Application, Calculation and Analysis of the Doubly Fed Longstator Linear Motor for the Wheel-on-Rail NBP Test Track

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Abstract
At the University of Paderborn a mechatronic railway system is developed, at which autonomous shuttles are guided by ordinary wheels and rails and driven by a doubly fed linear motor. The primary (i.e. stator) is installed between the rails, and the secondary (i.e. rotor) is fixed below the undercarriage. In this paper the modelling, calculation and analysis of a prototype of such a linear motor on a scale 1:2.5 are described in detail. Finally, the distribution of primaries along the NBP test track is also illustrated.

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 based on the operation of small shuttle units embedded in a complex logistic structure [5], in order to realize 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 with radius of curvature less than 20 m, high reliability etc[2].

The linear motor consists of two components, the primary (longstator), which is installed between the rails, and the secondary (rotor), which is 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 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 torque on the axle which must be compensated to retain a constant air gap[3].

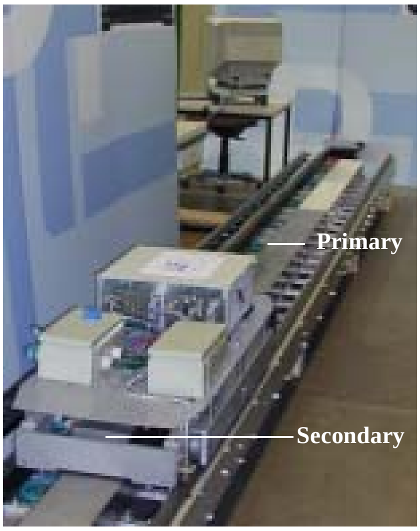

Fig. 1 Test stand of linear drive module

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

Since this spring a 530-m NBP test track with a scale 1:2.5 has been under building in Paderborn.

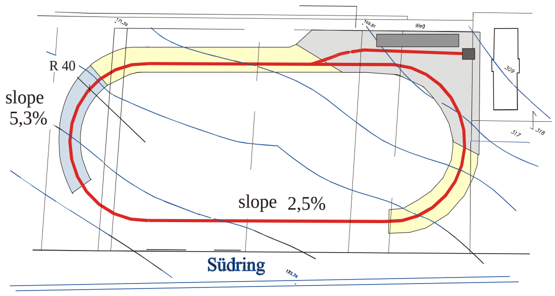

Fig. 2 NBP test track [HNI]

Doubly Fed Linear Motor

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 and 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 half parts in order to carry out the pitch control and to keep air gap constant between the secondary and primary [3].

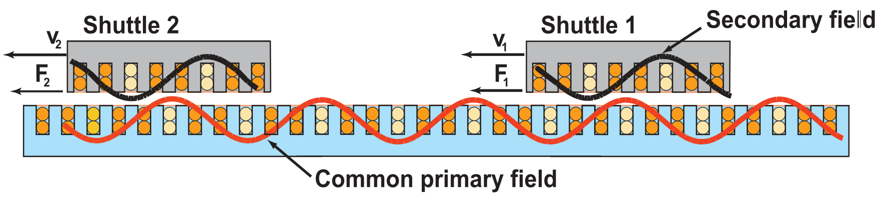

Fig. 3 Doubly fed linear motor

In order to realize the flexible driving in two directions, the shuttles should be able to accelerate and decelerate arbitrarily. Both the primary and secondary are fitted with three phase windings, so that they can generate different magnetic field 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 will be applied in this system. Moreover, the relative movement between two shuttles on the same primary segment is possible. Therefore, doubly fed linear motor is applied for the NBP railway system.

Modelling of the Linear Motor

The modelling and calculation is carried out on the basis of the following assumptions:

- Only the fundamental wave is taken into consideration.
- Iron loss is ignored due to the low operating frequency.

- Only steady state behavior of the linear motors is analyzed.
- No magnetic saturation.

Analysis Object:

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

Table I Main parameters of prototype linear motor

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

In order to analyze the behavior of the linear drive module, an equivalent circuit and mathematical equations 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.

