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MODELLING AND CONTROL OF A LONGSTATOR-LINEARMOTOR FOR A MECHATRONIC RAILWAY CARRIAGE

Markus Henke, Horst Grotstollen

University of Paderborn
Institute for Powerelectronics and Electrical Drives
D-33095 Paderborn, Germany
phone: +49 (5251) 602209, fax: +49(5251) 603443
e-mail: {henke, grotstollen}@lea.upb.de Internet: http://lea.upb.de

Abstract: This contribution presents a linear drive module as mechatronic actuator for a new railway carriage. Here, according to the mechatronic methods, a double-fed longstator-linearmotor will be chosen and the control structure will be designed by means of modelling. The next steps in mechatronic design procedures are simulation and experimental validation. The presented motor propells a mechatronic railway carriage, which is also fitted with active suspension/tilting and steering modules.

Keywords: Linear Motors, Modelling, Force Control, Simulation

1. INTRODUCTION

In conventional railway systems, the functions supporting, guiding, driving and braking are realized exclusively by means of tiny surfaces where the wheels touch the rail. The main disadvantage of this force-closed drive are the high friction between wheel and rail and the decrease in force closure in case of wet and icy rails. Systems driven by a linear motor like German Transrapid will offer the advantage of a frictionless drive of the respective vehicle. But many of these systems require a new line of their own. The environment will be extensively affected, so that will seriously endanger future realization. By means of mechatronic methodology the research team *Neue Bahntechnik Paderborn* (NBP)[1] has designed a mechatronic, modular railway system that combines the advantages of the two systems (Lückel, 1999). This new train system is based on three mechatronic function modules (MFM): Drive and brake module, suspension and tilt module and supporting and guiding module (Fig. 1). The drive- and brake modul consists of a longstator linear motor.

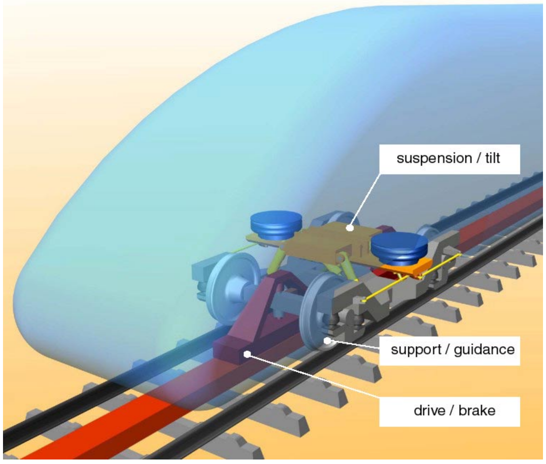

Fig. 1 – Mechatronic railway carriage

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Every MFM is based on the consistent use of information and communication techniques. In combination with actuators and sensors, information technique enables a completely novel mechatronic system boosting special performances. The dynamics of the controlled vehicle are determined by controllers, integrated in information processing units.

The basic concept is to realize the drive function not by way of the wheels but by a linear drive integrated into the existing rail system. By using the active suspension/tilt technology the ride comfort will be improved. In combination with an active steering, the wear of wheels and rails will be minimized. By coupling with the passive primary suspension, these three modules make up an Autonomous Mechatronic System (AMS) that allows to build up the fully automated shuttle, without a driver, and for the transport both of passengers and of goods. Several shuttles linked purely by information processing, are combined to make up a Crosslinked Mechatronic System (CMS) that corresponds to the highest hierarchical level.

As the mechatronic actuator the linear drive technology acts a very important part in this concept of new train system and its further details will be treated in this paper.

The design of such a complex system requires clear structuring. To analyze the behaviour of the linear motor its mathematical model is drawn up. A control structure has to be found to deal with disturbances affecting the system. After that the overall dynamical behaviour of the drive is analyzed via simulation and validated by experiments. The next step in the mechatronic design procedure is the optimization of the overall system.

2. THE SYSTEM STRUCTURE

The linear motor in the main consists of the primary (stator) which is installed between the rails and the secondary, being mounted on the undercarriage.

The stator is supplied with AC current, so that a magnetic travelling field is generated in the stator windings. It exerts a force on the electrically excited secondary in the carriage. Primary and secondary are interlinked magnetically by the air which is being ensured by the tracking of the carriage. A comfortable control of the longitudinal dynamics can be obtained because the propulsion force is directly transmitted to the secondary without losses due to the transmission.

In order to avoid constant power supply to the entire track, it is divided into segments that are supplied with voltage by different power-supply units (substations). They index the power supply to the next position in dependence of that of the coach. As a result, the energy consumption of the drive is optimized because the track is supplied with voltage only in the respective segment where there is a coach on the stator.

