ZÁPADOČESKÁ UNIVERZITA V PLZNI

FAKULTA ELEKTROTECHNICKÁ

KATEDRA ELEKTROMECHANIKY A VÝKONOVÉ ELEKTRONIKY

LINEÁRNÍ MOTORY

BAKALÁŘSKÁ PRÁCE

2013

LUCIE HORNÍKOVÁ

Prohlašuji, že jsem tuto bakalářskou práci vypracovala samostatně, s použitím odborné literatury a pramenů uvedených v seznamu, který je součástí této práce.

Dále prohlašuji, že veškerý software, použitý při řešení této bakalářské práce, je legální.

V Plzni, 1. června 2013

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vlastnoruční podpis

Ráda bych zde poděkovala vedoucímu bakalářské práce Ing. Romanovi Pechánkovi Ph.D. za jeho rady a čas, který mi věnoval při řešení dané problematiky.

Velké poděkování náleží celé mé rodině za podporu, trpělivost a povzbuzování po dobu mého studia.

ZÁPADOČESKÁ UNIVERZITA V PLZNI
Fakulta elektrotechnická
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ZADÁNÍ BAKALÁŘSKÉ PRÁCE

(PROJEKTU, UMĚLECKÉHO DÍLA, UMĚLECKÉHO VÝKONU)

Jméno a příjmení:	**Lucie HORNÍKOVÁ**
Osobní číslo:	**E10B0449P**
Studijní program:	**B2612 Elektrotechnika a informatika**
Studijní obor:	**Elektrotechnika a energetika**
Název tématu:	**Lineární motory**
Zadávající katedra:	**Katedra elektromechaniky a výkonové elektroniky**

Zásady pro vypracování:

1. Proveďte literární a patentovou rešerši lineárních motorů používaných v dopravě.
2. Seznamte se s principy magnetické levitace využívané pro dopravní prostředky.
3. Uveďte základní vlastnosti, principy a parametry daných strojů.
4. Zhodnoťte vývoj a využití magnetické levitace v dopravě v blízké budoucnosti.

Rozsah grafických prací: **podle doporučení vedoucího**

Rozsah pracovní zprávy: **20 - 30 stran**

Forma zpracování bakalářské práce: **tištěná/elektronická**

Seznam odborné literatury:

1. **Veřejně dostupné informační zdroje, databáze www.ieee.org**
2. **Toliyat, A. H., Kliman, B. G.: Handbook of electric motors, CRC Press, 2004, ISBN: 100-8247-4105-6.**
3. **Boldea, I.: Linear Motion Electromagnetic Devices, Taylor & Francis, 2001, ISBN: 9789056997021**

Vedoucí bakalářské práce: **Ing. Roman Pechánek, Ph.D.**
Katedra elektromechaniky a výkonové elektroniky

Datum zadání bakalářské práce: **15. října 2012**

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děkan

L.S.

Prof. Ing. Václav Kůs, CSc.
vedoucí katedry

V Plzni dne 15. října 2012

OBSAH

LIST OF SYMBOLS

v_s	synchronous speed	[m/s]
v	velocity of rotor	[m/s]
τ	pole-pitch	[m]
f	frequency	[s^{-1}]
s	slip	[-]
F	thrust	[N]
F_{syn}	synchronous thrust	[N]
F_{rel}	reluctance thrust	[N]
w_{Fe}	width of iron core	[m]
p	number of pole-pairs	[-]
B_δ	air-gap flux density	[T]
A_δ	cross-section density	[A/m^2]
A_1	active current density	[A/m^2]
δ_0	width of air-gap	[m]
c, c_1	material constants	[-]
G	goodness factor	[-]
ρ_s	surface resistivity	[Ω]
μ_0	permittivity of the free space	[-]
X_{sq}	synchronous reactance in q-axis	[Ω]
X_{sd}	synchronous reactance in d-axis	[Ω]
X_1	leakage reactance	[Ω]
X_{aq}	armature reaction reactance in q-axis	[Ω]
X_{ad}	armature reaction reactance in d-axis	[Ω]
L_1	leakage inductance	[H]

U_i	voltage induced	[V]
U_1	input voltage	[V]
N_1	number of armature turns per phase	[-]
$k_{\omega 1}$	armature winding factor	[-]
ϕ_f	excitation magnetic flux density	[Wb]
P_{elm}	electromagnetic power	[W]
m	number of phases	[-]
ε	force angle	[°]

LIST OF SHORTCUTS

LIM	Linear Induction Motor
LSM	Linear Synchronous Motor
SLIM	Single-sided Linear Induction Motor
DLIM	Double-sided Linear Induction Motor
TLIM	Tubular Linear Induction Motor
TFLIM	Transverse Flux Linear Induction Motor
PM	Permanent Magnet
HTS	High Temperature Superconductor
HSGT	High Speed Ground Transportation
Maglev	Magnetic Levitation
EMS	Electromagnetic Suspension
EDS	Electrodynamic Suspension
MBB	Messerschmitt-Bölkow-Blohm
HSST	High Speed Surface Transportation

ABSTRACT

Ground transportation system which would reach speeds up to 500 km/h needs to be levitated. For this reason the linear motors are suitable as a propulsion system. The principle of linear motor is explained. The main structural types are briefly described. Then different types of levitation are mentioned. For levitated transportation systems is used attractive or repulsive levitation, these two types are also explained. Finally, the summary of development of the maglev systems in the world is told.

Key words: linear induction motor, linear synchronous motor, levitation, maglev

ABSTRAKT

Pozemní doprava, která dosahuje rychlostí až 500 km/h musí být levitována. Pro tyto účely se jako pohony využívají lineární motory. V této práci je popsán princip těchto motorů. Ze strukturálního hlediska jsou zjednodušeně popsány nejpoužívanější typy. Levitované dopravní systémy využívají buď přitažlivé nebo odpudivé levitační síly, systémy využívající tyto síly jsou také vysvětleny. Závěrem je shrnut vývoj maglev systémů ve světě.

Klíčová slova: lineární indukční motor, lineární synchronní motor, levitace, maglev

INTRODUCTION

There always has been effort for fast and safe kind of transportation which would be economically available. With increasing demands for speed of the ground transportation there are only few options left. One of the most perspective possibilities is levitated transportation, or more precisely – levitated trains. The first thoughts for levitated vehicles came in 1930s and since then there has been a great development in this area.

Contactless trains need a suitable propulsion system. In case of magnetic levitation (maglev) system is necessary to provide a linear motion. That can be achieved by conventional rotational motors with transformation to the linear motion, but this transformation could be avoided by using a linear motor. As for rotational motors, there are two main types of linear motors – induction and synchronous. This thesis discusses about these types of linear motors, describes their structural options, principles, differences between linear and rotary motors and their applications.

Further, there are listed and briefly explained types of magnetic levitation systems which are used for high-speed maglev transport systems. Applications of these systems are mention at the end of this thesis.

1 THE LINEAR MOTORS FOR TRANSPORTATION SYSTEMS

In past 50 years has been a great interest in implementation of transportation systems with high-speed propulsion. To achieve speeds up to several hundreds of km/h is necessary to realize a levitated vehicle. From this follows that propulsion system has to be contactless. For this purpose are suitable linear motors. [5]

The main difference between a typical torque motor and a linear motor is, as the name suggests, that linear motor produces linear force instead of rotational. Which means the only degree of mechanical freedom is not a rotation but a translation [1]. This is achieved by “cutting” the rotational motor radially and unrolled, as illustrated on Fig. 1.1. So in theory every type of motor (synchronous, dc, induction and reluctance) could be operated as linear. But for economic reasons we usually want to motors without secondary excitation, thus reluctance motor, induction motor and synchronous motor with permanent magnets are suitable for the linear conversion [6]. However, in practice we have to respect a thrust characteristics, efficiency, losses and structural complexity of motor and because of that the most attention has been focused on linear induction motors and linear synchronous motors [1].

