Linear-Motor Drive with Long-Stator and Short-Stator Operation

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***Abstract* –At the University of Paderborn six chairs are developing a new railway system which is characterized by the use of linear-motor driven shuttles which travel on demand instead of scheduled trains. In the paper the track-side and vehicle-side electric parts of the system and their control are presented.**

KEYWORDS

Railway System, Linear Motor, Power Supply, Drive Control

I. INTRODUCTION

At the University of Paderborn a new railway system NBP (Neue Bahntechnik Paderborn) is under investigation which is characterized by the following features [1]:

• Instead of trains travelling according to a fixed schedule autonomous shuttles travelling on request are used for transportation of passengers and cargo. By this change short time for transportation can be achieved without high speed operation because passengers can travel any time and do not loose time by changing trains. On the other hand cargo does not spend most of transportation time on switch yards where trains are formed and split.

• On main routes all shuttles travel with the same speed of about 160 km/h; neither passenger traffic and cargo traffic nor short distance traffic and long distance traffic are separated. When arriving at its destination a shuttle has to leave the main track for disembarking people or unloading cargo.

• Shuttles travelling on the same track can form convoys and save energy by reducing the resistance caused by relative speed.

• For driving the vehicles linear motor technology is used which allows to generate great force and to climb steep slopes. With linear motor generation of thrust force is performed without moving parts and without causing wear at the wheels.

• Since the wheels are not driving it is easy to introduce active steering of the vehicles. This feature is required because conventional switches cannot react as fast as necessary when a shuttle, travelling in a convoy, has to leave the main route.

• Last not least, shuttles are equipped with hydraulic cylinders for active tilting and suspension which is introduced to allow higher speed and to improve the comfort for passengers in particular when driving through curves.

The undercarriage of the shuttle carrying one part of the linear drive, the active steering module and the suspension and tilting module forms a complex system which is developed following design strategy of mechatronics, see Fig. 1. In the following the drive module consisting of a converter-fed linear motor is discussed in more detail. A particularity of the drive is that the linear motor is of the long-stator type or the short-stator type depending on the equipment mounted on the tracks.

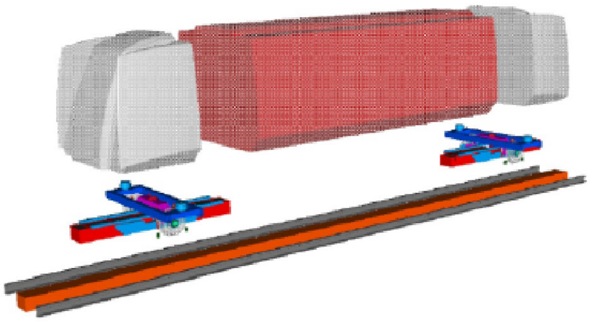

Fig 1. Modular design of shuttle

II. DOUBLY-FED LONG-STATOR LINEAR MOTOR

In particular with shuttles it is advisable for various reasons to avoid overhead wires and contact rails at high-density routes. That is why long-stator linear motor is used here at which the energy required for driving is delivered by the stator i.e. needs not to be transferred onboard of the vehicles. Consequently the stator is the primary of the linear motor which is carrying a three phase winding. As at Transrapid it is divided into sections which are not powered but when shuttles are driving on them.

Unfortunately, shuttles driving on the same stator section and making use of the same primary magnetic field need to drive with different speed when a convoy shall be formed or split. Therefore asynchronous operation of linear motors must be possible and synchronous motor used at Transrapid is not suitable for NBP system. To make asynchronous operation possible the vehicle-side motor part (secondary) is also equipped with a three-phase winding which is connected to the onboard DC link by three-phase power converters, see Fig. 2.