The drive module comprises the power supplies, the sensors and the information processing for vehicle- and stator field control (Fig. 2).

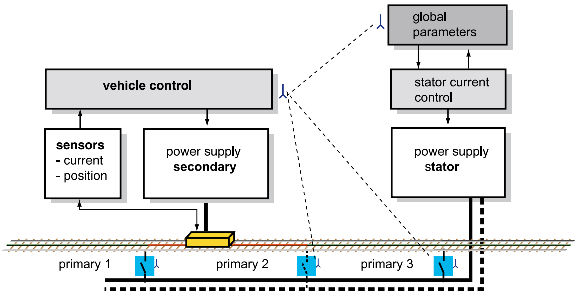

Fig 2 - Overall structure of the mechatronic drive system

In order to make the carriage motion flexible, a relative motion between different coaches on the same stator has to be made possible. This puts high demands on the actuators as well as on the control and information-processing units.

A synchronous long-stator linear motor is not able to produce the desired relative motion; therefore the secondary in the coach will be equipped with a three-phase winding. Thus the excitation flux can be varied relative to the position of the coach and an asynchronous operation comes within reach (Fig. 3).

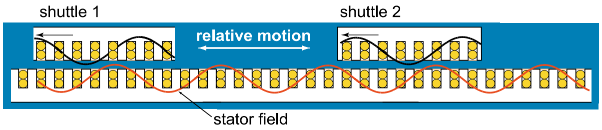

Fig. 3: Thrust build-up and relative motion

The actual thrust control is effected on board and the motor is double-fed, i.e., primary and secondary can align their magnetic fluxes at any time (Henke 1999, Kiel 1999).

3. MODELLING OF THE DRIVE SYSTEM

The primary and the secondaries share the same stator current as the statorflux linkage depends also on the magnetic flux of the secondary. The currents in the secondaries are going to be controlled according to a uniform coordinate system common to all coaches; thus the interactions between the shuttles can be traced clearly. The coordinate system employed is thus oriented according to the stator current. The stator-current orientation makes up the d-axis of the coordinate system with: $i_{Sq} = 0$.

The model of the secondary in the coach is also built up oriented according to the stator current.

The electrical subsystem of the double-fed linear motor relies on those of the asynchronous linear motor (Gieras 1995). Variables oriented according to the secondary are indexed *R*, all stator variables, *S*. As regards motor parameters, there are:

L_h, L_σ :mutual and leakage inductances

R_R, R_S :resistance of secondary and primary

ψ_R , ψ_S :flux linkages

ω_{KS} : angular velocity of the stator field

ω_{RS} : angular velocity of the secondary

σ , ρ : leakage and resistance coefficients

The equations of electrical machines can be subdevided into voltage- and force behaviour.The complex equations relating to the voltage of the primary and secondary are displayed in (1) and (2):

$$\sigma L_S \frac{d\underline{i}_S}{dt} = \underline{u}_S - R_S \underline{i}_S - \frac{L_h}{L_R} \underline{u}_R + \frac{L_h R_R}{L_R} \underline{i}_R + j\omega_{RS} L_h \underline{i}_R + j\omega_{KR} \frac{L_h^{\ 2}}{L_R} \underline{i}_S - j\omega_{KS} L_S \underline{i}_S \tag{1}$$

$$\sigma L_R \frac{d\underline{i}_R}{dt} = \underline{u}_R - R_R \underline{i}_R - \frac{L_h}{L_R} \underline{u}_S + \frac{L_h R_S}{L_R} \underline{i}_S + j\omega_{RS} L_h \underline{i}_S + j\omega_{RS} \frac{L_h^{\ 2}}{L_R} \underline{i}_R - j\omega_{KR} L_R \underline{i}_R \tag{2}$$

The stator current oriented coordinate system is used, so that (1) and (2) have to be transformed relating to the statorcurrent position. Transformation yields the real part of the equation (1) as follows:

$$\sigma L_S \frac{di_{Sd}}{dt} = u_{Sd} - R_S i_{Sd} - \frac{L_h}{L_R} u_{Rd} + \frac{L_h R_R}{L_R} i_{Rd} - \omega_{RS} L_h i_{Rq} \tag{3}$$

The imaginary part is

$$\sigma L_S \frac{di_{Sq}}{dt} = u_{Sq} - R_S i_{Sq} - \frac{L_h}{L_R} u_{Rq} + \frac{L_h R_R}{L_R} i_{Rq} - \omega_{RS} L_h i_{Rd} + \omega_{KR} \frac{L_h^{\ 2}}{L_R} i_{Sd} - \omega_{KS} L_S i_{Sd} = 0 \tag{4}$$