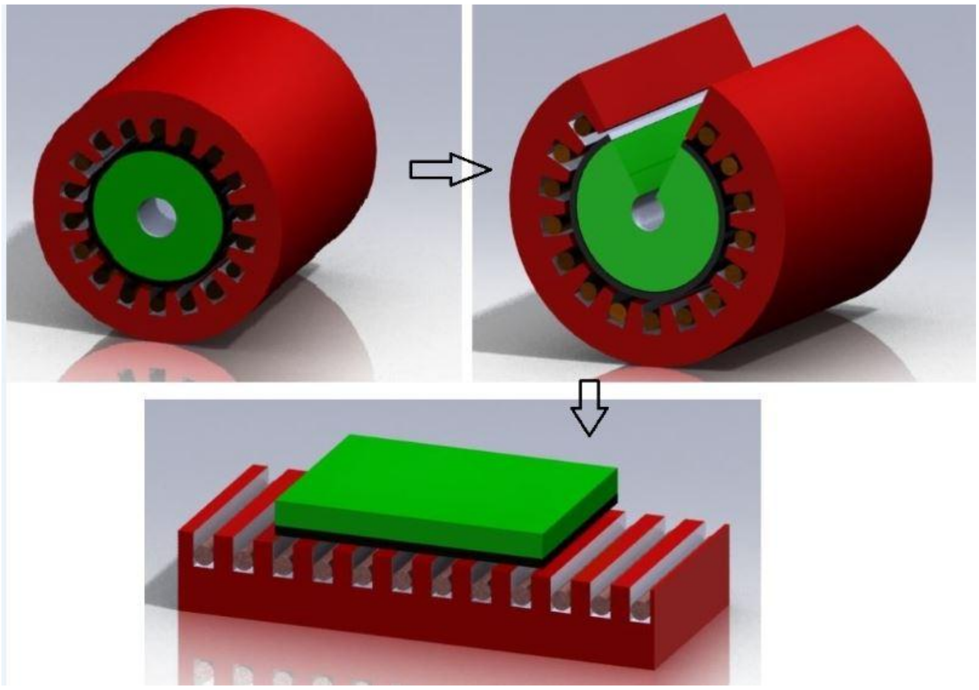

Fig. 1.1: Rotary to linear transformation [6]

Lately these two types of propulsions have been associated with a linear motor-powered transportation. The major advantage of these systems is that the linear motors are able to produce a direct thrust. That means there is no need for transfiguration of rotational energy into translational energy. This advantage provides thrust which does not depend on adhesion between rail and wheel. Above that, linear motor gives a normal force, which is used to support a vehicle [2].

As have already been said, based on type of construction, the linear motors for transportation system are divided to induction and synchronous machines. According to the length of stator (which is usually the active part) and rotor (passive part) are defined the long-stator and the short-stator linear motors (Fig. 1.2). The main differences between these two types are demonstrated on Fig. 1.3 [2].

In case of short-stator system, the stator with multi-phase winding is connected to the vehicle, so with this design is necessary power transmission system for feeding traction energy to the vehicle. From this follows that if the design speed increases the weight of vehicle increases too [2].

On the contrary, the long-stator system has multi-phase winding installed along the track which is fed by stationary power converters. So, the main advantage of the long-stator linear motor is that the vehicle is the passive part and it is unnecessary to provide traction energy for the vehicle, this allows high speeds up to 500km/h [2].

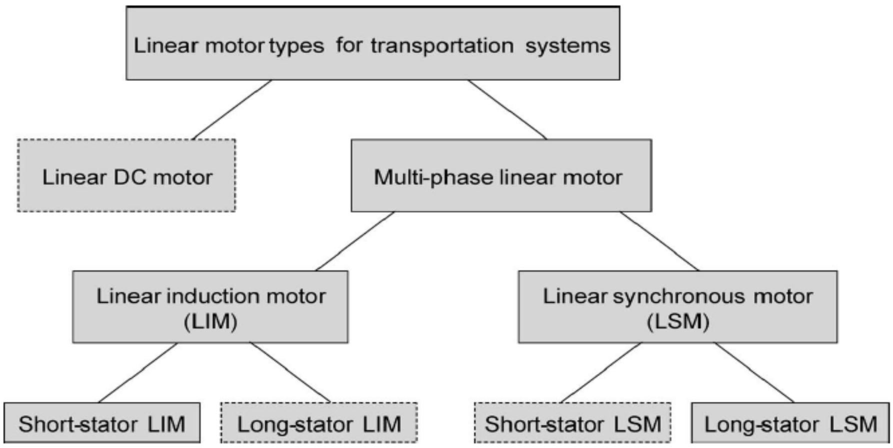

Fig. 1.2: Types of linear motors for transporatiton [2]

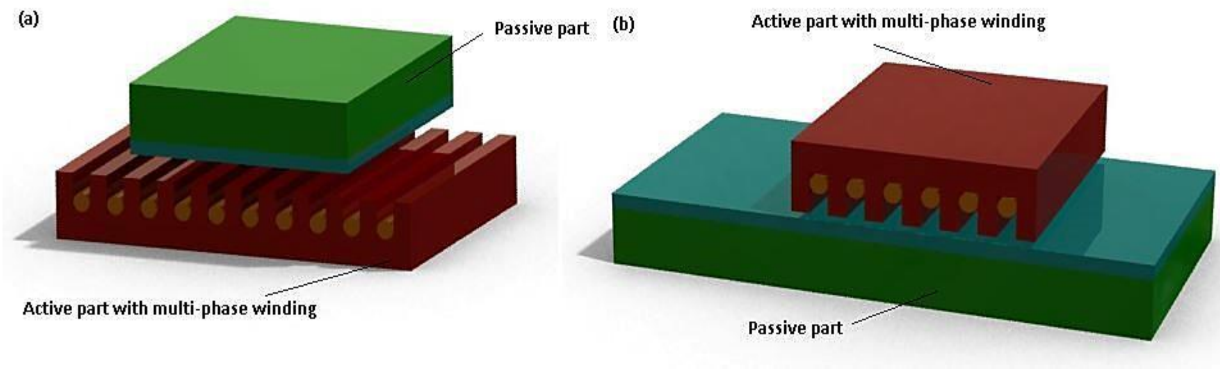

Fig. 1.3: (a) Long-stator linear motor, (b) Short-stator linear motor [2]

1.1 LINEAR INDUCTION MOTORS

1.1.1 THE STRUCTURAL OPTIONS

There are several options for construction of linear induction motor (LIM). The first type is induction motor with squirrel-cage (Fig. 1.4a), where the secondary is formed by discrete conductors which are shorted on both sides by end-bars. This method is similar to a conventional rotary squirrel-cage asynchronous motor [1].

Second option is to substitute the squirrel-cage with a sheet of conducting material backed by iron (Fig. 1.4b). For the sheet is usually used aluminum, which is nonmagnetic material but a magnetic material such as an iron or a copper, can be used as well. There are two types of back iron – solid and laminated, but usually the solid back iron is used. Despite to bigger ohmic losses, which are caused by eddy currents , the solid back iron produce thrust which depends on the relative permeability of the back iron (lower permeability means lower thrust and low power factor) [1].

