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Application, Calculation and Analysis of Doubly Fed Long Stator Linear Motor for NBP Test Track

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Preliminary communication

At the University of Paderborn a novel mechatronic railway system is developed, whose shuttles are guided by ordinary wheels and rails and driven by a doubly fed linear motor automatically. The primary (stator) is installed between the rails, and the secondary (rotor) fixed below the undercarriage. In this paper the modeling, calculation and analysis of a prototype of such a linear motor on a scale 1:2.5 are described in detail.

Key words: electrical machines, linear drives, modeling

1 INTRODUCTION

Since 1997 a mechatronic railway system NBP – »Neue Bahntechnik Paderborn« – has been researched and developed by six institutes at the University of Paderborn.

The main principle of this railway system is to realize the drive motion by integrating linear motor into the existing railway system on the basis of modular design [1]. It mainly contains four modules: linear drive module, guidance and steering module, suspension and tilting module, energy module. In addition, the concept is carried on the operation of small shuttle units embedded in a complex logistic structure [5], in order to achieve autonomous, effective, flexible and non-stop driving.

Linear motors convert electrical energy into linear motion directly. By using linear motor as propulsion machine ensures many advantages: high level of automatization and computerization, propulsion and braking independent of adhesion, low level of noise, ability to cope with high slopes and sharp bends, high reliability etc [2].

The linear motor consists of two components, the primary (long stator) installed between the rails, and the secondary (rotor) fixed under the carriage. The emerging tangential magnetic forces (thrust) between primary and secondary accelerate or brake the carriage. In this case, the wheels are used only for steering, carrying and guidance, the wear will be reduced additionally [3]. From the point of saving energy and improving efficiency, the primaries are divided into many segments that are supplied by different power supply substations. Depending on the position of the carriage the primary segments are switched on accordingly.

Moreover, the single axle structure undercarriage is adopted instead of conventional two axle structure. Such a design makes the shuttle lighter and simpler than the bogie variant. The thrust and normal forces between the primary and secondary result in respective pitching torque on the axle which must be compensated to retain a constant air gap [3].

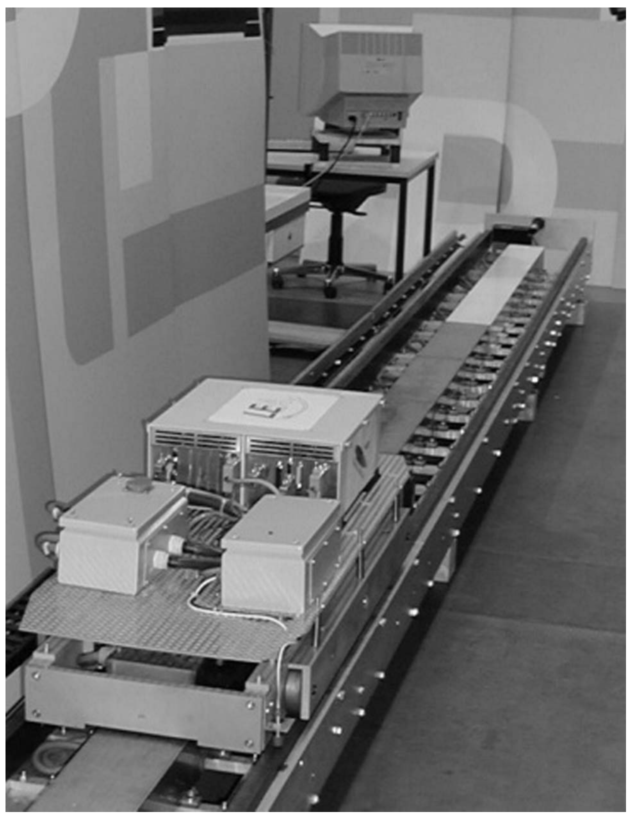

Fig. 1 Test bed of linear drive module

Up to now, a 8-m linear drive module (Figure 1), guidance and steering module, suspension and tilting module of this railway system have been realized as test beds in the laboratories.

Since 2003 a 530-m NBP test track (Figure 2) on a scale 1:2.5 has been built in Paderborn.

