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VYUŽITIE LINEÁRNYCH MOTOROV PRI VOZIDLÁCH S MAGNETICKOU LEVITÁCIOU A PRI ŽELEZNIČNÝCH VOZIDLÁCH

LINEAR MOTORS UTILIZATION FOR BOTH MAGLEV AND RAILWAY VEHICLES

Trakčné systémy s lineárnymi strojmi sa skúmajú dlhý čas. Existovali a existujú niektoré aplikácie so synchrónnym lineárnym strojom s dlhým statorom, napr. demonštračná linka maglevu v Berlíne MAGNETBAHN vybudovaná v roku 1983, vysokorýchlostná trať TRANSRAPID, na ktorej sa skúšalo vozidlo TR06 od roku 1984, či skúšobná trať YAMANASHI postavená v roku 1990 v Japonsku. Technika lineárneho motora sa nemusí využívať len na pohon nových lineárnych vlakov. Ak uvážime adhézne problémy konvenčných rušňov pri vlhkom počasí, je tiež možné využiť príťažlivú silu lineárnych strojov na zvýšenie ťažnej sily rušňa podmienenej adhéziou medzi kolesom a koľajnicou.

Traction Systems with Linear Machines have been under investigation for a long time. There were and are several applications with synchronous long stator linear machines, e.g. the maglev demonstration line in Berlin MAGNETBAHN (built in 1983), the high speed maglev line TRANSRAPID where the TR06 has been tested since 1984 or the YAMANASHI Test Line in Japan, built in 1990. The linear - motor technology cannot only be used for propulsion of new linear trains. When thinking of adhesion problems of conventional locomotives under wet weather conditions, it is also possible to use the magnetic attraction force produced by linear machines to increase the adhesion - based tractive effort between wheel and rail.

1. Introduction

Conventional modern electric railway drive systems consist of inverter-fed rotating AC machines (mainly induction machines, apart from special solutions such as TGV, 1st generation, with electrically excited synchronous motors). Via gear, flexible suspension such as cardan hollow shaft and the wheel-rail contact, tractive effort is generated. As an alternative, inverter-fed linear electric motors are much more simple. Gearing and mechanical transmission parts can be omitted. In the case of magnetic levitation even wheel and rail is no longer needed. Thus, linear drives have long been of common interest. The linear three-phase AC winding is either installed as a "long - stator" on the track with the secondary, e.g. DC - excited poles within the transportation vehicle, yielding a long stator linear synchronous machine. If the secondary, e.g. a linear cage, is mounted on the track, with a short linear three-phase AC - winding fixed to the vehicle, one gets a so-called "short - stator" linear induc-tion machine. Both short and long stator version of synchronous and asynchronous linear machines have been utilized in the past but proved to be rather expensive solutions when compared with the conventional drive train. Therefore, their technical use is commonly restricted to those applications, where due to magnetic levitation ("Maglev") no wheels are used. In addition, recently small linear machines as additional thrust ("Boosters") are discussed, which should yield additional tractive effort. This additional thrust is needed, when under wet weather conditions the adhesion force between wheel and rail is reduced.

Basic principle of the AC linear machine is the electromagnetic traveling wave in the air gap δ between primary (carrying the AC winding) and the secondary (cage, reactive part, DC pole or permanent magnet arrangement). The speed v_{syn} of the traveling wave is exactly the speed of the train in the case of a synchronous motor, or nearly the speed of the train - due to slip s - in the case of linear induction motors. The inverter generates a three-phase voltage system with variable frequency f, feeding the linear AC winding, thus generating the traveling magnetic field in the air gap. For example, with the synchronous linear motor data of the German TRANSRAPID 06 high-speed maglev train (data see Table 3), a maximum speed of

$$v_{syn,max} = 2 \cdot f_{max} \cdot \tau_p = 2 \cdot 215\ Hz \cdot 0.258\ m = = 111\ m/s = 400\ km/h \tag{1}$$

is achieved (τ_p: pole pitch). In comparison, a linear booster motor, designed for accelerating assistance in the low-speed range (data see Table 6) operates up to

$$v_{syn,max} = 2 \cdot f_{max} \cdot \tau_p = 2 \cdot 74\ Hz \cdot 0.16\ m = = 23.7\ m/s = 85\ km/h. \tag{2}$$

Its dimensions are much smaller than those of the linear drive solution of a TRANSRAPID or YAMANASHI (Japanese maglev,

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Table 4) concept, as the booster force should be only about 20 % – 30 % of the nominal tractive effort. Two effects generate additional tractive effort due to booster motors:
- tangential linear thrust force F_t of the linear booster,
- increased wheel – rail adhesion force ΔF_z due to attractive force F_n of the linear booster.