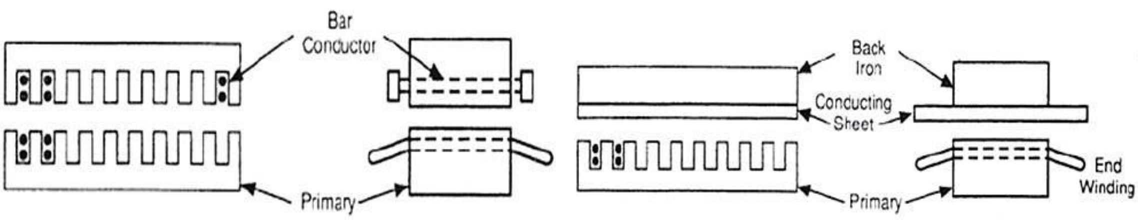

Fig. 1.4: (a) LIM with a squirrel-cage secondary, (b) with conducting sheet for secondary [1]

If the LIM is constructed as single primary with secondary facing it, we talk about single-sided linear induction motor – SLIM. The model which contains two SLIMs is called double-sided linear induction motor, otherwise DLIM. With combination of two single-sided motors, as it is illustrate on Fig. 1.5, the force is doubled [1].

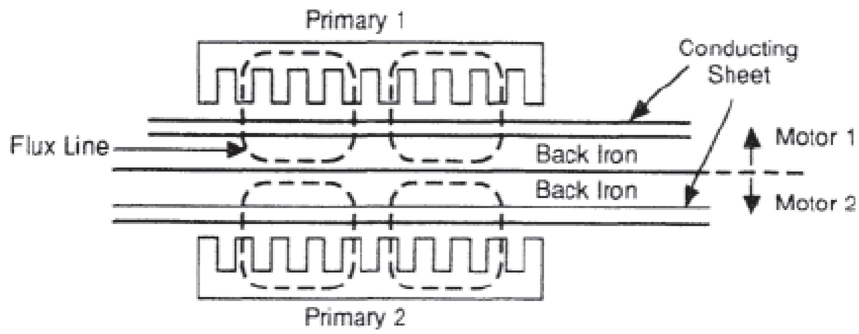

Fig. 1.5 Double-sided linear induction motor [1]

1.1.2 THE PRINCIPLE

The principle of LIM is not so different from conventional rotary induction motor [2]. But generally the LIM needs to be operated with larger air gap, then with rotational ones. This is cause by worse capability of controlling the mechanical clearances. Unlike the torque motor, the primary of linear motor has finite length and open end. This is causing that electromagnetic field in the air gap is not periodic in space, but conversely is fluctuating along the length of motor and extends beyond the motor's length. In the field of linear motors is this phenomenon known as the end-effect. Because of large air gap and end-effect the efficiency and the power factor are substantially lower than with rotating motors [1].

Theoretical analyze of LIM performance is quite difficult. The problem was gradually simplified by using the one-, two-, and three-dimensional field solution. Which means that for example in case of one-dimensional analysis is considered just one axis (usually x). One-dimensional analysis is not quite accurate but is sufficient to analyze the end effect [1].

The synchronous speed

The linear synchronous speed is given by:

$$v_s = 2 \cdot \tau \cdot f \quad (1)$$

Where τ represents the width of one pole-pitch [m] and f is the supplied frequency [Hz]. From this is obvious that the linear speed of traveling magnetic wave is independent on a number of poles but it is given by the pole-pitch width. There are two options how to achieve higher linear speed: design longer pole-pitch or higher frequency [2].

The slip

In case of slip there is no modification, the definition corresponds with the conventional rotational induction motor and is given by (2). Practically, the slip of the LIM is about 10 %.

$$s = \frac{v_s - v}{v_s} \tag{2}$$

Where v_s represent the linear synchronous velocity and v is the velocity of the rotor [6].

If we take these two equations, we can easily derive the velocity of the rotor:

$$v = (1 - s) \cdot v_s \tag{3}$$

The thrust characteristics

If an ac current is connected to the primary windings of linear motor, a traveling wave is produced. This wave induces currents in the secondary and by that create secondary magnetic field. The reaction between primary and secondary fields is causing creation of linear thrust [1].

The important indicator for rotary machines is torque, for linear motors one of the most important defining values is thrust. On the Fig. 1.6 is thrust-speed characteristic of linear induction motor. If the end-effect is not considered the thrust characteristic is approaching to the characteristic of rotary induction motor, with the end-effect the thrust is dropping below the ideal maximum value. For the LIMs with low-speed characteristics, the end-effect causes positive thrust even at synchronous speed. In case of LIMs with high-speed characteristics the thrust is lower than at low-speed case and at synchronous speed the thrust has breaking character [1]. To determine the amount of the thrust is formula:

$$F_x(x,t) = \int_0^{w_{Fe}} \int_0^{2p\tau} A(x,t) \cdot B_\delta(x,t) dxdy \tag{4}$$

Where w_{Fe}represents the width of the iron core and $2p$ is the number of poles.

The B_δ is the air-gap flux density which in case of the LIM is defined as:

$$B_\delta = c_1 \cdot A_1 \cdot \frac{\tau}{\delta_m} \tag{5}$$

Then, the final thrust of the LIM is given by (6) [2]

$$F_x = c \cdot A_\delta \cdot A_1^2 \cdot \frac{\tau}{\delta_m} \tag{6}$$

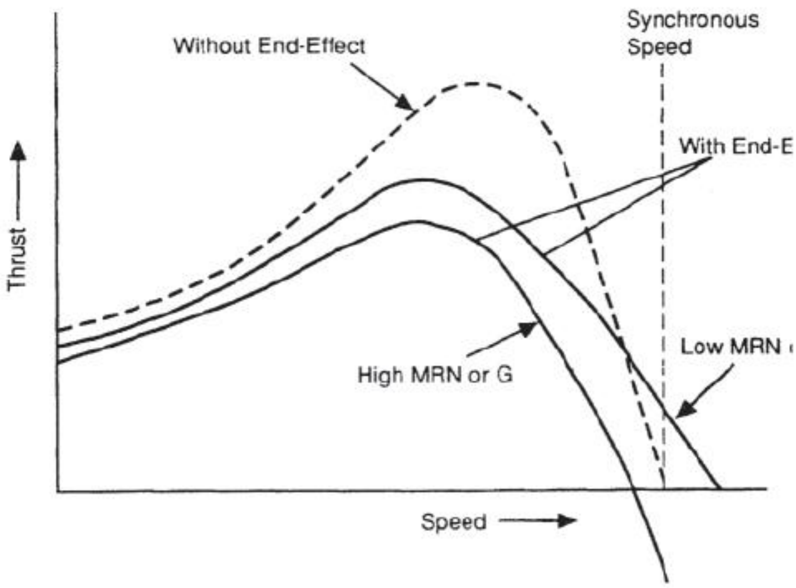

Fig. 1.6: The thrust characteristics of LIM [1]

The thrust depends on the size and dimensioning of the machine and so linear motors used for transportation could reach values up to several thousands of Newton [7]. To limit the end-effect and idealize the thrust characteristics is good to increase number of poles [1].

The goodness factor

As the power is transfer from the primary to the secondary, it's crossing the air gap. Consequently, there are losses between the power transferred across the air gap and the mechanical energy. The higher mutual reactance X_m the better the performance of the motor, the same applies for lower resistance R_2. These two values define the goodness factor G. Higher goodness means better performance of the LIM.

$$G = \frac{2 \cdot \mu_0 \cdot f \cdot \tau^2}{\pi \cdot \rho_s \cdot \rho_0} \tag{7}$$

Where f represents the input frequency, τ is the pole-pitch of the primary winding, ρ_s is the surface resistivity of the secondary conducting sheet, ρ_0 demonstrates the air gap and μ_0 is the permittivity of the free space [1].