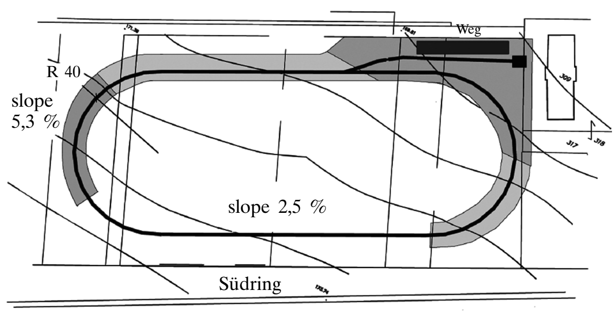

Fig. 2 NBP test track

2 DOUBLY FED LINEAR MOTOR

2.1 Application of doubly fed linear motor

As mentioned above, the vehicles are small shuttle units which are equipped with two linear drive modules. Each linear drive module includes one secondary, some primaries, one axle, two wheels, sensors, converters etc. The axle is located above the middle point of the secondary. In case the arising torque on the axle is not zero, the secondary will pitch up and down. As a result, the secondary winding is divided into two parts in order to carry out the pitch control and to keep air gap constant between the secondary and primary [3].

In order to realize the flexible driving, the shuttles should be able to accelerate and decelerate arbitrarily. Both the primary and the secondary are fitted with three phase windings, so that they can generate different magnetic fields independent from each other completely. As a result, energy can be transferred from the primary to the secondary for the on board power supply, in other words, neither overhead wires nor contact rails are required in this system. Moreover, the relative movement between two shuttles on the same primary segment becomes possible. Therefore, a doubly fed linear motor is applied for the NBP railway system (Figure 3).

2.2 Modeling of the linear motor

The modeling and calculation of the linear motor is carried out on the basis of the following assumptions:

- Only the fundamental wave of the magnetic field is taken into consideration.
- Iron loss is ignored due to the low operating frequency.
- Only steady state behavior of the linear motors is analyzed.
- Magnetic saturation is neglected.

Analysis Object:

- Linear Motor: a prototype for NBP Test Track.
- Model: N shuttles on one primary segment.

The main parameters of the prototype linear motor are shown in Table 1.

Table 1 **Main parameters of prototype linear motor**

mechanical air gap, mm	10
max. thrust force per secondary, N	750
max. velocity, m/s	10
pole pitch, mm	120
length of primary, m	1.068
length of secondary, m	1.35

In order to analyze the behavior of the linear drive module, mathematical equations and an equivalent circuit (Figure 4) of the whole system are set up, including voltage and force equations. The d-axis primary current oriented frame is selected and common to all secondaries, and q-axis current is set to zero by definition.

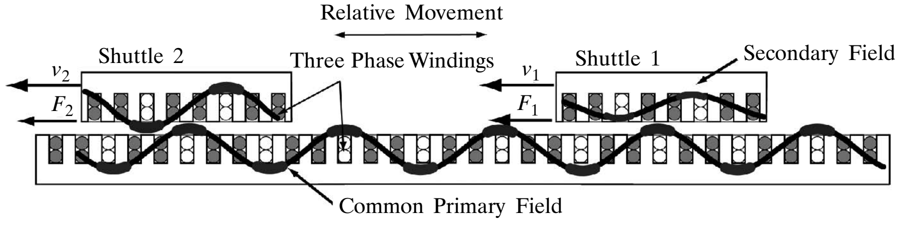

Fig. 3 Doubly fed linear motor

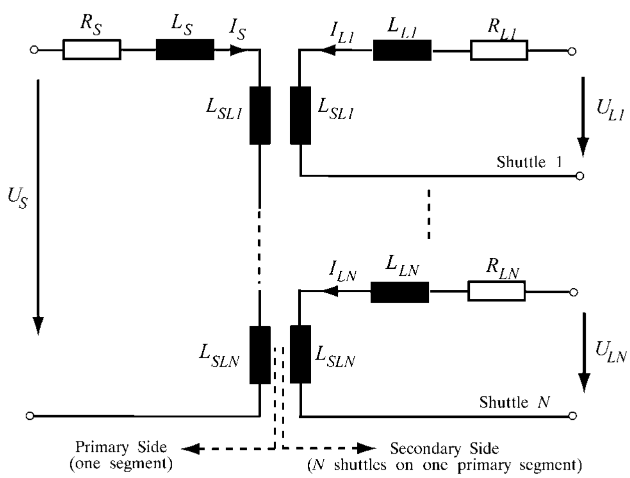

Fig. 4 Equivalent circuit

The slip is equal to

$$s=\frac{\omega_L}{\omega_S}=\frac{(\omega_S-\omega_M)}{\omega_S}=\frac{(v_S-v_M)}{v_S}. \tag{1}$$