The angular frequency of the stator current results in

$$\omega_{KS} = \frac{1}{L_S i_{Sd}} \left(u_{Sq} - \frac{L_h}{L_R} u_{Rq} + \frac{L_h R_R}{L_R} i_{Rq} - \omega_{RS} L_h i_{Rd} + \omega_{KR} \frac{L_h^{\ 2}}{L_R} i_{Sd} \right) \cdot \tag{5}$$

The dynamics of the stator current are represented in equations (3) and (4). To determine the electrical states in the secondary, the equations of the secondary voltage have to be derived; they yield the secondary current components:

$$\sigma L_R \frac{di_{Rd}}{dt} = u_{Rd} - R_R i_{Rd} - \frac{L_h}{L_S} u_{Sd} + \frac{L_h R_S}{L_S} i_{Sd} - \omega_{KS} \frac{L_h^{\ 2}}{L_R} i_{Rq} + \omega_{KR} L_R i_{Rq} \tag{6}$$

$$\sigma L_R \frac{di_{Rq}}{dt} = u_{Rq} - R_R i_{Rq} - \frac{L_h}{L_S} u_{Sq} + \omega_{RS} L_h i_{Sd} + \omega_{KS} \frac{L_h^{\ 2}}{L_R} i_{Rd} - \omega_{KR} L_R i_{Rd} \tag{7}$$

The force equation of the motor is the following:

$$F_m = -\frac{3\pi}{2\tau_p} L_h \cdot i_{Sd} \cdot i_{Rq} \quad . \tag{8}$$

The power is proportional to the stator current i_{Sd} and to the secondary component i_{Rq}. Fig. 4 displays the block diagram of the motor. Here, five variables have to be controlled: The velocity of the coach, the components of the rotor current, the stator-current frequency, and the amplitude of the stator current (i_{Sd}) .

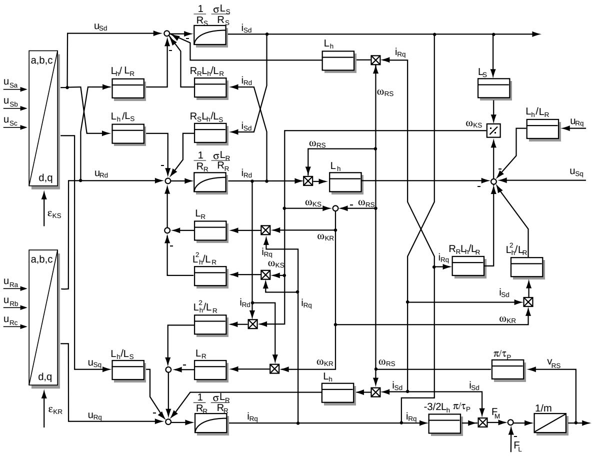

Fig.4 - Double-fed linear motor

4. DRIVE CONTROL

We have already stated that the system behaviour forces us to decouple the stator-field control from the control of the coach.

4.1 Control of the Stator Field

Contrary to conventional linear drive systems, the stator here is a unit whose current has to be controlled as to constant frequency and amplitude during operation. The frequency depends on the vehicle velocities and affects the energy flow between stator and secondary. Several vehicles on the same stator segment are coupled via the stator windings. Disturbances in stator current control are the voltages induced by several shuttles operating on the same stator.

4.2 Control of the Longitudinal Dynamics

Every coach controls its own longitudinal dynamics via the electrical position of the secondary current and uses the stator flux common to all coaches. Here, the control takes into account the switching between the stator segments. The segments the shuttle is running into, have to build up the current just before the secondary enters the segment. As the stator current i_{Sd} is fixed at a constant value, the only remaining actuating variable for thrust control is the q-component i_{Rq} of the secondary current, cf. Equ. (8).

The actual values of the current components i_{Rd} and

i_{Rq} are directly determined from the measured primary and secondary currents.

Fig. 5 displays in detail the overall structure of the coach control:

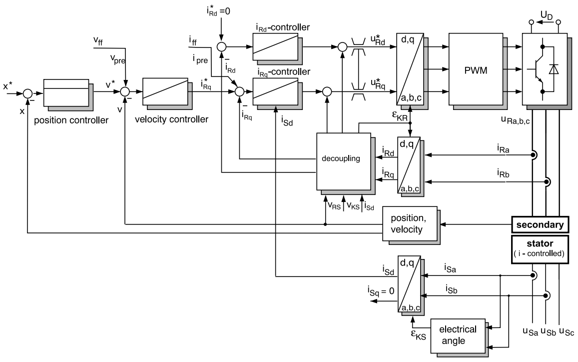

Fig. 5 - Stator-current-oriented control structure

A converter is generating the voltage values required by the controllers. On board, a converter supplies the on-board batteries and the excitation windings.

