2} and k_c are positive gains.
The flux of the reaction plate is estimated by using a sliding mode flux observer. The differential equations are given by

$$\begin{cases} \dot{\tilde{i}}_{L\alpha} = -\gamma_1 i_{L\alpha} + \frac{\beta}{T_{RS}}\tilde{\psi}_{RS\alpha} + \beta p\omega_m\tilde{\psi}_{RS\beta} + \gamma_2 u_{L\alpha} - \rho_1 sign(e_1) \\ \dot{\tilde{i}}_{L\beta} = -\gamma_1 i_{L\beta} + \frac{\beta}{T_{RS}}\tilde{\psi}_{RS\beta} - \beta p\omega_m\tilde{\psi}_{RS\alpha} + \gamma_2 u_{L\beta} - \rho_2 sign(e_2) \\ \dot{\tilde{\psi}}_{RS\alpha} = \frac{L_m}{T_R} i_{L\alpha} - \frac{1}{T_{RS}}\tilde{\psi}_{RS\alpha} - p\omega_m\tilde{\psi}_{RS\beta} - \rho_3 sign(e_3) \\ \dot{\tilde{\psi}}_{RS\beta} = \frac{L_m}{T_R} i_{L\beta} - \frac{1}{T_{RS}}\tilde{\psi}_{RS\beta} + p\omega_m\tilde{\psi}_{RS\alpha} - \rho_4 sign(e_4) \end{cases} \tag{10}$$

where the estimated errors and their time derivative are equal to

$$e = \begin{bmatrix} e_1 \\ e_2 \\ e_3 \\ e_4 \end{bmatrix} = \begin{bmatrix} \tilde{i}_{L\alpha} - i_{L\alpha} \\ \tilde{i}_{L\beta} - i_{L\beta} \\ \tilde{\psi}_{RS\alpha} - \psi_{RS\alpha} \\ \tilde{\psi}_{RS\beta} - \psi_{RS\beta} \end{bmatrix} \qquad \dot{e} = \begin{bmatrix} \dot{e}_1 \\ \dot{e}_2 \\ \dot{e}_3 \\ \dot{e}_4 \end{bmatrix} = \begin{bmatrix} \frac{\beta}{T_R}e_3 + \beta p\omega_m e_4 - \rho_1 sign(e_1) \\ \frac{\beta}{T_R}e_4 - \beta p\omega_m e_3 - \rho_2 sign(e_2) \\ -\frac{1}{T_R}e_3 + -p\omega_m e_4 - \rho_3 sign(e_3) \\ -\frac{1}{T_R}e_4 + p\omega_m e_3 - \rho_4 sign(e_4) \end{bmatrix} \quad (11)$$

and the parameters are defined as

$$\beta = \frac{M}{\sigma L_L L_{RS}}, \; \gamma_2 = \frac{1}{\sigma L_L}, \; \gamma_1 = \gamma_2\left(R_L + \frac{M^2}{L_{RS}T_{RS}}\right),$$

with ρ_1, ρ_2, ρ_3 and ρ_4 as positive control gains.

Because the currents of secondary are measurable, after the estimated currents converge to the measured one, the estimated errors of flux can be determined by respective errors of current. The design of the sliding mode controller and flux observer, as well as a comparison with field oriented control are described in [7] in detail.

2.3 Control Strategy for the Transition

Due to different drive principles and reference frames of long stator and short stator linear drives, an appropriate control strategy for the transition turns out to be very important. If the shuttle drives into the reaction plate area, then the angular frequency of the secondary will be increased to induce the eddy current in the reaction plate based on eqn. (4). The electromagnetic linkage between the secondary and reaction plate will generate a thrust force to drive the secondary.

During the switching of control structure, a stable drive ensuring continuous movement without jerk must be achieved in transition area. It deals with an optimal switching between two different control structures. When and how the switching takes place is a decisive point.