The relation between the mechanical speed and synchronous speed is given by

$$v_M+v_L=v_S \qquad \omega_M+\omega_L=\omega_S \tag{2}$$

and the currents of primary and secondary respectively

$$\underline{I}_S=I_S\cdot e^{j0}\Rightarrow \underline{I}_S=I_{Sd}+jI_{Sq}=I_S+j0$$
$$\underline{I}_L=I_L\cdot e^{j\vartheta}\Rightarrow \underline{I}_L=I_{Ld}+jI_{Lq}=I_L\cos\vartheta+jI_L\sin\vartheta. \tag{3}$$

The voltage equations of the primary side and secondary side are calculated directly by those of conventional asynchronous machines.

$$\begin{aligned}\underline{U}_S&=(R_S+j\omega_S L_S)\cdot \underline{I}_S+\\&\quad+j\omega_S(L_{SL1}\cdot\underline{I}_{L1}+L_{SL2}\cdot\underline{I}_{L2}\ldots+L_{SLN}\cdot\underline{I}_{LN})\\ \underline{U}_{L1}&=(R_{L1}+j\omega_{L1}L_{L1})\cdot\underline{I}_{L1}+j\omega_{L1}L_{SL1}\cdot\underline{I}_S\\&\ldots\\ \underline{U}_{LN}&=(R_{LN}+j\omega_{LN}L_{LN})\cdot\underline{I}_{LN}+j\omega_{LN}L_{SLN}\cdot\underline{I}_S.\end{aligned} \tag{4}$$

And the apparent powers are

$$\begin{aligned}\underline{S}_S&=3\underline{U}_S\underline{I}_S^*\\ \underline{S}_{L1}&=3\underline{U}_{L1}\underline{I}_{L1}^*,\ldots,\underline{S}_{LN}=3\underline{U}_{LN}\underline{I}_{LN}^*\\ \underline{S}_L&=\underline{S}_{L1}+\underline{S}_{L2}+\ldots+\underline{S}_{LN}.\end{aligned} \tag{5}$$

The active power is the real part of the apparent power

$$\begin{aligned}P_S&=\mathrm{Re}\{\underline{S}_S\}=3R_S\cdot I_S^2+3\omega_S\cdot\mathrm{Re}\left\{jL_{SL1}\underline{I}_{L1}\underline{I}_S^*+\right.\\&\quad\left.+jL_{SL2}\underline{I}_{L2}\underline{I}_S^*+\ldots+jL_{SLN}\underline{I}_{LN}\underline{I}_S^*\right\}\\ P_{L1}&=\mathrm{Re}\{\underline{S}_{L1}\}=3R_{L1}\cdot I_{L1}^2+3\omega_{L1}L_{SL1}\cdot\mathrm{Re}\left\{j\underline{I}_S\underline{I}_{L1}^*\right\}\\&\ldots\\ P_{LN}&=\mathrm{Re}\{\underline{S}_{LN}\}=3R_{LN}\cdot I_{LN}^2+\\&\quad+3\omega_{LN}L_{SLN}\cdot\mathrm{Re}\left\{j\underline{I}_S\underline{I}_{LN}^*\right\}\\ P_L&=P_{L1}+P_{L2}+\ldots+P_{LN}.\end{aligned} \tag{6}$$

On the one hand, from above equations the mechanical power guaranteed by any secondary (e.g. secondary N) can be calculated by

$$\begin{aligned}P_{MN}&=3\omega_S\,\mathrm{Re}\left\{jL_{SLN}\underline{I}_{LN}\underline{I}_S^*\right\}+3\omega_{LN}\,\mathrm{Re}\left\{jL_{SLN}\underline{I}_S\underline{I}_{LN}^*\right\}=\\&=3(\omega_S-\omega_{LN})L_{SLN}\,\mathrm{Im}\left\{\underline{I}_S\underline{I}_{LN}^*\right\}\end{aligned} \tag{7}$$