For the control of the carriage, there are thus three remaining variables to be controlled: the components of the secondary current and, superordinated, the velocity v_{RS} of each carriage. All these control loops are realized with PI-controllers. The decoupling structure is used to decouple the d- and q-loops of the secondary currents. Feedforward control of velocity and secondary current yields a reduction of the position error.

The air gap between the primary and the secondary has to be assessed because a change would immediately affect thrust and braking forces (Gieras 1995). Alterations in the air gap affect the build-up of force and voltage as alterations in the gain, so the thrust controller will have to be adapted accordingly.

The described control structure can be used to control several vehicles on the same stator segment. Each vehicle is fitted with local thrust and velocity control. The stator current is controlled seperately (Fig. 6).

5. SIMULATION

A simulation model has been made for the control shown above. It includes the cascaded vehicle control and the power management of two shuttles, operating on the same stator segment. The energy flow between stator and secondary can be analysed via currents and voltages in primary and secondary.

Fig. 7 displays the simulation results. At t = 0.1s, a step in the reference value of the velocity up to 10 m/s affects shuttle 1. Shuttle 2 accelarates up to 13 m/s. The stator field is controlled to 12 m/s. In this operation point, shuttle 1 runs subsynchronous because its velocity is lower than the stator-field velocity.

Both shuttles are supplied the same secondary current to run at constant speed with constant load. The secondary voltages are different and represent the difference in energy consumption. Shuttle 1 is able to reload its batteries, and shuttle 2 has to deliver energy for moving faster than the stator field.