The end-effect

As has been mentioned earlier, in the field of linear motors is phenomenon called the end-effect. Generally, the magnetizing component of the primary current and air gap flux decreases with the higher value of the slip. In case of LIM at entry end has flux density small values and gradually rises until it reach the exit end. In some cases the flux density doesn't even reach the nominal level. Consequences of the end-effect are illustrated on Fig.1.7 [1].

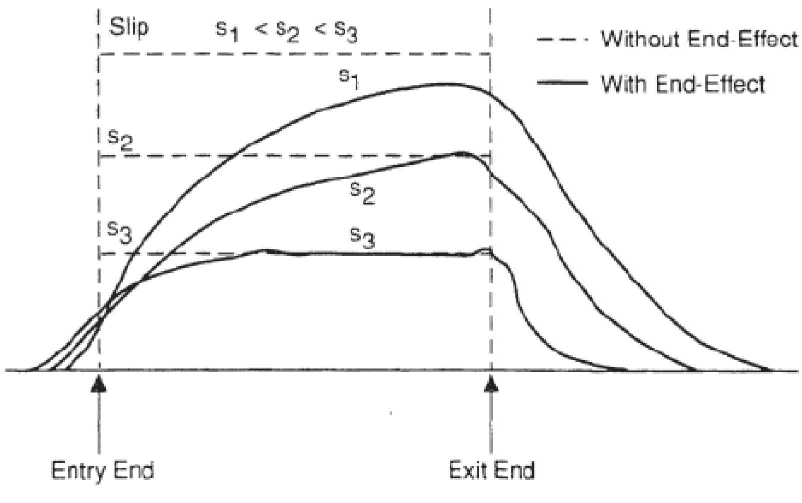

Fig. 1.7: Spreading of the flux density in LIM [1]

The edge-effect

Next effect common in linear induction motors is edge effect. Reason is that the travelling wave is only in the excited part, usually in the primary. The result of edge effect is increasing of the secondary resistivity and by that decreasing of the performance [6].

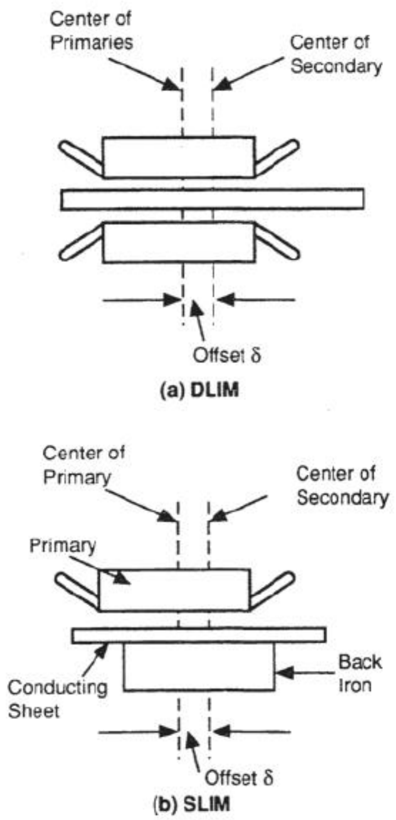

Fig. 1.8: The Transverse Asymmetry of (a) DLIM (b) SLIM

1.1.3 THE CONSTRUCTION TYPES OF LIM

LIM with Solid Iron Secondary

In common models of the linear induction motor the secondary is made as a nonmagnetic sheet with a back iron. For the sheet material is used copper and aluminum. However, another possibility is an all-iron secondary, so this model represents a solid-rotor induction motor. There are two options of DLIM which depend on thickness of the secondary. In case of thick secondary, the two primaries of DLIM act as two independent SLIMs, this is caused by skin effect. On the contrary, if the secondary is thin the primaries will work as classical DLIM. The thrust of the DLIM depends on the saturation of the iron.

In SLIM configuration, the secondary iron affects the magnetic circuit of the LIM. Higher iron saturation means increase of the effective gap [1].

LIM with Transverse Asymmetry

If the transverse symmetry is considered, the lateral force between the primary and the secondary is equal to zero. For some practical applications is exploit the resulting lateral force. This is achieved when LIM topology is asymmetrical in the transverse direction. Both, DLIM and SLIM can be operated with transverse asymmetry as illustrated in Fig.1.8. In case of DLIM the asymmetry is not usually used, because the resulting lateral force is not large and causes destabilization in a DLIM.

The asymmetry is rather used in SLIM configuration, for example in contactless vehicle propulsion, where the lateral force induced by transverse asymmetry is used to guide the vehicle along the track. The lateral force is increased with offset while thrust and normal force are reduced (Fig.1.9) [1].

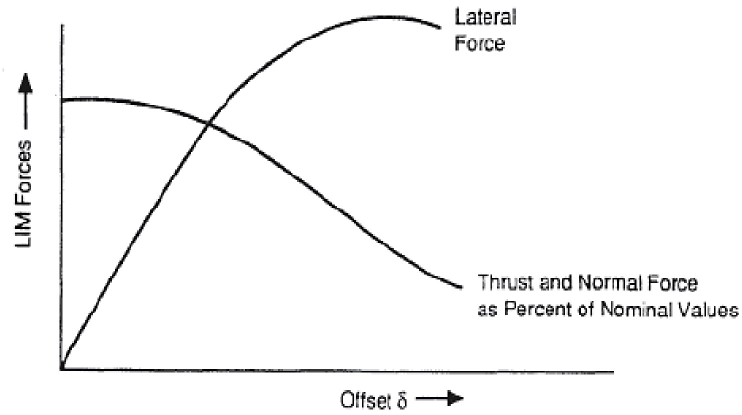

Fig. 1.9: Dependence of the LIM forces on the offset [1]

Tubular Linear Induction Motor

As has been explained earlier, if a rotary induction motor is unrolled then circumference of the rotary induction motor represents the length of the linear motor. If the pole pitch is larger than the LIM width, the resistance and the leakage reactance increase because of the long end windings, so the motor will be inefficient. This can be avoided by rerolling the LIM in the transverse direction as demonstrated on Fig.1.10. This construction is usually used for door openers and electromagnetic pumps [1].

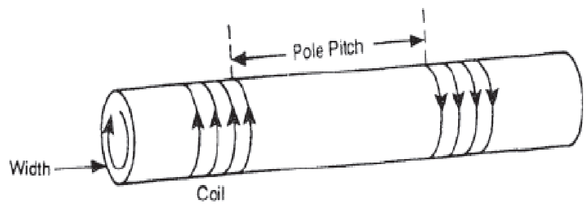

Fig. 1.10: Tubular linear induction motor (TLIM) [1]

Transverse Flux LIMs

So far we have considered LIMs with longitudinal-flux – the air gap flux lines were in direction of motion. In this case, with larger pole pitch, the flux per pole and maximum flux carried by the primary yoke increase too. This brings problem with dimensions of the machine. Thickness of the primary core and of the back iron and total length of the LIM could increase beyond acceptable levels. Resolution of these problems is transverse-flux configuration of LIMs (TFLIM). Primary coils are wound on each leg of the C-cores, which are placed along the length of the LIM, the secondary is made by conducting sheet backed iron (Fig.1.11.). In this case, the air gap flux lines are perpendicular to the direction of motion. There are not huge differences between thrust, lateral and normal force characteristics of the TFLIM and the SLIM [1].