On the other hand, the mechanical power is established by the thrust force multiplied by the mechanical velocity.

$$P_M=v_M\cdot F_M=2\tau_P\cdot f_M\cdot F_M=\frac{\tau_P}{\pi}\cdot\omega_M\cdot F_M. \tag{8}$$

From equation (7) and equation (8) the thrust force for the rotary motor can be described by the following equation:

$$F_x'=-\frac{3\pi}{\tau_p}\cdot L_{SL}\cdot I_S\cdot I_{Lq}\cdot\sin\vartheta. \tag{9}$$

An outstanding difference between the linear motor and rotary motor is the half filled end slots windings, the corresponding end effect of the linear motor will influence the thrust force on a large scale, considering the end effect, the modified equation of thrust force is [4],

$$F_x=-\frac{(2p-1.5)}{2p}\frac{3\pi}{\tau_p}\cdot L_{SL}\cdot I_S\cdot I_{Lq}\cdot\sin\vartheta. \tag{10}$$

And the ratio of thrust force to normal force is,

$$\frac{F_x}{F_Z}=\frac{2\pi\cdot\delta'}{\tau_p}\cdot\frac{\sin\vartheta}{\dfrac{N_S\xi_S}{N_L\xi_L}\cdot\dfrac{I_S}{I_L}+\dfrac{N_L\xi_L}{N_S\xi_S}\cdot\dfrac{I_L}{I_S}+2\cdot\cos\vartheta}. \tag{11}$$

2.3 Calculation and analysis of the doubly fed linear motor

As can be seen from equation (10), thrust force depends on the product of I_S and I_{Lq}, therefore I_{Ld} should be controlled to be zero, namely $I_{Ld}=0$, to avoid unnecessary power losses. Moreover, the ratio

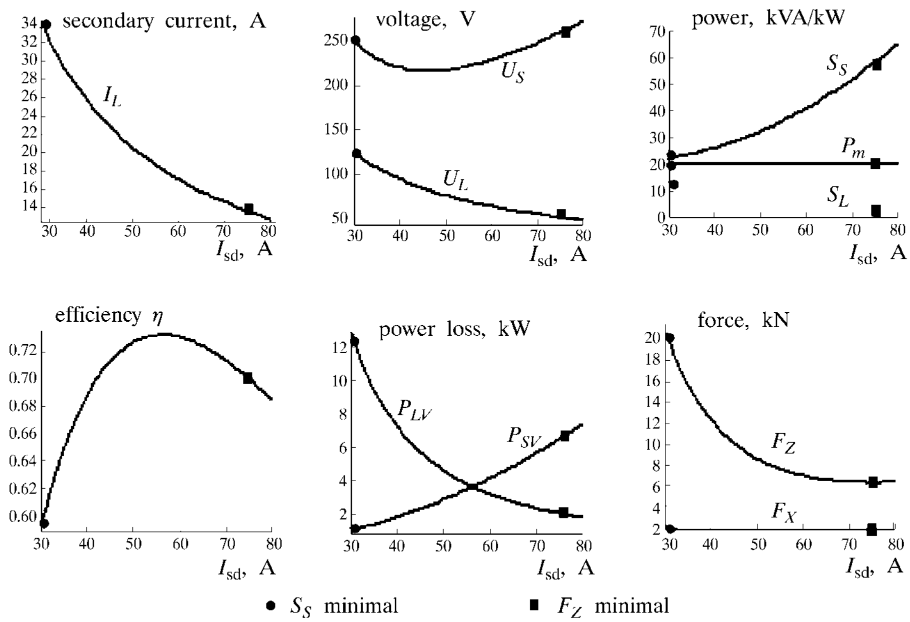

Fig. 5 Influence of current ratio on characteristics of the linear drive

of I_S and I_{Lq} remains a degree of freedom on which determine most characteristics of the drive shown in Figure 5.