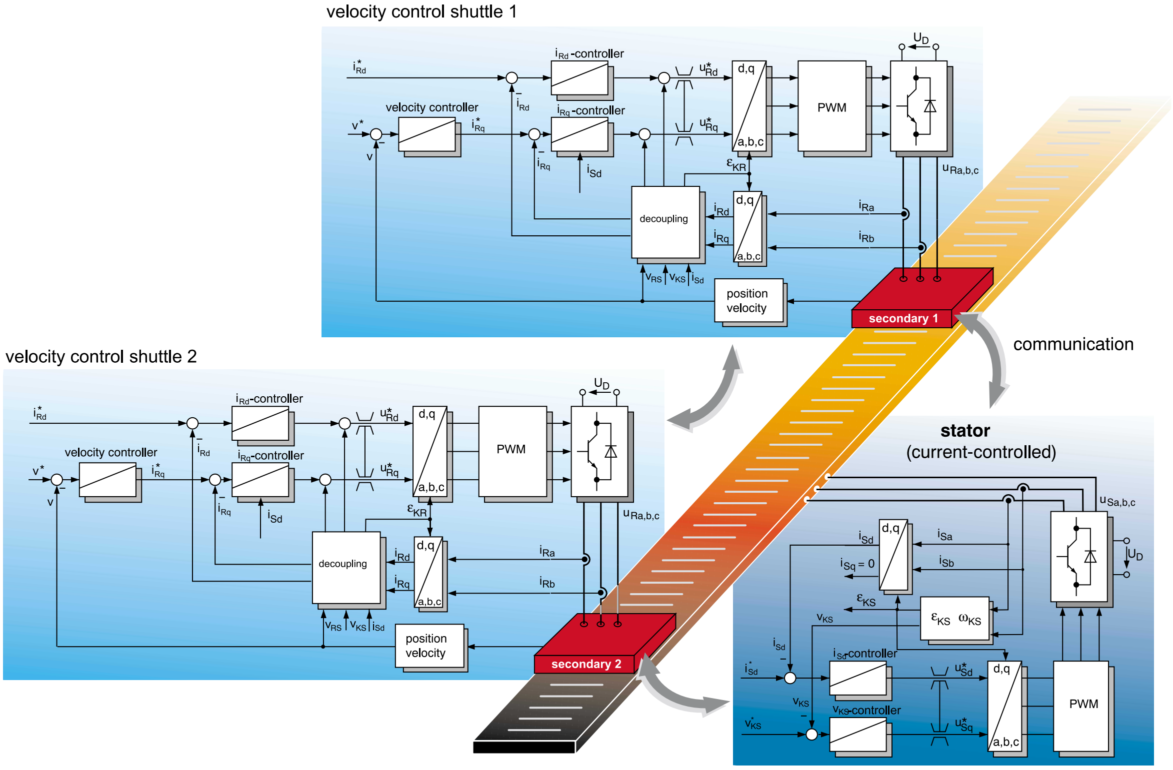

Fig. 6 – Control of two shuttles on the same stator

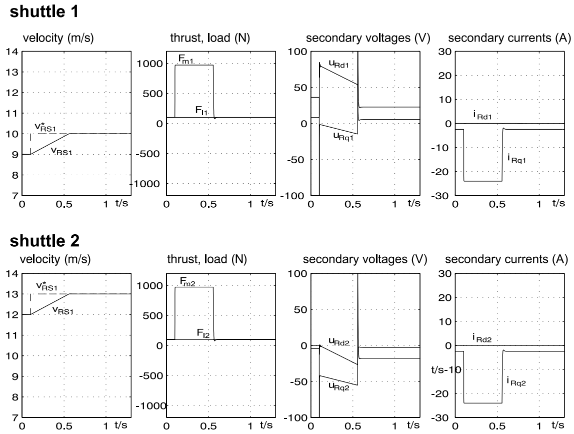

Fig. 7 - Simulation results

6. EXPERIMENTS

To validate the theoretical investigations, a testbed has been built up. It is designed to reproduce the real system in 1:2.5 scale. The secondary's mass is 120 kg, and the position range is 6.8 m.

The power supplies of primary and secondary are realized by two converters. They communicate via an interface board with the DSP-Board. The control of the stator current, and the motion control is also realized on the digital signalprocessor (Fig. 8).

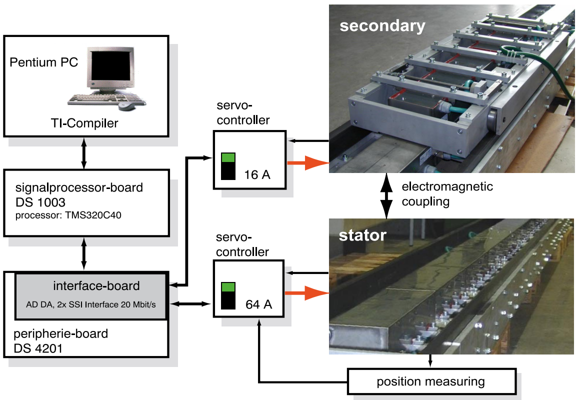

Fig. 8 – Testbed for the linear drive

The references of position, velocity and acceleration are shown in Fig. 9. They are calculated off-line and used for feedforward control.

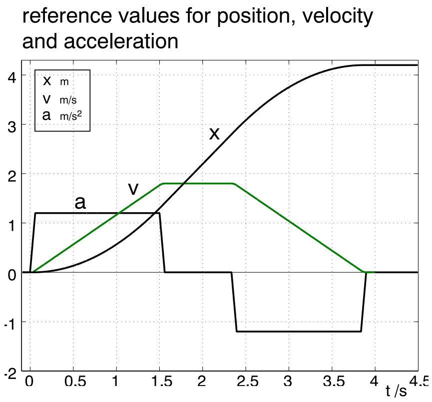

Fig: 9 – Reference profile

The vehicle accelerates with a maximum acceleration of 1.2 m/s^2 up to a velocity of 1.8 m/s .

Fig. 10 shows the measured secondary current i_{Rq} and the position difference. While acceleration the current reaches its maximum. It shows oscillations which appear because of the construction of the stator segments. The end of each segment is fitted with less windings, so that the main inductivity L_h depends on the secondaries position. This yields in force disturbances which have to be compensated by the current control, cf. Equ. (8).

The disturbances can be stored in a characteristic scale, so that the current controller can be adapted to compensate them.

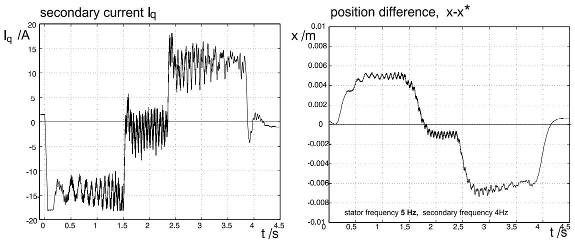

Fig. 10 – Secondary current and position difference

7. CONCLUSION

The presented double-fed linear drive has been analyzed by means of mechatronic methodology. The mathematical model has been set up and the equations have been analyzed. A control structure with stator current orientation emerged. The longitudinal dynamics of the carriage are controlled by the linear drive, and the stator current is treated seperately. Finally, experiments on the testbed close the mechatronic design procedure.

8. REFERENCES

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