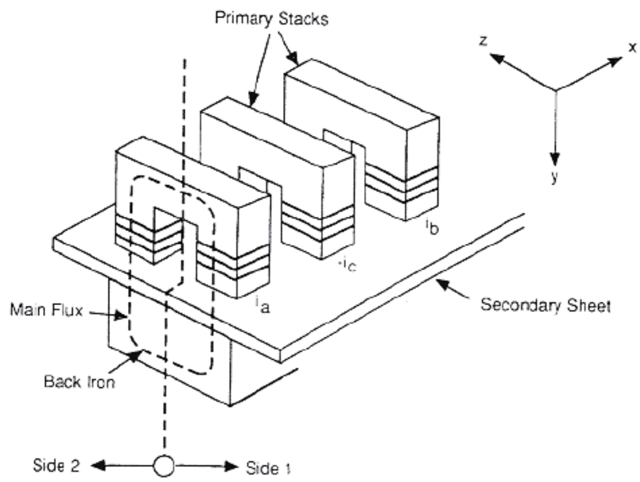

Fig. 1.11: Transverse Flux Linear Induction Motor (TFLIM) [1]

1.1.4 THE APPLICATIONS OF THE LIMS

The most extensive application of the LIMs in past several years has been in the field of ground transportation. LIMs are used as propulsion systems for low-speed and high-speed transportation of passengers and also booster-retarders. Because of quite large air gap (up to 20 mm) the performance of the LIM cannot be compared with performance of the conventional rotating motor. However, rotating motors are not suitable for contactless propulsion systems, where is necessity for low-profile vehicle and light design, so in this cases are LIMs more adequate [1][2].

Possibilities of application include [1]:

- Propulsion system for tracked levitated vehicles
- LIM-rotary motor hybrid system for high-speed rail vehicles
- LIM propulsion system for urban rail vehicles
- Booster-retarder in classification yards

1.2 LINEAR SYNCHRONOUS MOTORS

1.2.1 STRUCTURAL OPTIONS

Basically the linear synchronous motors (LSM) have the same constructional possibilities as LIMs – they can be short-stator or long-stator and also can be single- or double sided [12]. Based on the geometry of the LSM there are several structural types which were also described in chap.1.1.3:

- Flat or tubular
- Transverse flux or longitudinal flux
- Slotted or slotless
- Iron-cored or air cored [12]

Most of these topologies are suitable for all types of following excitation systems:

- Permanent magnets (PMs) in the reaction rail
- PMs in the armature
- Electromagnetic excitation system
- Superconducting excitation system
- Passive reaction rail with saliency (reluctance motors) [12]

For transportation systems some of this topologies are uneconomic, because of this reason are implement two kinds of topologies: the active-guideway LSM (electromagnetic or superconducting excitation system), and the passive-guideway LSM (PM in the reaction rail) [2],[12].

1.2.2 THE PRINCIPLE

Like LIMs, the linear synchronous motors are based on the similar principles as rotary synchronous motors [2]. In case of LSMs, we don't use designation *primary* and *secondary*, because operation of a LSM doesn't depend on which part is stationary and which is movable [1].

The propulsion force has two components – synchronous component which is produced by travelling magnetic field and dc magnetic flux, and reluctance component which is also produced by traveling magnetic field and changeable reluctance in the d- and q- axis. The difference between d- and q- axis reluctances and traveling field can cause the creation of the reluctance component of the thrust – this kind of motor is called the ac reluctance LSM. The difference between d- and q- reluctances can be achieved by salient ferromagnetic poles or using ferromagnetic and nonferromagnetic materials [1].

The speed of the moving part

The velocity of the moving part is defined as:

$$v = v_s = 2 \cdot f \cdot \tau = \frac{\omega}{\pi} \cdot \tau \tag{8}$$

Unlike LIM the linear synchronous motor (LSM) has mechanical motion in synchronism with magnetic field, in other words – the mechanical speed is the same as the speed of the traveling magnetic field and it depends on the input frequency f and pole pitch τ [1].

The synchronous reactance

The synchronous reactance of salient pole LSM has two components:

$$X_{sd} = X_1 + X_{ad} \tag{9}$$

$$X_{sq} = X_1 + X_{aq} \tag{10}$$

Where $X_1 = 2\pi f L_1$ represents the armature winding leakage reactance (L_1 is the armature winding leakage inductance), X_{ad}(or X_{aq}) is the d-axis (q-axis) armature reaction reactance, in some publications also called the mutual reactance [1]. Practically, in every case applies $X_{ad} > X_1$ and $X_{ad} > X_{aq}$ (except for PM synchronous motors) [1] [8].

The Voltage-induced

Voltage-induced in one phase of armature winding is defined by:

$$U_i = \pi\sqrt{2} f N_1 \phi_f k_{\omega 1} \tag{11}$$

N_1 is the number of armature turns per phase, $k_{\omega 1}$ is the armature winding factor and ϕ_f represents the excitation magnetic flux density [1].

The thrust

Electromagnetic thrust of LSM is given by:

$$F = \frac{P_{elm}}{v_s} \qquad (12)$$

In case of salient pole LSM, the reluctance component is added so the equation has form:

$$F = F_{syn} + F_{rel} \qquad (13)$$

where synchronous part is given by (14) and is demonstrated on Fig. 1.12:

$$F_{syn} = \frac{m_1}{v_s}\frac{U_1 U_i}{X_{sd}} sin\varepsilon \qquad (14)$$

and reluctance part is:

$$F_{rel} = \frac{m_1 U_1^2}{2v_s}\left(\frac{1}{X_{sq}} - \frac{1}{X_{sd}}\right) sin2\varepsilon \qquad (15)$$

Where m_1 represents the number of phases and ε is the force angle.

There are two options how generate the thrust, it could be generated as an action of traveling magnetic field induced by an ac current in three-phase windings and a series of magnetic poles, or magnetic field induced by an electronically switched dc current windings and a series of magnetic poles [1]. Thrust characteristic of the LSM is illustrated on Fig. 1.12.

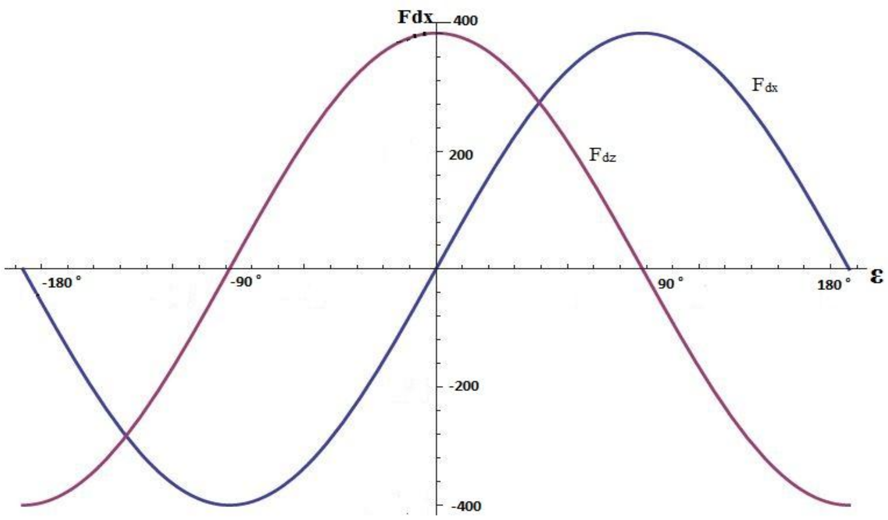

Fig. 1.12: Thrust F_{dx} and normal force F_{dz} as function of the force angle ε for typical parameters of LSM (without reluctance part) [1]

1.2.3 THE CONSTRUCTION TYPES OF LSMS

Linear synchronous motors have two arrays of conductors – the armature winding, which carries the system of currents which induce the traveling wave and the field winding, in other words the excitation winding. LSMs can be divided into two types – heteropolar (active-guideway) and homopolar (passive-guideway) [9].