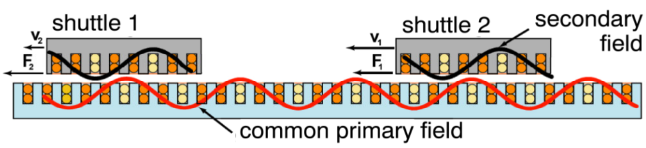

Fig 2. Principle of doubly-fed long-stator motor

If the secondary is fed with DC the linear motor behaves like a synchronous motor and (mechanical) speed of the shuttle

v_M equals the speed of the primary field v_1 being determined by the stator frequency f_1 according to $v_1 = 2\tau_P f_1$. If sinusoidal three-phase current is applied to the secondary the associated field will move relatively with regard to secondary and shuttle with speed $v_2 = 2\tau_P f_2$ (τ_P: pole pitch) being determined by the secondary frequency f_2. To achieve a torque that is constant (or has a constant component) the magnetic fields of primary and secondary must move with exactly the same speed which is realized when $v_M + v_2 = v_1$ is fulfilled. This equation corresponds directly to the well known frequency requirement $f_M + f_2 = f_1$, where the shuttle's speed is related to a corresponding frequency $v_M = 2\tau_P f_M$.
As with slip-ring induction motor energy is transferred from the primary to the secondary. This phenomenon can be used to feed the on-board power supply via the linear motor and neither overhead wires nor contact rails are required. However subsynchronous operation is necessary which means that the magnetic field must travel faster than the vehicle. Consequently the stator frequency must be increased with regard to synchronous operation. Due to higher frequency the impedances of the primary and the voltage demand increase which means that the motor as well as the inverter of the power supply must be designed for higher apparent power.
From the voltage equations of the windings the active power P_1 transmitted from the primary to the travelling field and the active power P_2 absorbed by the secondary from the magnetic field can be calculated. Under steady-state conditions, when phasors can be used, this results in

$$P_1 = 6\pi L_m f_1 \Re(j\underline{I}_2 \underline{I}_1^*)$$
$$P_2 = -6\pi L_m f_2 \Re(j\underline{I}_1 \underline{I}_2^*) = 6\pi L_m f_2 \Re(j\underline{I}_2 \underline{I}_1^*) \quad (1)$$

where L_m is the coupling inductance of the windings. From these the electromechanically converted power $P_M = P_1 - P_2$ and the thrust force $F_M = P_M / v_M = P_M /(2\tau_P f_M)$ result,

$$P_M = 6\pi L_m (f_1 - f_2) \Re(j\underline{I}_2 \underline{I}_1^*)$$
$$F_M = \frac{3\pi}{\tau_P} L_m \Re(j\underline{I}_2 \underline{I}_1^*) \quad (2)$$

Obviously the expressions for active power do not differ but by frequency and we get some simple relations

$$P_1 : P_M : P_2 = v_1 : v_M : v_2 \qquad F_M = \frac{P_1}{v_1} = \frac{P_M}{v_M} = \frac{P_2}{v_2} \quad (3)$$

According to (1) the power transmitted to the secondary is proportional to the thrust force the shuttle produces. This is why the total thrust force necessary for driving a convoy can be divided to the shuttles according to their energy requirement.
Doubly-fed long-stator linear motors offer interesting possibilities. Investigation of economy will show under what conditions use of long-stator motor and application of power supply of the shuttle via the motor make sense.

III. SHORT-STATOR LINEAR MOTOR

Installation of long stator is expensive and cannot be economic at low-traffic routes. Here the short-stator version of linear motor would be a suitable choice, see Fig. 3. Fortunately this type of motor can be realized without change of the shuttle-side equipment because the three-phase winding can be used as primary as far as energy for driving is transferred to the shuttle by overhead wires or contact rails. At the tracks only a simple reaction plate is required.

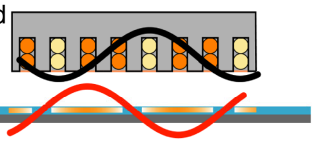

Fig 3. Principle of short-stator motor

The total power for driving now has to be handled by the shuttle-side converter and motor part. Since the rated power of this units normally is smaller than the rated power of the track-side units power and speed of the shuttle at short-stator operation will be lower than at long-stator operation with the ratio depending on the design of the system.

IV. CONTROL OF LINEAR MOTOR AT LONG-STATOR AND SHORT-STATOR OPERATION

Commands on destination and speed of travelling are send to shuttles via radio transmission which is also used for monitoring the traffic and the condition of shuttles. Drive control is performed on-board the shuttles and depending on situation the variable to be controlled can be speed (when travelling alone), position (when forming or splitting a convoy) or thrust force (when travelling in a convoy). In any case an underlaid current control is existing the structure of which depends on the type of linear motor.