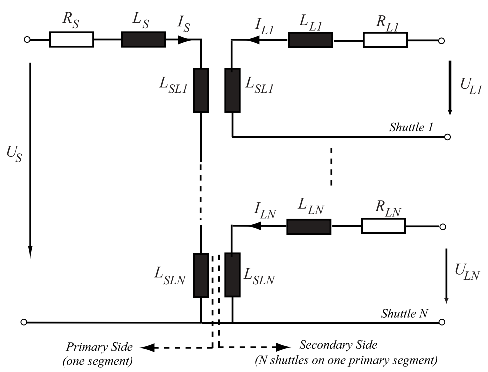

Fig. 4 Equivalent circuit

The slip is equal to

$$\omega_L / \omega_S = (\omega_S - \omega_M)/\omega_S = (v_S - v_M)/ \quad (1)$$

and the turns ratio (2)

$$a = (N_s \xi_S)/(N_L \xi_L) \quad (3)$$

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

$$v_M + v_L = v_S \qquad \omega_M + \omega_L = \omega_S \quad (4)$$

and the currents of primary and secondary respectively,

$$\underline{I}_S = I_S \cdot e^{j0} \quad \Rightarrow \quad \underline{I}_S = I_{Sd} + jI_{Sq} = I_S + j0$$
$$\underline{I}_L = I_L \cdot e^{j\vartheta} \quad \Rightarrow \quad I_L = I_{Ld} + jI_{Lq} = I_L \cos\vartheta + jI_L \sin\vartheta \quad (5)$$

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

$$\underline{U}_S = (R_S + j\omega_S L_S) \cdot \underline{I}_S + j\omega_S (L_{SL1} \cdot \underline{I}_{L1} + L_{SL2} \cdot \underline{I}_{L2} \ldots + L_{SLN} \cdot \underline{I}_{LN})$$
$$\underline{U}_{L1} = (R_{L1} + j\omega_{L1} L_{L1}) \cdot \underline{I}_{L1} + j\omega_{L1} L_{SL} \cdot \underline{I}_S$$
$$\ldots \quad (6)$$
$$\underline{U}_{LN} = (R_{LN} + j\omega_{LN} L_{LN}) \cdot \underline{I}_{LN} + j\omega_{LN} L_{SL} \cdot \underline{I}_S$$
$$\underline{U}_L = \underline{U}_{L1} + \underline{U}_{L2} + \ldots + \underline{U}_{LN}$$

And the apparent powers are,

$$\underline{S}_S = 3 \underline{U}_S \underline{I}_S^*$$
$$\underline{S}_{L1} = 3 \underline{U}_{L1} \underline{I}_{L1}^*, \quad \ldots, \quad \underline{S}_{LN} = 3 \underline{U}_{LN} \underline{I}_{LN}^* \quad (7)$$
$$\underline{S}_L = \underline{S}_{L1} + \underline{S}_{L2} + \ldots + \underline{S}_{LN}$$

The active power is the real part of the apparent power,

$$\begin{aligned} P_S &= \Re\{\underline{S}_S\} = 3R_S \cdot I_S^2 + 3\omega_S \cdot \Re\{jL_{SL1}\underline{I}_{L1}\underline{I}_S^* + jL_{SL2}\underline{I}_{L2}\underline{I}_S^* + \ldots + jL_{SLN}\underline{I}_{LN}\underline{I}_S^*\} \\ P_{L1} &= \Re\{\underline{S}_{L1}\} = 3R_{L1} \cdot I_{L1}^2 + 3\omega_{L1}L_{SL1} \cdot \Re\{j\underline{I}_S\underline{I}_{L1}^*\} \\ &\ldots \\ P_{LN} &= \Re\{\underline{S}_{LN}\} = 3R_{LN} \cdot I_{LN}^2 + 3\omega_{LN}L_{SLN} \cdot \Re\{j\underline{I}_S\underline{I}_{LN}^*\} \\ P_L &= P_{L1} + P_{L2} + \ldots + P_{LN} \end{aligned} \tag{8}$$

In addition, the relation between the primary and the secondary is presented by the mechanical power: the thrust force multiplied by the mechanical velocity.