The behavior of two shuttles on one primary segment is shown in Figure 5, when shuttle generates 1000 N and drives at a speed of 10 m/s. The characteristics are dependent on the primary segment length and the thrust force, therefore, the length of primary segment and the thrust force are given in advance.

It is well known, some part of the primary segment covered by secondaries is named active primary, the rest named passive primary. The magnetic coupling between the primary and the secondary exists only in the area of active primary. The energy in the other area will result in losses. For this reason, the shorter the primary segment is, the better the efficiency of the overall system. However, the equipment of the power supply substations will be more complex correspondingly. A tradeoff should be made to achieve a balance between the cost and the efficiency.

Figure 5 displays the change of all variables if the primary current varies in the range of 30 A to 80 A. Clearly, the normal force and the apparent power are two contradictory parameters. If the normal force is minimum, the apparent power is not at its minimum and vice versa.

It follows three cases:

- The magnetic field of secondary side is stronger than the primary side. ($I_S < 56$ A)

  Advantages: low apparent power of primary side.

  Disadvantages: high energy requirement in the secondary, cooling problem in the secondary, heavy secondary.
- The magnetic field of primary side is stronger than the secondary side. ($I_S > 56$ A)

  Advantages: natural cooling, light secondary.

  Disadvantages: high apparent power of primary side.
- Two magnetic fields are same strong.

  The power loss of linear motor is minimal and the efficiency is maximal.

3 DISTRIBUTION OF PRIMARIES ALONG NBP TEST TRACK

The primary will be mounted between the rails. Considering the heat expansion of the primary, there is a small gap between two primaries. On the basis of pole pitch and the length of the primary, the gap between two primaries is set as 12 mm.

The NBP test track is composed of two parts: a straight track and an oval (Figure 2). They are connected together via a switch. The discontinuity of primaries in the switch area cannot be avoided. In the switch area a bilayer reaction plate consisting of aluminum and iron, is applied to replace the primary, for the sake of flexibility of the distribution and the safety of the shuttle operation [6].

4 CONCLUSION

Modeling, calculation and analysis of characteristics of a doubly fed long stator linear motor have been presented in this paper.

The NBP test track, which was built in 2003, offers an excellent opportunity to implement further research on this linear motor.

APPENDIX – VARIABLE LIST

f_M	mechanical frequency, Hz
F_x	thrust force, N
F_z	normal force, N
$\underline{I}_L$, I_L	current of secondary, A
$\underline{I}_S$, I_S	current of primary side, A
L_{SL}	mutual inductance, H
$N_L\xi_L$	number of turns per phase and winding factor of secondary
$N_S\xi_S$	number of turns per phase and winding factor of primary
p	number of poles
P_L	active power of secondary side, kW
P_M	mechanical power of the analyzed object, kW
P_S	active power of primary side, kW
R_L	resistance of secondary side, Ω
R_S	resistance of primary side, Ω
s	slip
$\underline{S}_L$	apparent power of secondary side, kVA
$\underline{S}_S$	apparent power of primary side, kVA
$\underline{U}_L$	voltage of secondary side, V
$\underline{U}_S$	voltage of primary side, V
δ, δ'	mechanical and magnetic air gap, mm
v_M	mechanical speed, m/s
v_S	synchronous speed, m/s
ϑ_L	force angle
τ_P	pole pitch of linear motor, m
ω_L	angular frequency of secondary side, rad/s
ω_S	angular frequency of primary, rad/s

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Primjena, proračun i analiza dvostruko napajanog statora linearnog motora za željeznički NBP ispitni poligon (NBP – nova prijevozna tehnika Paderborn)**.** Na sveučilištu Paderborn razvijen je novi mehatronički vučni pogon za željeznički transport. Vučni pogon je realiziran s linearnim motorom s dvostruko napajanim statorom, pri čemu se koristi postojeći mehanički sustav kotača s tračnicama. Statorski dio linearnog motora je postavljen između tračnica a rotorski ispod pomičnih vučnih kola. Modeliranje, proračun i analiza mehatroničkog vučnog pogona načinjeni su na prototipnom modelu u razmjeri 1:2,5.

Ključne riječi: električni strojevi, linearni pogoni, modeliranje

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