LSM with electromagnetic excitation

This excitation system is quite similar to the salient pole rotor of the conventional rotary motor [12]. It's heteropolar motor, also known as the active-guideway LSM. It uses the long-stator topology and has either an iron core or an air core. As can be seen on Fig.1.13, in case of iron core motor it could be use conventional electromagnets or permanent magnets. Both systems are controlled by sensor of position [2].

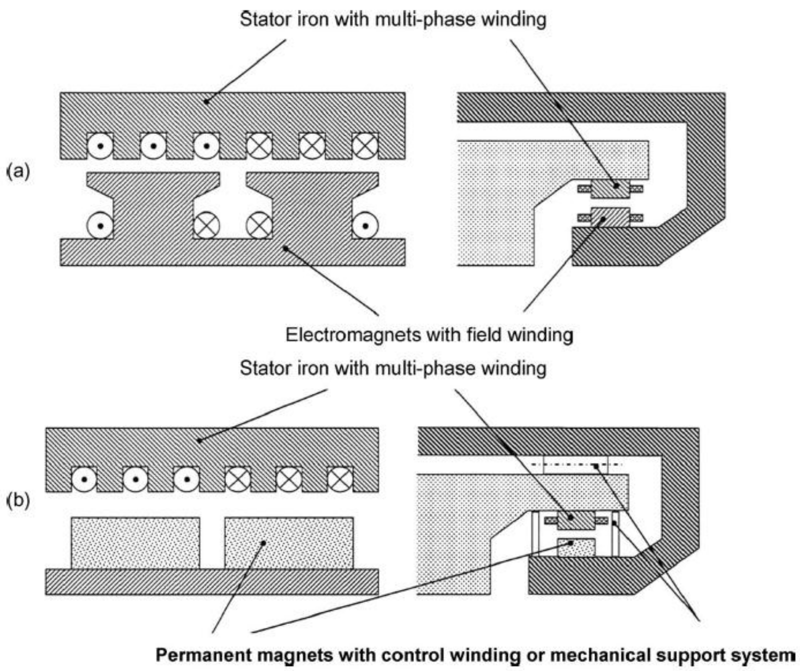

Fig. 1.13: Active-guideway LSM (a) controllable electromagnetic system (b) controllable PM system [2]

Tubular LSM with permanent magnets

As it is with LIM, if the flat PM linear synchronous motor is wrapped parallel into the axis direction of the motion as it is shown on Fig. 1.14 we will get a tubular LSM. This model does not have end winding, which means it is not facing the edge effect and does not have additional impedance. Tubular PM LSM has simple structure and it is suitable for designing high-speeds levitation trains. But attention must be paid on cooling and starting thrust which is vulnerable to voltage fluctuations [10].

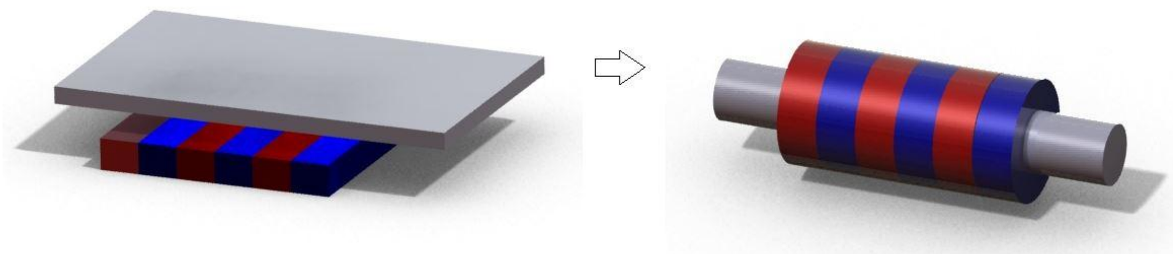

Fig. 1.14: The transformation of flat LSM with PM to tubular LSM with PM [10]

High Temperature Superconducting LSM

To create higher magnetic field, the combination of high temperature superconducting (HTS) bulk and permanent magnets could be used. Such model is demonstrated on Fig. 1.15, where the primary is composed of three-phase copper windings and the secondary is made by HTS bulks which are put in cryogenic vessels. The PM-guideway is consisted of the NdFeB permanent magnets and assembled magnetic iron. This construction has smaller volume, less weight, bigger propulsion and higher power factor than conventional LSM. This system also has strong levitating force and unlike other types levitated systems it has self-stabilizing nature, so there is no need for air-gap control system [11].

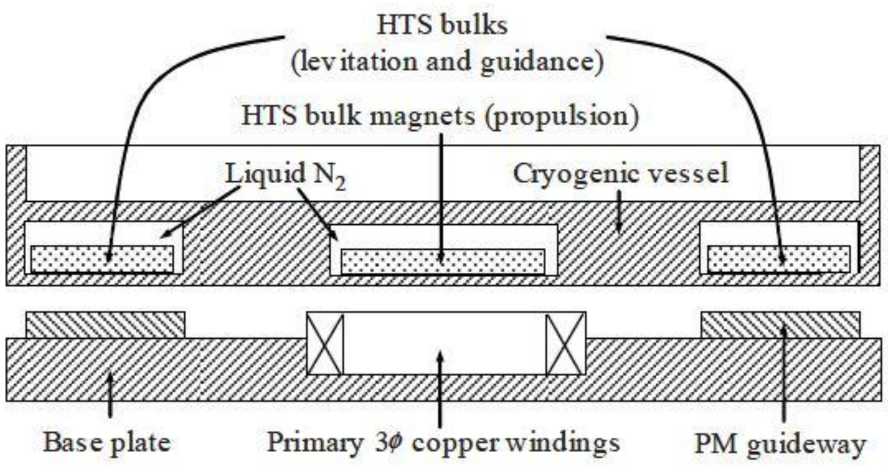

Fig. 1.15: HTS LSM levitated by HTS – magnetic levitation system [11]

Permanent magnet LSM with passive-guideway

Economic utilization of PMs which can be implemented in transportation systems is *to apply PM excitation system to the short armature that magnetizes the long reaction rail and creates magnetic pole in it* [12]. This kind of motor is known as homopolar LSM. Such a LSM is illustrated on Fig. 1.16. It's double-sided type of LSM with two polyphase armature systems. Each of this system contains stack with armature winding, PMs are located between these stacks and U-type yoke, which provides mechanical and magnetic connection. The reaction rail is passive, its poles are magnetized by PMs through the air gap. The thrust is produced by traveling magnetic field of armature winding and salient poles of the reaction rail. The PMs could be replaced by electromagnets [12].