$$P_M = v_M \cdot F_M = 2\tau_P \cdot f_M \cdot F_M = \frac{\tau_P}{\pi} \cdot \omega_M \cdot F_M \tag{9}$$

The primary and secondary are magnetically interlinked by a 10-mm air gap. The thrust force for the rotary motor can be fixed by the following equation,

$$F'_x = -\frac{3\pi}{\tau_P} \cdot L_{SL} \cdot I_S \cdot I_L \cdot \sin\vartheta \tag{10}$$

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],

$$F_x = -\frac{(2p-1.5)}{2p}\frac{3\pi}{\tau_P} \cdot L_{SL} \cdot I_S \cdot I_L \cdot \sin\vartheta \tag{11}$$

And the ratio of thrust force to normal force is,

$$\frac{F_x}{F_z} = \frac{2\pi \cdot \delta'}{\tau_P} \cdot \frac{\sin\vartheta}{\frac{N_S\xi_S}{N_L\xi_L} \cdot \frac{i_S}{i_L} + \frac{N_L\xi_L}{N_S\xi_S} \cdot \frac{i_L}{i_S} + 2 \cdot \cos\vartheta} \tag{12}$$

Calculation and Analysis of the Doubly Fed Linear Motor

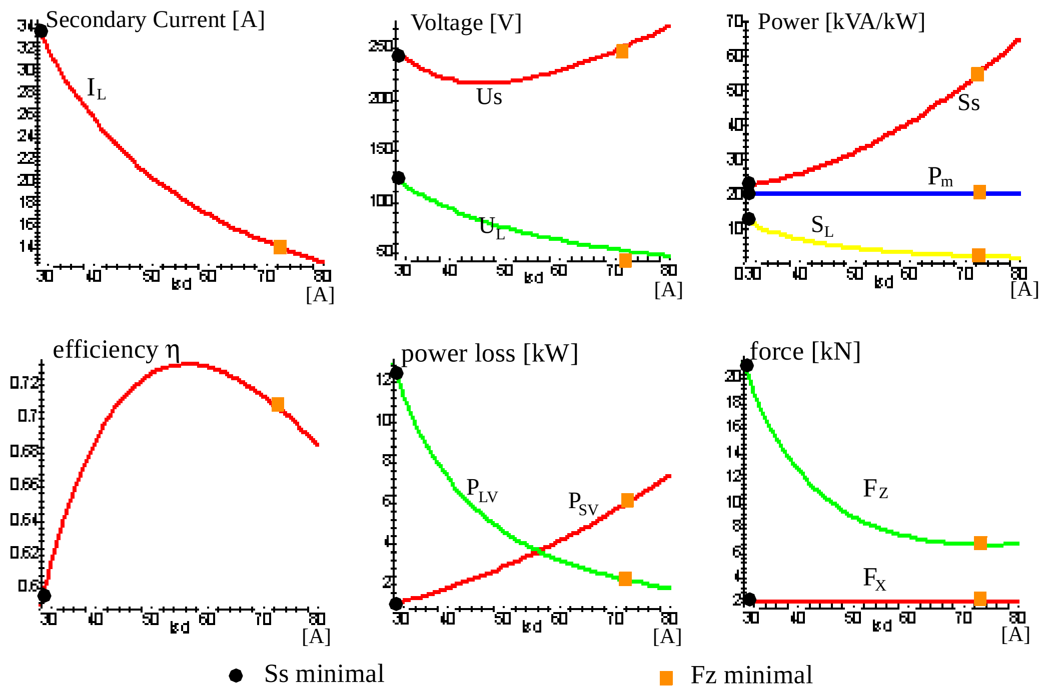

Fig. 5 Behavior of the analysis object

The behavior of two shuttles on one primary segment is shown in Fig. 5. Each shuttle should generates 1000 N and drives at a speed of 10 m/s.

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 compromise should be found out to make a balance between the cost and the efficiency.

Fig. 5 displays the change of all variables if the primary current varies from 30A to 80A. The normal force and the apparent power are two contradictory parameters. If the normal force is minimum, the apparent power maximum, and vice versa.