For example, the nominal vertical force per wheel of German heavy-duty loco class 152 is about 107.5 kN. With an adhesion coefficient $f_x = 0.35$ (dry rails) a maximum tractive effort (2 bogies, 4 wheelsets) of

$$F_z = 2 \cdot 4 \cdot 0.35 \cdot 107.5\ kN = 300\ kN \quad (3)$$

is possible, which may decrease under wet weather conditions down to $f_x = 0.25$.

$$F_z = 2 \cdot 4 \cdot 0.25 \cdot 107.5\ kN = 215\ kN \quad (4)$$

If two boosters per bogie with an attractive force per booster of 30 kN are mounted, an additional tractive effort of

$$\Delta F_z = 4 \cdot 0.25 \cdot 30\ kN = 30\ kN \mathrel{\hat{=}} 14\ \%\ \text{of}\ 215\ kN \quad (5)$$

is possible. With an additional thrust $F_t = 35$ kN a total tractive effort of

$$F_z = 215\ kN + 30\ kN + 10\ kN = 255\ kN \quad (6)$$

is achieved. In the following applications of linear motors for electric traction are briefly reviewed and summarized. Technical data are given and actual limits of booster machines are discussed.

Magnetic Transportation systems thus can be divided in low speed, high speed, and booster applications. For low-speed applications one can mention e.g. Maglev line MAGNETBAHN Berlin, the Maglev line Qingcheng – Mountain – Dujiang – Barrage in China, the Maglev Line at Birmingham airport or the HSST in Japan. High-speed applications are e.g. the TRANSRAPID high speed train in Germany and the YAMANASHI test – line near Tokyo in Japan. Booster applications are currently under investigation at several universities and research labs of electrical vehicle manufacturers.

2. Linear motors for low speed applications

Pseudo-Maglev line MAGNETBAHN Berlin

As a local transportation system the synchronous long stator maglev line Berlin started operation in 1989. It was a so called "people – mover". The excitation of this permanent magnet synchronous long stator arrangement was done by permanent magnets within the vehicle. The length of the track was about 1.6 km. Small passenger wagons (Fig. 1) controlled by a fully automatic train control system were operated as a shuttle between the railway stations "Kemperplatz" and "Gleisdreieck" in Western – Berlin. The permanent magnets were also used for electromagnetic levitation of the cars. Uncontrolled electromagnetic levitation is unstable, so a rather complicated design of additional wheels between car an track was necessary to provide a constant clearance between magnets and track. Thus, the vehicles were running on wheels with reduced wheel-set load due to the levitation force.

Fig. 1. Maglev-vehicle MAGNETBAHN Berlin [1]

In 1991 the line gained license for passenger carriage. A part of the track of MAGNETBAHN was placed on a part of the underground-line U2, which was out of order since the Berlin wall divided Berlin into East and West Berlin. After the destruction of the wall in 1989 there was the decision to rebuild the underground-line U2. So the MAGNETBAHN had to be dismantled. Nowadays one of the MAGNETBAHN wagons can be seen at the museum of transportation in Nuernberg, Germany.

Technical data of MAGNETBAHN [2] Table 1

Mass per wagon	9.5 t	Length of wagon	11.76 m
Passengers per wagon	80	Width of wagon	2.31 m
Wagons per train	1–4	Height of wagon	2.3 m

Maglev line Qingcheng - Dujiang in China

The people mover in China will start operation in 2001. It will be a 3-wagon application carrying a maximum of 80 passengers. The length of the track is about 10 km connecting Qingcheng and Dujiang. It is a synchronous long stator motor application using conventional excitation coils. Magnetic levitation with controlled magnets is applied.