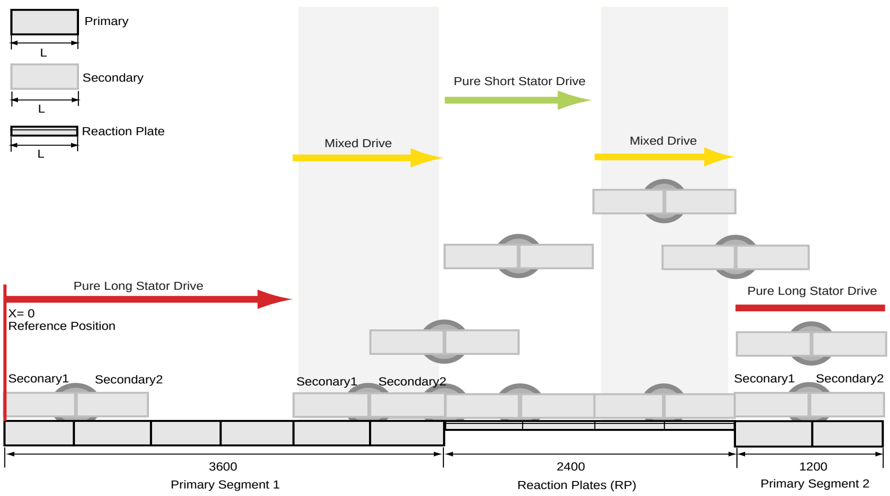

Fig. 5 Sketch of combined operation at the test bench

A sketch of the test bench (described in detail in 3.1) with two secondaries and eight primaries is shown in Fig. 5. A reaction plate is mounted between two primary segments. Except for pure long stator and pure short stator drive areas, there are also mixed operation areas, which are indicated in shade.

If the secondary is located in the transition area, not only the angular frequency of the secondary but also that of the primary should be increased to make the best use of whole secondary in order to generate the thrust force, in other words, one part of a secondary is operated as short stator on the one hand, on the other hand, it is also a secondary for long stator drives. To realize this, the angular frequency of primary current must orientate itself to the angular frequency of secondary according to eqn. (3), which is assigned by the short stator operation with equation (4).

Hence, it is important to determine the position x_0 (Fig. 6), where the switching of control structure should begin. This position should be fixed in a way that the minimal power is consumed from the on-board power system while satisfying the demand of the thrust force as well.

It is well known that the majority of thrust force is generated by the primary at long stator operation. The secondary current contains only q-axis component. Whereas, the required thrust force is provided completely by the secondary during short stator operation. In addition, the amplitude and the frequency of secondary current is assigned based on the principle of asynchronous motor, i.e. the secondary needs more power and causes more power loss at short stator operation than at long stator operation. Obviously, the short stator operation should be activated as late as possible. However, if the short stator operation is turned on too late, the required thrust force may not be achieved due to part of secondary above the primary. As a result, there is an optimal value of x_0, which can be fixed by taking the following factors into consideration: an optimal energy consumption of primaries and secondaries, the velocity of the secondary, the demand of thrust force and an optimal dynamic performance.

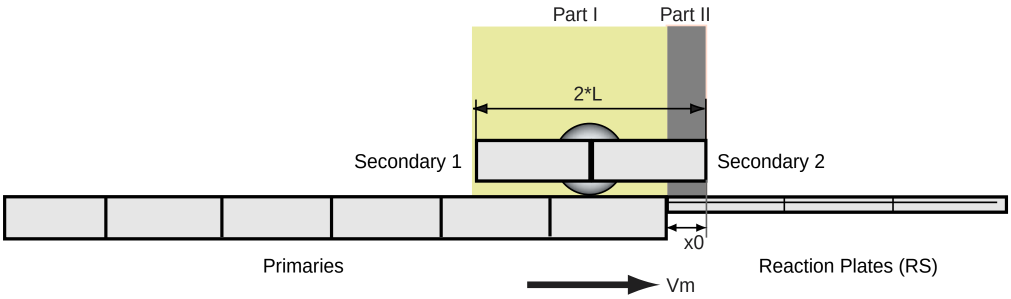

Fig. 6 Transition area at test bench

As above mentioned, the primary and the secondary can generate their magnetic fields independent from each other due to doubly feeding nature of the motor. For this reason, there are two control strategies for the transition:

- the angular frequency of the primary remains unchanged

Regardless of the drive mode - pure long stator, pure short stator or mixed drive, the angular frequency of the primary remains the same.This is the simplest strategy because the control of the shuttle takes place only in the shuttle, however it is not an effective strategy. In the transition areas, only a part of the secondary covers the primary. The rest is above the reaction plates. A jerk to the secondary could result. The asynchronous magnetic fields of the primary and the secondary could accelerate or brake the drive module alternately, influencing the dynamic behavior to a large extent.

- the angular frequency of the primary is increased accordingly

In the transition areas (shaded in Fig. 5), the angular frequency of the primary is increased according to that of the secondary, in other words, the magnetic fields of the primary and the secondary are moved synchronously.

Once one of the secondaries drives into the reaction plate area, it is operated in short stator linear driving mode. The angular frequency of the primary is set to be equal to that of this secondary, the other secondary is operated still as long stator linear drive, until all the secondaries are within the reaction plate area. Then, two secondaries are operated as short stator linear drive.

The second control strategy is applied on the test bench to implement the combined drives of long stator and short stator motors.