There are three cases:

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

Advantages: low apparent power of primary side

Disadvantages: cooling problem in the secondary, high energy requirement in the secondary, heavy secondary

- The magnetic field of primary side is stronger than the secondary side. (Is >56A)

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.

Distribution of Primaries along the NBP Test Track

The primary will be mounted in the middle of the rails. Considering the heat expansion of the primary and in order to make continuous pole pitch, there should be a gap between two primaries. On the basis of pole pitch and the length of the primary, the gap between two primaries is decided as 12 mm.

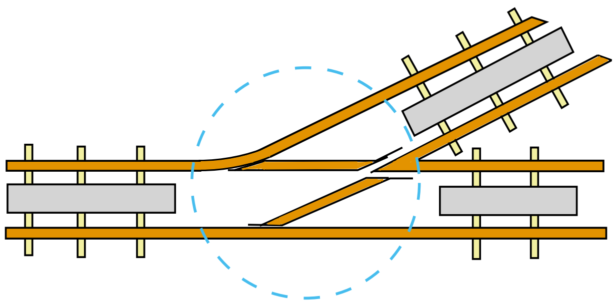

Fig. 6 Sketch of the switch

The NBP test track is composed of two parts: a straight track and an oval. They are connected together via a switch. The discontinuity of primaries in the switch area cannot be avoided.

As a result, the intersection point of the switch and the oval is selected as the starting point of the distribution, which is carried out anti-clockwise. The position of end point is depended on the primary length, length of the primary segment, length of test track and the distance between primaries. In the switch area the two-layer reaction plates consisting of Aluminum and Iron, will be planed to replace the primary, in order to ensure the flexibility of the distribution and the safety of the shuttle operation.[1]

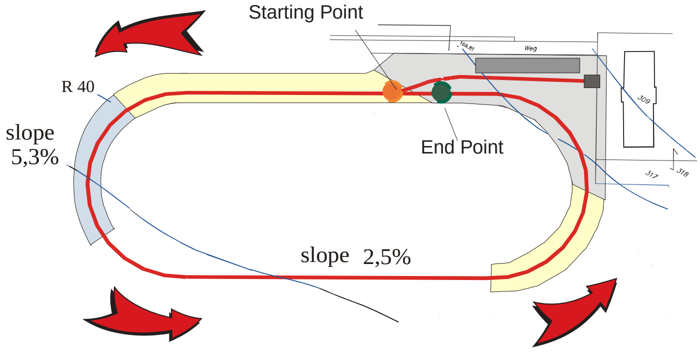

Fig. 7 Distribution of the primaries along the test track

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Appendix - Variable List

a turns ratio

b_P effective width of the armature yoke [m]

s Slip

ω_L angular frequency of secondary side [rad/s]

ω_S angular frequency of primary [rad/s]

V_S synchronous speed [m/s]

V_M mechanical speed [m/s]

δ , δ' mechanical and magnetic air gap [mm]

$N_s\xi_S$ number of turns per phase and winding factor of primary

$N_L\xi_L$ number of turns per phase and winding factor of secondary

$\underline{I}_S$, I_S current of primary side [A]

$\underline{U}_S$ voltage of primary side [V]

1. The design of the reaction plates and the control strategy in the switch area will be presented in the future papers.

$L_{S\sigma}$ leakage inductance of primary side [H]

L_{SL} mutual inductance [H]

R_S resistance of primary side [Ω]

$\underline{I}_L$, I_L current of secondary [A]

$\underline{U}_L$ voltage of secondary side [V]

$L_{L\sigma}$ leakage inductance of secondary side [H]

R_L resistance of secondary side [Ω]

$\underline{S}_S$ apparent power of primary side [kVA]

$\underline{S}_L$ apparent power of secondary side [kVA]

ϑ force angle

P_S active power of primary side [kW]

P_L active power of secondary side [kW]

P_M mechanical power of the analyzed object [kW]

f_M mechanical frequency [Hz]

τ_P pole pitch of linear motor [m]

p number of poles

F_x thrust force [N]

F_z normal force [N]