Technical data of Chinese people – mover Quingcheng Table 2

Mass per wagon	10 t	Length of wagon	11.2 m
Passengers per wagon	80	Controlled air gap	8 mm
Wagons per train	3	Maximum velocity	80 km/h

Birmingham Maglev line

From 1984 until 1995 a shuttle was in operation along a 700 m distance between the Birmingham airport and the Birmingham railway station. It was an asynchronous short stator motor application with controlled magnets for levitation. Refurbishment was too expensive so the company shut down the service when investments where necessary in 1995 to refurbish the electrical equipment. Now there are intentions to replace this line by a cable car shuttle. Meanwhile bus transfer operates transportation between railway station and airport.

3. Linear motors for high speed applications

TRANSRAPID

In comparison to MAGNETBAHN the TRANSRAPID is a high-speed transport system. The TRANSRAPID vehicles are levitated and guided by controlled electromagnets. The TRANSRAPID is propelled by a synchronous linear long stator motor mounted on the underside of the guide way. When levitation magnets are energized, the vehicle is lifted towards the guide way. The air gap then is about 10 – 15 mm. To maximize energy efficiency, the long stator motor is divided into sections, which are automatically energized as the train approaches and are deactivated after the train leaves the considered section of the track. The stator coils with one coil per pole and phase ($q = 1$) are distributed in two rows beneath the guide way resulting in two linear motors, operating parallel to each other. Inside the vehicle there are levitation magnets supplied with power from on-board batteries. Linear generators charge the batteries when the vehicle is moving at a speed higher than 120 km/h. At the EMSLAND Test Line in Northern Germany several generations of TRANSRAPID vehicles were tested, e.g. the TRANSRAPID 06 (Fig. 2, Table 3), which established a speed record of 412 km/h in 1988 [4]. Afterwards it was replaced by a new version TRANSRAPID 07, which can travel with a velocity of about 500 km/h (Fig. 3).

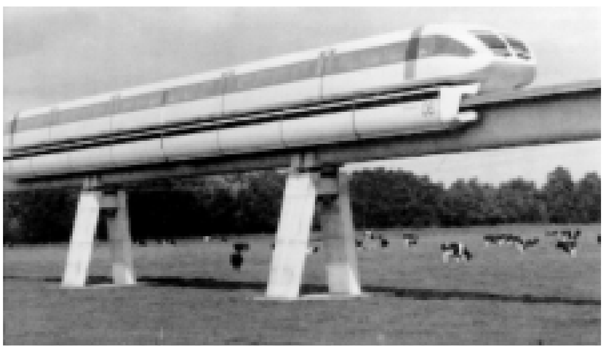

Fig. 2. TRANSRAPID 06 at EMSLAND Test Track in Northern Germany [3]

Fig. 3. TRANSRAPID 07 at the EMSLAND Test Track [5]

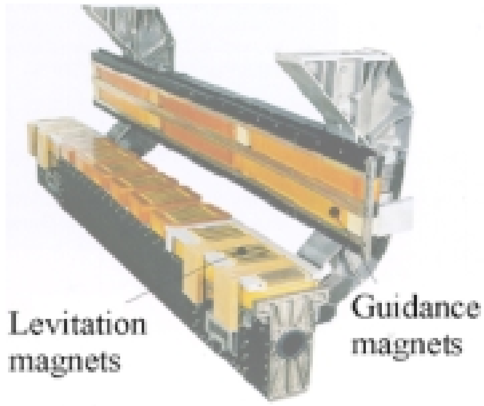

Fig. 4. Magnets of vehicle TRANSRAPID. The levitation magnets are also used as secondary of the long stator linear synchronous motor

Data of the TRANSRAPID vehicle T06 II — Table 3

Length of two sections	54 m	Weight (empty vehicle, two sections)	120 t
Width	3.7 m	Controlled air gap	10 - 15 mm
Height	4.2 m	Power on board	450 kW
Max. speed	400 km/h	Maximum thrust	85 kN
Motor current	1200 A	Motor voltage	4250 V
Frequency	0 ... 215 Hz	Efficiency (at 400km/h)	0.93
Pole pitch	258 mm	Power factor (at 400km/h)	0.84