4.1 Long-Stator Operation

As already mentioned more than one shuttle can be travelling on a stator section and generate their thrust forces in interaction with the same magnetic field and the same primary current. Of course the reference value of the stator current cannot be determined but by one shuttle which either is travelling alone or which is declared to be master when travelling in a convoy. However the control of the thrust forces which can be different for each shuttle must be performed onboard the shuttles. Drive control is performed by means of vector control for which the coordinate system is oriented to the vector of primary current, $\underline{i}_S = i_S + j0$, i.e. $i_{Sq} \equiv 0$ [2].

When determining the current references of the primary and the secondary current several requirements have to be considered:

• To achieve the required thrust force the primary current and the q-component of secondary current have to be set in accordance with (2). Considering $i_S = \sqrt{2} I_S$, $i_{Lq} = \sqrt{2} I_{Lq}$ we get

$$F_M = -\frac{3\pi}{2\tau_P} L_m i_S i_{Lq} \quad (4)$$

• The power transferred to the shuttle via the linear motor is determined by the relative speed between the magnetic field and the shuttle. Therefore power transmission demanded by the on-board energy management is used to establish the reference of the stator frequency.

• The ratio of the currents i_S / i_{Sq} determining the thrust force and the d-component of the secondary current are degrees of freedom which can be used different purposes e.g. for minimization of losses.

• The reference of the stator current must be transferred to the stationary power converter of the primary section by radio transmission which cannot be performed but with a low sampling rate. For thrust control which is performed on-board by variation of the secondary current this causes no problem. But the position of the stator current vector must be know exactly at every moment.

To achieve this knowledge the stator current vector is given an amplitude and an angular speed (i.e. frequency) which are assumed to be constant between successive radio transmissions. The references of these variables are sent from the shuttle (master shuttle) to the power converter of the actual primary section (and to other shuttles of the convoy). By a handshake procedure and a synchronism mechanism safety of operation and exact knowledge of primary current position on-board the shuttle (shuttles) are ensured.

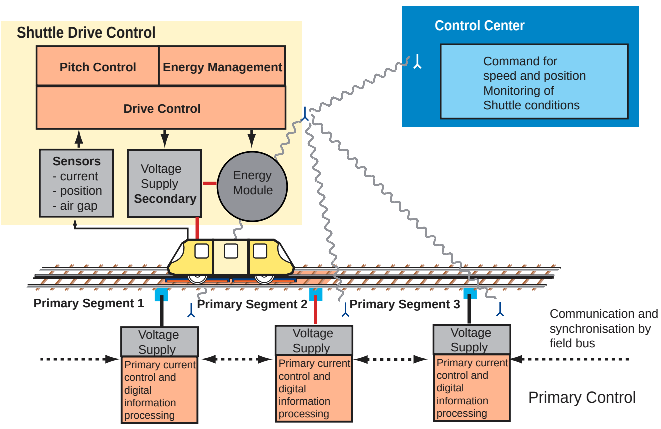

Fig 4. Control structure at long-stator operation

The control scheme used for operation of a single shuttle travelling in the long-stator mode is shown at Fig. 4.

At the control center the commands for speed and position are set and transmitted to the shuttle by means of radio communication. On board the shuttle the currents of the secondaries are controlled by use of three-phase inverters which are connected to a dc link being coupled to a battery. Onboard the shuttle the amplitude and frequency of the primary currents are also set. They are transmitted to the three-phase inverter, supplying the primary section in which the shuttle is moving.

4.2 Short-Stator Operation

On routes which are not equipped with a long-stator the power for driving has to be delivered by the motor-part onboard the shuttle which then acts as the primary. Unfortunately current control cannot be performed as usual with rotating motors because problems are existing at switches where continuous reaction plates are very difficult to be implemented. Due to discontinuities of the reaction plate the parameters of the linear motor can change considerably and rapidly. This is why sliding mode controlinstead of field oriented control is used for current and thrust control.