3. Experimental Results

3.1 Test Bench

An 8-m test bench was built for a linear drive module with 8 primaries and 2 secondaries. The primaries are divided into two segments supplied by two converters. A single axle undercarriage is applied, on which two secondaries are fixed via the middle of them [1]. For the purpose of testing the combined drives a 2.4-m double layer reaction plate is mounted between two primary segments. The mechanical air gap of long and short stator linear motors are set about 10 mm.
The cascade and feed forward controls for one linear drive module are executed on a DSP platform in this system.

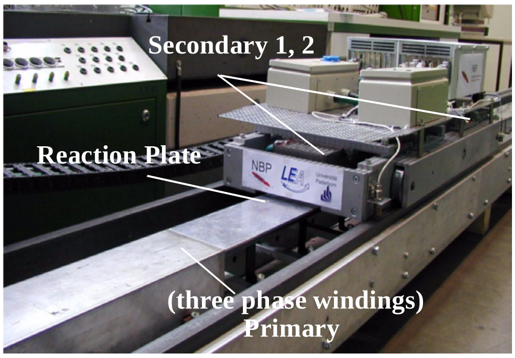

Fig. 7 Test bench of linear drive module in Lab

3.2 Flexible Drive Profile

The maximal thrust force, generated by the secondary and the reaction plate in short stator operation amounts to a quarter of that by the secondary and the primary in long stator operation, in other words, the accelerating ability of the carriage depends on the position of the carriage. Considering this situation, a profile generator is designed to calculate a most practicable profile, including acceleration, speed and position for the automatic operation of the drive module.

3.3 Experimental Results

A trapezoidal speed command is applied to the test bench in order to test the performance of the proposed control strategy. x0 is equal to half of the secondary length.
The drive module drives automatically from the origin to the middle of the reaction plate and then stops. Results of actual position and speed shown in Fig.8 prove that the proposed control strategy works very well. The angular frequency of primary current is increased along with that of the secondary current.

4. Conclusion

A novel solution for long stator linear drive systems by introducing short stator drive mode is presented in this study, which was successfully realized in the laboratory.

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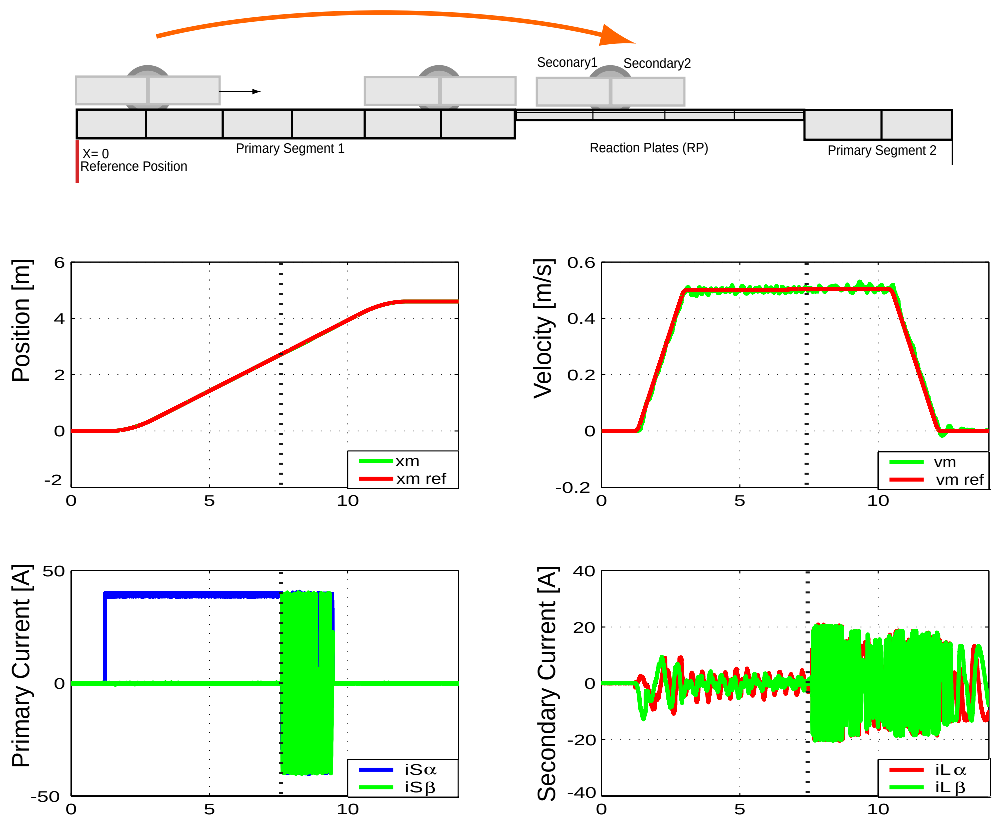

Fig. 8 Experimental results of combined drives on the test bench