On January 23, 2001 a contract was signed between Germany and China to erect a TRANSRAPID line in China. The application concerns a 30 km shuttle connection between Pudong Shanghai

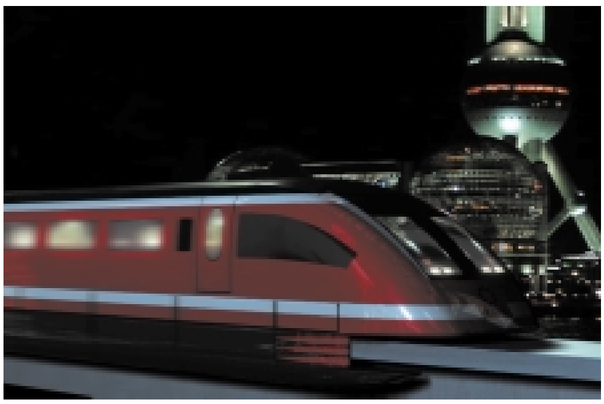

Fig. 5. TRANSRAPID in Shanghai (paste-up) [5]

International Airport and the Shanghai financial district Lujiazui (Fig. 5). The first operation is planned with a maximum speed of 430 km/h for the beginning of 2003.

YAMANASHI Test Line in Japan

The YAMANASHI Test Line of 43 km (Fig. 6) between Sakaigawa and Akiyama near Tokyo is the Japanese MAGLEV high-speed project. The vehicles are levitated electrodynamically, different to TRANSRAPID. The vehicles are equipped with superconducting magnets cooled with liquid helium at 4.2 K. Along the track two types of copper coils are installed. A three-phase long stator winding (without iron back) is designed for propulsion as synchronous linear motor. The second ones are short-circuited coils for electrodynamic levitation. Due to the electrodynamic levitation principle at low speed ($v < 100$ km/h) the levitation forces are too low, thus the vehicles are running on rubber tires. The levitation and guidance coils are installed within the sidewalls of the guide way. Passing at high speed the superconducting magnets of the vehicle are inducing eddy currents in the short-circuited coils. Due to the forces produced by these currents the train is levitated. In 1999 with vehicle MLX01 (Fig. 7) a maximum cruising speed was achieved at 552 km/h [6, 7].

Fig. 6. YAMANSHI TEST LINE, short open air segment between two tunnels [8]

Fig. 7. Vehicle MLX01, being operated unmanned for testing up to 550 km/h [8]

The feeding system of the YAMANASHI Test Line is a triplex feeding system, so that the power conversion system consists of three inverter units. The propulsion coils of the three-phase long stator winding are installed on both sides of the guide way. There are sections on both sides of the track overlapping each other. For that two inverters are needed operating at the same time. Due to the superconducting DC magnets high flux densities of several Tesla, and a big levitation and motor air gap of about 15 cm are possible. Human exposure to high DC fields must be avoided due to the magnetic forces acting on iron parts such as keys. Pacemakers are not inflicted by DC magnetic fields. Thus, magnetostatic shielding of the passenger cabins is necessary.

Inverter specification (GTO) of Japanese YAMANASHI train system — Table 4

Rated output	38 MVA	Voltage	0 – 22 kV
Rated output current	960 A	Rated modulation frequency	500 Hz
Rated output frequency	56.6 Hz	Control method	PWM

4. Booster applications

Several industrial and research institutions are investigating linear motors for electric traction application. At the Institute for Electrical Energy Conversion at Darmstadt University of Technology there are induction motors and magnets under investigation, which should improve the tractive effort between wheel and rail of a standard high-power electrical locomotive (Fig. 8). This can be achieved by using the rails of the track as secondary or by installing an additional reaction plate or linear cage on the track. This idea is completely different from the solutions mentioned above. As there should be no active components in the track the first two versions, which will be presented as asynchronous short stator machines, similar to the Birmingham maglev line. The third one is a DC-actuator.