4.3 Change between Long-Stator and Short-Stator Operation

When a shuttle leaving a long-stator and entering a short-stator or vice versa it will partly on a long-stator and partly on a reaction plate for a certain time. At this situation the correct choice of frequencies is of great importance. Consider a shuttle coming in the synchronous mode from the long-stator at which the secondary current is DC. When entering the reaction plate the magnetic field of the secondary will act as an eddy-current brake and cause a lurch of thrust force. This can be avoided when the frequency of the shuttle-side motor winding is changed to the value required for short-stator operation before entering the short-stator section. At the same time the frequency of the track-side long-stator motor winding has to be changed, too, to fulfil the requirement $f_M + f_2 = f_1$ [3].

V. PITCHING CONTROL

Because of the small size of the shuttles traditional bogies cannot be used. Instead a single axle undercarriage has been developed in order to reduce the weight. The secondary of the linear motor is fixed to the axle and can rotate with regard to the axle being the center of rotation. The thrust force between primary and secondary driving the shuttle initializes such rotation since its line of application does not cross the center of rotation, i.e. the axle. Due to this fact torque is generated during the operation, in other words, a pitch motion of the secondary cannot be avoided and the air gap between primary and secondary will vary accordingly.

In order to prevent the secondary from hitting the primary and keep the air gap constant, the secondary windings an additional control loop is introduced: The winding of each secondary is divided into two parts, which are supplied separately. By feeding the two parts with different currents different normal forces F_{Z1} and F_{Z2} can be achieved which are used for controlling the pitch angle Θ to zero (Fig. 5).

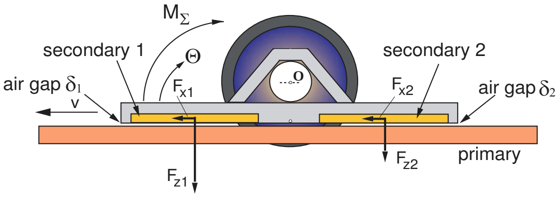

Fig 5. Structure of a linear drive module

Thus the secondary currents have to fulfill an additional control demand besides the required velocity control.

Pitching control proofs to be a demanding task because the balanced condition is instable due to the nature of magnetic forces. Considering that the secondary currents consist of two components two simple possibilities for performing the control are existing and have been investigated.

According to eqn.(1), the d-axis current of the secondaries has no influence on the thrust force. If d-axis current is used to control the normal forces of the secondaries compensating pitching torque is completely decoupled from control of thrust force and speed which is performed by use of q-current. On the other hand the q-currents of the half windings generating the thrust force can be varied in opposite sense to generate a torque which is used to control the pitching angle.

Therefore, a decoupled and a coupled pitch and velocity controller have been designed and implemented. Considering the decoupled controller, pitch angle and velocity of the linear drive module are controlled separately. The d-axis currents of the two secondaries are defined as control variables for pitch controller. In the case of the coupled controller, the pitch angle and pitch velocity are controlled by using only q-axis secondary currents, which are applied to velocity control at the same time. This coupled controller utilizes normal forces and thrust forces of the secondary to balance the pitch torque on the axle. In order to avoid an interference with velocity control, the sum of the q-axis secondary currents should be kept unchanged to achieve a constant thrust force for the linear drive module [4].

VI. ON-BOARD POWER SUPPLY

Each drive module is fitted with two secondaries, which are supplied by two inverters separately. All inverters are coupled via a DC link voltage. The link voltage is controlled by a DC/DC converter connecting the energy module with the main circuit. This converter ensures a DC link voltage in the range of 550V to 750V. The energy module comprises the combination of a Ni/Cd-battery and power caps(Fig. 6).

The battery consists of 280 cells connected in series delivering a voltage which is approximately half of the DC link voltage. Battery voltage varies between 250 V when discharged and 406 V when charged. As already mentioned charging of the batteries is performed via the linear motors.

However, at braking of the drive high power is fed back from the mechanical system resulting in high currents which should not be applied to the battery. Therefore power caps will be added to the energy module. Due to lower rated voltage power caps cannot be connected to the batteries directly, therefore another DC/DC converter is applied to adapt the voltage levels of battery and power caps. A dedicated energy management in combination with a coordinated control of the DC/DC converters makes possible to optimize the efficiency of energy storage in the energy module and increases the life cycles of the batteries.