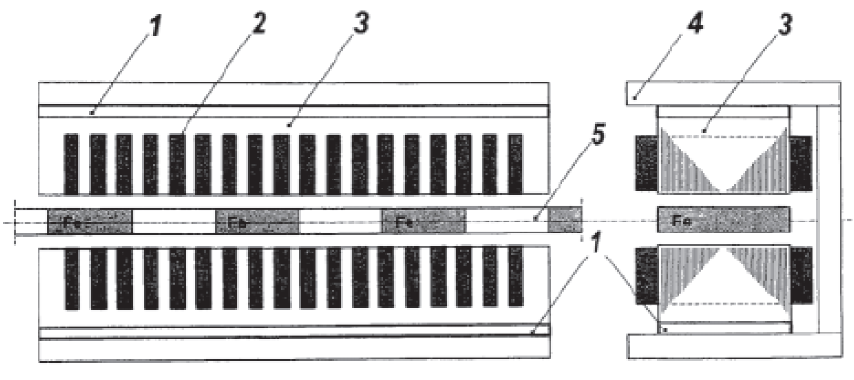

Fig. 1.16: Double-sided PM LSM with passive reaction rail, 1 – PM; 2 – armature winding; 3 – armature stack; 4 – yoke; 5 – reaction rail [1]

1.2.4 THE APPLICATIONS OF THE LSMS

The linear synchronous motors are mainly used in two fields – industrial automation systems and transportation systems. As regards to transportation, linear synchronous motors are implemented as propulsion systems for high-speed levitated trains (mainly based on electrodynamic suspension – explained in chap. 2.2.2). Also there have been researches for ropeless elevators which use this kind of propulsion [1].

From industrial automation systems can be mentioned [1]:

- Positioning stages
- Machining centers
- Welding robots
- Diamond processing laser systems, and so on

2 MAGNETIC LEVITATION IN TRANSPORTATION SYSTEMS

2.1 THE PRINCIPLE OF MAGNETIC LEVITATION

The levitation can be realized by several options. In this thesis will be explain magnetic levitation (in world literature also known as maglev) which uses magnetic field for operation and its principle is important for High Speed Ground Transportation (HSGT) [3].

2.1.1 LEVITATION WITH PERMANENT MAGNETS

The easiest physical principle of magnetic levitation is demonstrated on Fig. 2.1, the system is using a repelling force of the same poles. This method can be used for magnetic bearings [3].

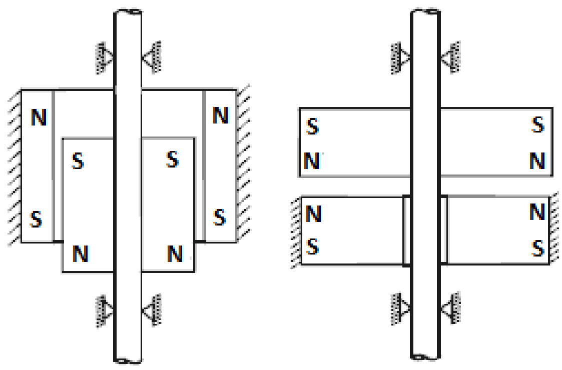

Fig. 2.1: Two types of demonstration of magnetic levitation by PMs [3]

Other option is utilization of behavior of diamagnetic material in inhomogeneous magnetic field. Unlike a paramagnetic or ferromagnetic materials diamagnetic solid in inhomogeneous magnetic field is repelled. Unfortunately natural diamagnetic materials have relative permeability close to one, so levitation force is too weak [3].

That is the reason why lately the magnetic levitation is associated with superconductors, since they are behaving as an ideal diamagnetic, which means its relative permeability goes to zero and the levitation force is much stronger than with natural diamagnetic [3]. When we put a permanent magnet above a superconductor cooled by liquid nitrogen to temperature below the critical temperature the repelling force is created and the PM is levitated (Fig. 2.2), such a phenomenon is called the Meissner effect [13].

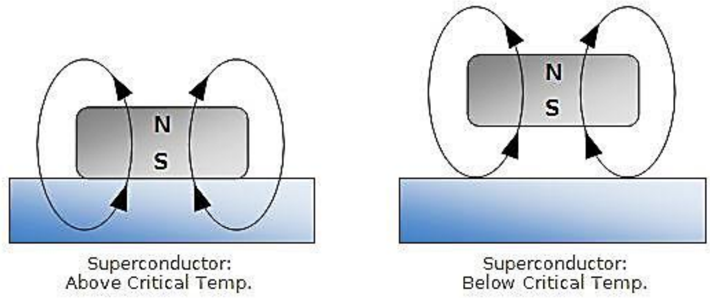

Fig. 2.2: The Meissner effect [14]

2.1.2 TRANSFORMATION LEVITATION

If we put a piece of conducting material into the alternating magnetic field created by excitation coil, the transformer voltage will be induced in this piece and causes eddy currents. These currents will interact with magnetic field of the excitation coil so the piece of conducting material will be levitated. This phenomenon is used in induction furnace for levitation of melted metal. [3]

2.1.3 LEVITATION WITH HALBACH ARRAY

Few years ago was developed a levitation system with permanent magnets which compared to existing models is cheaper, simpler and safer. It’s array of NdFeB permanent magnets which are rotate by 90° in different directions. This special arrangement illustrated on Fig. 2.3 creates a strong magnetic field and it’s known as the Halbach array. Because the magnetic fields of individual PMs are added, the resulting magnetic flux at the bottom of the array has values about 1 T. If the moving Halbach array is placed above the system of levitation coils than the repelling force is created. This levitation system is used for a HTGS Indutrack, which will be described later [16].

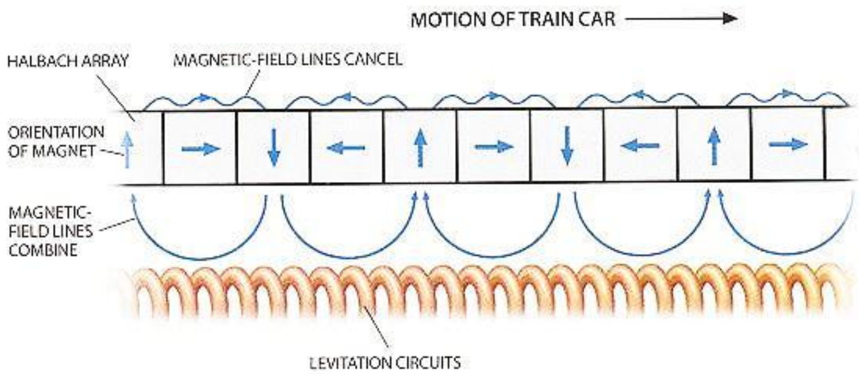

Fig. 2.3: Levitation system with Halbach array [16]

2.2 TYPES OF MAGLEV SYSTEMS

2.2.1 EMS

Electromagnetic suspension (EMS) is kind of levitation system which uses an attractive force between electromagnets on the vehicle and ferromagnetic rails which are mounted to guideway [17].

In EMS system the air-gap values are in the range of 0.5 to 2.5 cm [5]. Typical values for maglev systems are: short stator LIM δ_0 = 12 mm, iron-core long stator LSM δ_0 = 8-12 mm. EMS systems operated with higher air-gap (20-25 mm) could be also realized by permanent magnetic or superconducting excitation [2].

Unfortunately these systems are unstable which can be explained by Fig. 2.4. If we are considering attractive force F which is smaller than the weight of ferromagnetic than the force F is too weak so the ferromagnetic falls down. In other case when the force F is greater than the weight of ferromagnetic than the ferromagnetic is attracted to the electromagnet. Because of this a regulation system is necessary for optimization of exciting current which leads to stable levitation. The feedback control system could be realized as optical sensor of the air-gap or as RLC circuit [3]. From economical view the EMS is not suitable for long distances [5].