Fig. 8. Class 152 heavy duty locomotive (86 t, 140 km/h, 6.4 MW), which could be equipped with boosters

ASYNCHRONOUS LINEAR MACHINE (ALIM) using the rails as a secondary

Supported by the German railway company Deutsche Bahn, an investigation on the application of asynchronous linear motors for railway systems was completed. The main task was to develop a machine with nearly the same major dimensions as the eddy-current brake of ICE 3 [9], but with additional features such as speed – independent attractive force and thrust. The braking capability of the eddy-current brake which is already in operation with the German high-speed train ICE 3 (Fig. 9) should be used as a benchmark for the development of the linear motor.

The new booster should be able to get similar braking forces as the eddy current brake, and furthermore, it should be possible to obtain attracting, braking and accelerating forces independently from each other and from the train speed. To fulfill these requirements, a frequency inverter is needed to control the mode of operation of the asynchronous machine.

The complex geometry of the linear machine and of the rail demands a 3-D numerical calculation. Accompanying 2-D calculations in numerical and analytical way shall give deeper insight into the basic functions of the machine [10,11,15].

Since the ALIM should be mounted on the bogie of existing locomotives, it is necessary to stay within the limits, which are demanded by regulations [12]. The maximum space limits for the ALIM are listed in Table 5.

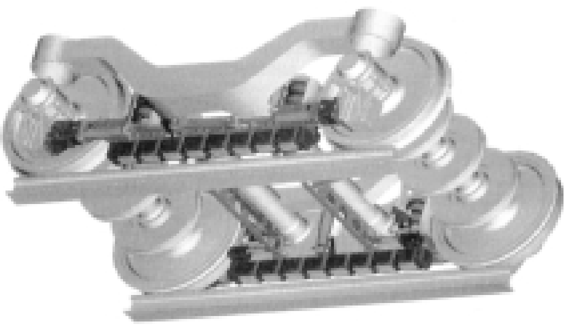

Fig. 9. Eddy-current-brake mounted on ICE 3 bogie [9], showing the available space for the booster

Maximum sizes available for the ALIM — Table 5

Length	Width	Height
1413 mm	135 mm	250 mm

In order to realize short winding-overhangs and to avoid crossing of phases, a fractional slot winding with the number of slots per pole and phase $q = 1/2$ was chosen, yielding three coils U, V, W per pole pair (Fig. 10). The mechanical air gap of about $\delta = 6.5$ mm is reduced to about 4 mm under load due to the bending of the structure caused by the magnetic attractive force.

The drawback of the fractional slot winding is the generation of additional MMF space harmonics, which result in a drastic reduction of electromagnetic thrust force. The low conductivity of

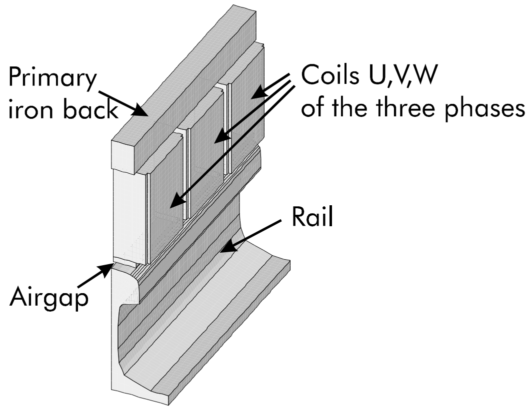

Fig. 10. 3-D numerical model for force calculation of an asynchronous linear booster motor

the rail and the rather large air gap of about 4 mm (in the middle of the rail) yield a big amount of magnetizing current ($\cos\varphi \approx 0.1$) and a rather low thrust force production. Further, the booster operation allows only a small increase of attractive force, e.g. for loco class 152 the vertical force per wheel of 107.5 kN can be increased by about 12.5 kN without generating a braking force. Thus a reduction of adhesion coefficient of only 12 % can be compensated.