Last not least a separate 1.8 kW DC/DC converter is required delivering a separate 24 V supply voltage for sensors, actuators and control hardwares of the mechatronic carriage. This converter is fed directly by the battery and therefore has to handle an input voltage which varies between 250 V and 406 V[5].

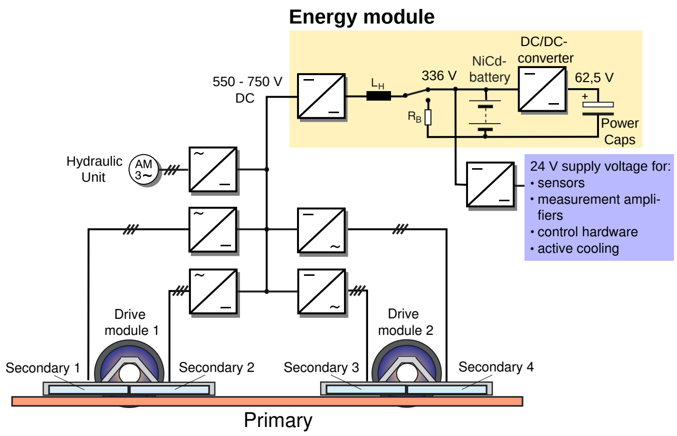

Fig 6. On-board power supply system

VII. EXPERIMENTAL RESULTS

Three years ago a test bed for a linear drive module was built in the laboratory. It is 8 m long and consists of 8 primaries which form two separately fed sections. On the test bed a carriage with two axles is moving carrying a secondary. To allow investigation of pitching control the secondary is fixed rotatable and its winding consists of two halfs which are fed by separate three-phase inverters.

For the purpose of testing the combination of long-stator and short-stator operation, a 2.4-m double layer reaction plate can be mounted instead of two primary segments, see Fig. 7. The mechanical air gap of long-stator and short-stator linear motor sections is set to 10 mm.

At this test bed motion control, energy transfer, control of pitching angle and combination of long-stator and short-stator operation are investigated. All control tasks of the linear drive module are executed on a DSP platform (Motorola Power PC 750, 480MHz) in this system.

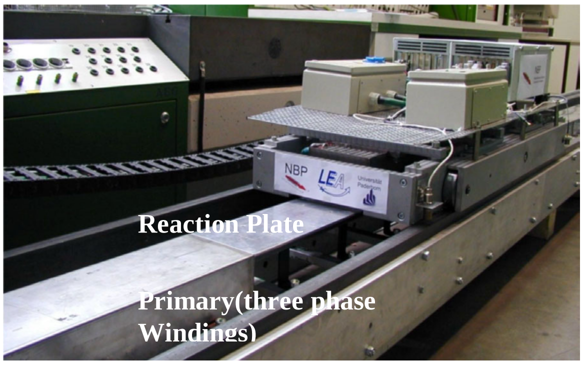

Fig 7. Test bed of linear drive module in Lab

At first experimental results of pitching control are presented for decoupled and coupled control method, see Fig. 8.