ALIM parameters (conventional rail as secondary) — Table 6

Number of phases *m*	3	Overall width	135 mm
Slots per pole and phase *q*	0.5	Overall length	1390 mm
Frequency *f*	0 ...74 Hz	$\cos\varphi$	0.1
Pole pitch τ_p	160 mm	Ampere turns Θ	22 kA
Air gap under load δ	4 mm		

ASYNCHRONOUS LINEAR MACHINE using an extra secondary in the track

By using an extra secondary, e.g. a linear copper cage and iron back, the forces can be increased. The ALIM shall provide additional accelerating and braking forces and an attractive force between wheel and rail. With the asynchronous linear machine it should be possible to substitute an additional second locomotive, which usually is used for banking heavy trains on steep slopes, in combination with the standard locomotive. The primary part with the three-phase winding will be mounted on the bogie between the two wheel-shafts as a short stator motor (two ALIMs per bogie, Fig. 11). The secondary will be a linear cage and iron stack, mounted on the track between the two rails of the track. Using the ALIM only at low velocity below the rated speed, it is possible to feed the driving inverter from the DC link of the locomotive [13].

The ALIM should operate up to a maximum velocity of 85 km/h, using the power reserve of the locomotive's AC/DC converters. The loco investigated is the German heavy-rail loco class 152 for heavy-duty traction [13]. It is a four-axle 6.4 MW locomotive. Its tractive effort at standstill is about $F_z = 300$ kN (Fig. 12).

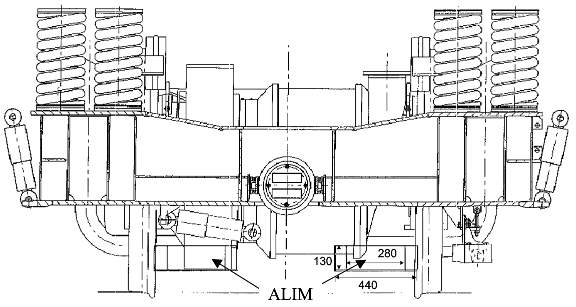

Fig. 11. Bogie of loco class 152 with ALIM front view

Due to the additional thrust and attractive force of the ALIM the tractive effort F_z of the loco increases.

$$F_z = F_t + f_x(v) \cdot F_n \qquad (7)$$

The adhesion coefficient $f_x(v)$ is depending on velocity according to measurements of CURTIUS and KNIFFLER, performed during the late 1940's [14].

$$f_x(v) = \frac{7.5}{v\,[km/h] + 44} + 0.08, \; f_x(0) = 0.25 \text{ (wet rails)} \qquad (8)$$

As already mentioned, the use of the ALIM will be restricted to tracks with steep slopes where the motor could substitute a second locomotive. On these tracks of limited distance it is possible to mount an extra reaction rail (a linear cage) as secondary part of the ALIM on the track.

The advantage of such an arrangement in comparison to the iron rails of the track as secondary is the lower current-force ratio due to the higher conductivity of the copper cage and larger motor surface.

ALIM parameters (linear copper cage as secondary) Table 7

Number of phases m	3	Overall width	440 mm
Slots per pole and phase q	2	Overall length	1390 mm
Frequency f	0 - 74 Hz	$cos\varphi$	0.5
Pole pitch τ_p	160 mm	Ampere turns Θ	2.4 kA
Air gap under load δ	4 mm		

Of course, the mounting space is larger as it would be when using the rail as secondary. Due to the necessity of the reaction cage in the middle of the track the ALIM booster operation is not possible on normal tracks. It has to be ensured that it is possible for the locomotive with such an ALIM primary to drive on international tracks. For that the ALIM is lifted up by a hydraulic mechanism so that the small air gap distance at working position (4 mm) increases to get the demanded UIC clearance of 80 mm.

DC ACTUATOR

Linear motors with an extra secondary mounted on the track are expensive. Using the rail as a secondary is much cheaper but

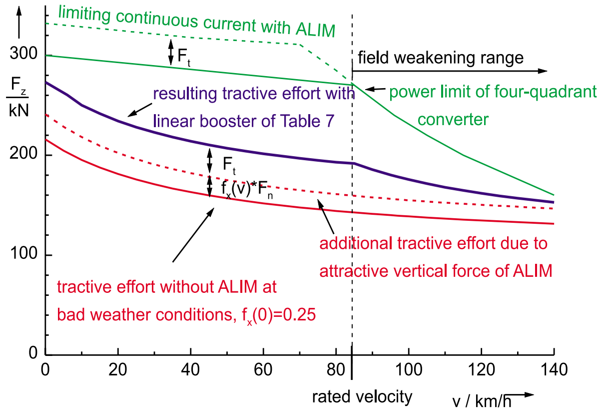

Fig. 12. Tractive effort vs. velocity of loco class 152 with linear booster of Table 7. Adhesion coefficient $f_x(v)$ [14], attractive and tangential forces at the wheel F_n, F_t

the amount of reactive power is large. Further, only the additional attractive force gives the booster effect, as the thrust force is rather small. Therefore, a DC-fed actuator mounted in the bogie of a locomotive is proposed. The actuator has two DC-poles. The poles are symmetrical to the middle of the rail. The secondary again is the conventional rail. For that only one half of the actuator is modeled in Fig. 13. The excitation winding is placed in the middle of the two poles. This design of the booster also has to fit the restricted mounting volume demanded by regulations. The chosen arrangement is to get high attractive forces, whereas the parasitic tangential braking force should be low. This is achieved by reducing the percentage of end effects. As it is a DC-excitation, the flux-density in the middle part of the actuator is constant. For that there are no induced currents in the secondary. Only at the front and rear end of the machine the flux-density distribution is changing, thus inducing eddy-currents in the secondary (end effects).

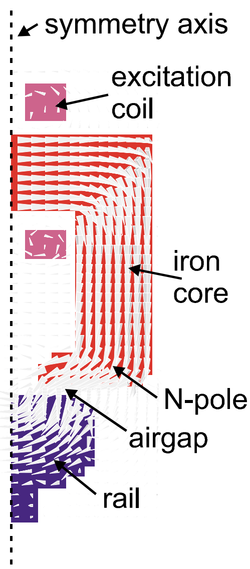

Fig. 13. View of one half of the DCactuator

DC actuator Table 8

Pole arrangement	DC 2 pole	Stator length l_s	1200 mm
Ampere turns Θ	20 kA	Stator width b	130 mm
Air gap δ	5 mm	Excitation power	10 - 15 kW

Comparison of Booster Applications

In Table 9 the performances of the three booster applications are compared for an air gap of about 4 mm. Excitation of the three boosters is designed for air-cooling and short-time operation of 3 min. Forces produced by the short stator ALIM with the rail as a secondary are rather low due to the mentioned restrictions. Forces produced by the linear motor using a linear copper cage as a secondary are significantly higher. Nevertheless, it is restricted to tracks were this reaction-part is installed. The DC actuator only produces attractive forces but no thrust. Due to the special pole arrangement braking forces are very small. So this is a rather cheap solution for increasing of tractive effort when weather conditions lead to wet rails and decreased adhesion coefficients.

Comparison of performance of different boosters and brakes Table 9

Forces per wheel set	Max. attractive force F_n *1)	Max. tangential force F_t (−) braking; (+) thrust
ALIM with rail	25 kN	+ 0.75 kN / −3 kN
ALIM with linear copper cage	30 kN	+ 10 kN / −10 kN
DC actuator	35 kN (at standstill)	−0.4 kN (at 90km/h)
DC eddy current brake (ICE 3)	70 kN (at standstill)*2)	−10 kN (at 60 km/h)

**1) Attractive force is restricted not to damage the track (e.g. movable parts of switches) and to fit the maximum allowed axle load of 25 t.*

**2) Too high for operation; therefore, excitation should be reduced at low velocities*

5. Conclusions

In the paper a brief overview of different linear motor applications is given. Due to their rather big overall costs, linear motors for electrical traction are still an exotic solution, which of course is technically necessary if magnetic levitation is used. Nevertheless, for high-speed transportation they are an interesting alternative, considering the difficult mechanism of wheel-rail contact and guidance at high speed. Also linear boosters or actuators as boosters could be an interesting option for traction assistance under wet weather conditions, helping to reduce time delays and extra cost for a second locomotive.

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