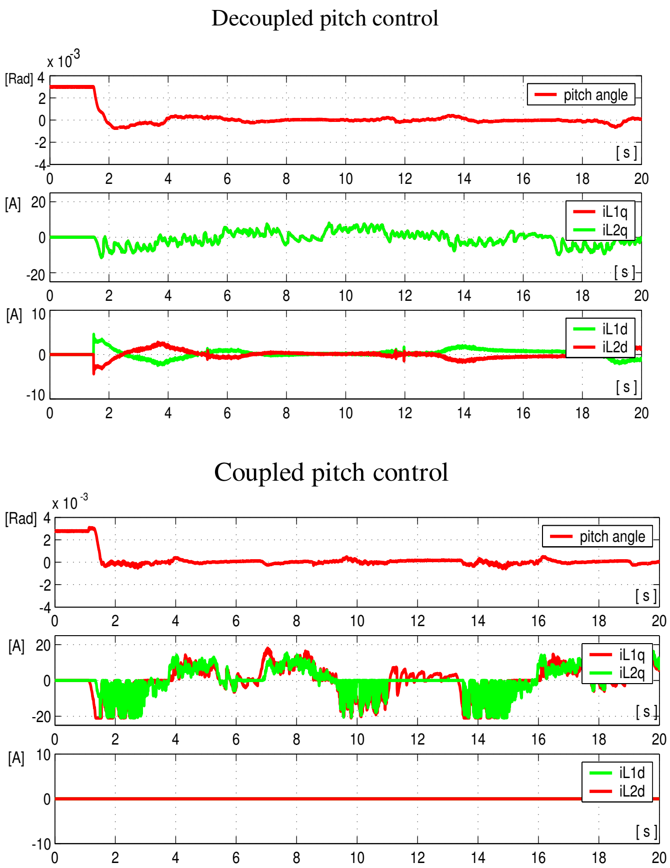

Fig 8. Experimental Results of Pitch Control

As illustrated in the figures, after the activation of the pitch controller, the pitch angle is controlled from maximal pitch angle to close to zero, i.e., the air gap between the secondary and the primary is kept unchanged [4].
At Fig. 9 the result of combined long-stator and short-stator operation is shown.
A trapezoidal speed command is applied to the drive module which moves automatically from the origin to the middle of the reaction plate and stops for a short time, then returns to the origin. Plots of actual position and speed shown in Fig. 9 prove that the control strategy works very well.

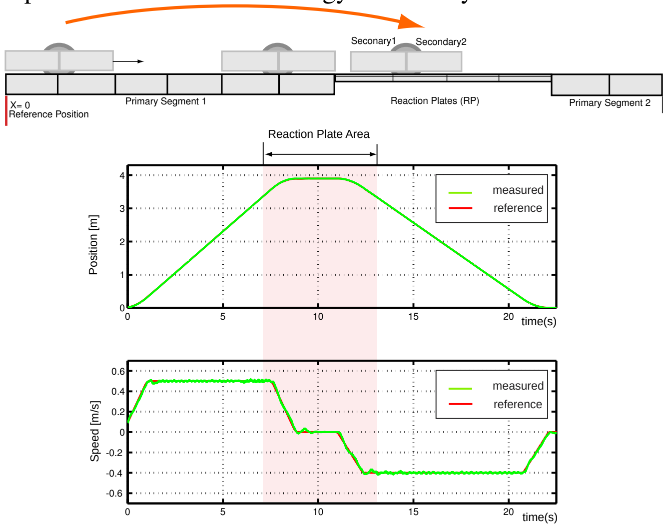

Fig 9. Experimental results of mixed long-stator and short-stator operation

VIII. CONCLUSION

In this paper, a new railway system, especially it's drive system is described in detail. All basic control strategies have been implemented and tested at test beds in the Power Electronics and Electrical Drives Laboratory. Experimental results achieved at this test bed are reported.
On June 18th, a 1:2.5 scale test track with a length about 530 m and a maximum gradient 5.3 % has been put into operation. The track is composed of a straight track and an oval, which are connected together via a switch.
Firstly, the basic control of linear motor, the radio communication, the synchronization of the primary magnetic fields and the interaction of all mechatronic subsystems in the shuttle will be investigated and tested. Lastly, up to three shuttles will be operated on the test track to investigate and demonstrate the operation of convoys.

REFERENCES

[1] M. Henke, *"Antrieb mit doppeltgespeistem Linearmotor fuer eine spurgefuehrtes Bahnfahrzeug"* (in German). Dissertation. ISBN 3-18-353312-X, VDI Press, 2003.

[2] M. Henke, B. Yang, H. Grotstollen, "*Linear Drive System for the NBP Railway Carriage, World Congress on Railway Research (WCRR 2001)*", Cologne, Germany, 2001.

[3] B. Yang, H. Grotstollen, *"Control Strategy for a Novel Combined Operation of Long Stator and Short Stator Linear Drive System"*, EPE 2003, Toulouse, France, 2003.

[4] B. Yang, M. Meyer, H. Grotstollen, *"Coupled Pitch and Velocity Control of a Douly-Fed Linear Motor*", ISICT 2003, Peking, China, 2003.