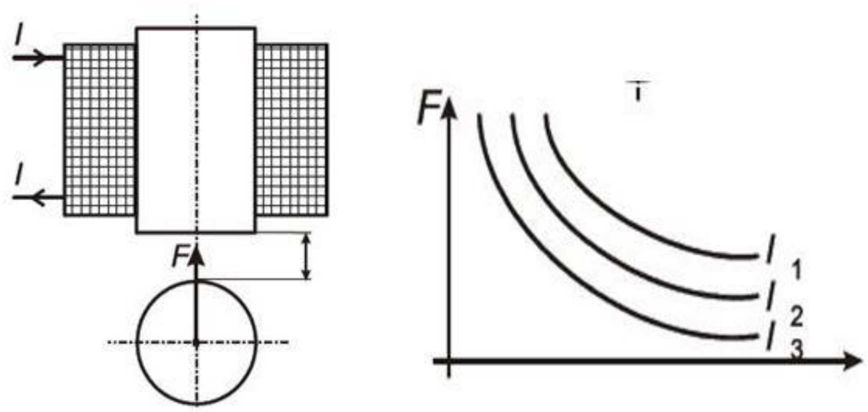

Fig. 2.4: The principle of unstable EMS [3]

2.2.2 EDS

Electrodynamic suspension (EDS) is repelling levitation system which uses a repulsive force between magnets which are mounted on the moving vehicle and conductive guideway [17]. Considering rectangular superconducting coil powered by dc excitation current and mounted on the bottom of the truck which is placed above conductive aluminium track, as it is shown on Fig. 2.5. If the coil is still there are no forces between coil and track. However, if the coil moves the eddy currents are induced in the track, which are in interaction with the excitation current of the coil [3]. The resulting repulsive forces produce stable levitation, but for sufficiently large lift forces needs to be overcome a critical speed which is approximately 40 km/hour. For this reason vehicle has to be equipped with auxiliary wheels which are used during takeoff and landing.

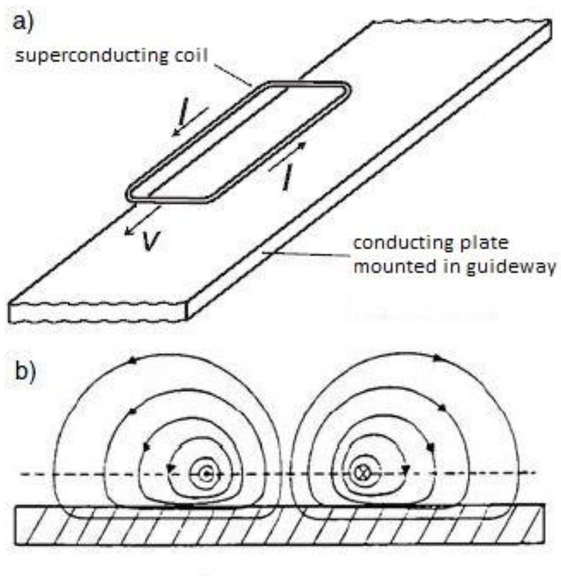

Fig. 2.5: The principle of EDS with moving superconducting coil [3]

There are lot of researches and experiments with EDS systems, lately there has been effort for utilization of superconducting magnets or Halbach arrays with permanent magnets [16], [17] .

Unlike EMS systems the EDS systems are operated with larger air-gaps up to 10 to 25 cm [5].Best known option propulsion for EMS maglev system is air-cored long-stator LSM [2].

2.3 Development of linear motor-powered transportation

In the field of transportation there always has been effort to achieve a high speeds with high operational reliability. First thoughts for levitated transport systems came in 1930s. Many scientists were involved in this development, when in 1934 the patent for magnetic levitated train was given to German engineer Hermann Kemper [2].

2.3.1 GERMANY

For a long time Germany held a first place in developing and researching of the maglev train system. With support of the Federal Ministry of Transport, the investigation and application of high speed rails systems began in year 1969. The result of this research was first passenger-carrying vehicle – Transrapid 01, based on electromagnetic levitation system (EMS) by Messerschmitt-Bölkow-Blohm (MBB) with short-stator linear induction motor propulsion system presented in 1971. This vehicle was tested on 660 meters long trial track and reached speed 90 km/h [18].

Since then, Germany commissioned two prototypes – Transrapid 02 and Transrapid 04 (appendix A), which were based on the same propulsion system as MBB vehicle [18].

In 1979 the Transrapid 05 was exhibited at the International Transportation Exhibition in Hamburg. This vehicle was operated on 908 meters long track and was able to achieve 75 km/h. The Transrapid 05, illustrated on appendix B, was first vehicle operated with EMS with long-stator LSM propulsion [18].

Since 1987, Germany had the world´s largest test facility for levitation vehicles which was located in Emsland. It was a closed circuit with two loops and total length 31,5 km. The first vehicle tested on this trial track was Transrapid 06 (appendix C), which reached speed of 400 km/h. Its successor was Transrapid 07 with speed up to 500 km/h [18].

At 1999 Germany presented Transrapid 08 and also signed agreement with China for 30 km long Transrapid line from Pudong International Airport to Shanghai's city center [18].

The Transrapid 08 uses the long-stator synchronous linear motor (illustrated on Fig. 2. 6), which means that ferromagnetic stators are mounted along the entire track. The support magnets, which represent an excitation part, are located on the both sides of the vehicle and they are electronically controlled – the air-gap stays constant for the whole time (nominally 10 mm). The lateral guidance of the vehicle is realized by guidance magnets. The long-stator LSM is used both as propulsion and braking system. The speed is regulated by changing the frequency of the ac current. The contactless braking is achieved by reversing the direction of the traveling wave, then the motor becomes a generator and the braking energy can be fed back into electrical network [18].

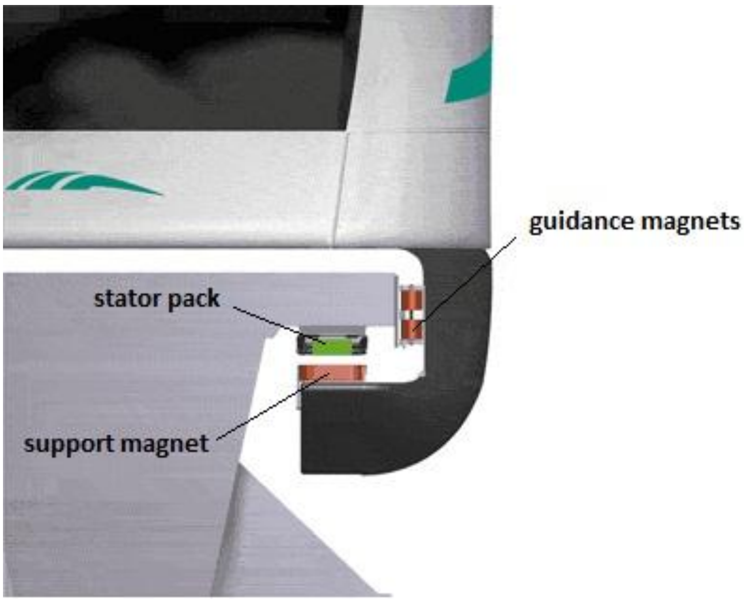

Fig. 2.6: The Transrapid 08 system [18]

The latest German model was Transrapid 09, illustrated on appendix D, commissioned in 2007, its parameters are not so different from model 08.

Unfortunately the operation license for trial track in Emsland has expired in 2011 and the test track was closed. Germany was also planning maglev track between Berlin and Hamburg for acceleration of travel, the plan has been canceled considering massive cost overrun [20].

2.3.2 JAPAN

In Japan are two maglev transportation operational systems. First is JR-Maglev, suspension type is EDS which uses superconducting coils and it's driven by long-stator LSM, which powers the coils at the guide-way. The development started in 1969 and was tested at the Miyazaki test track, where in 1979 was achieved record of 517 km/h. In 1997 the maglev test facility moved to Yamashi, which was originally 18 km long and now is being extended to 42 km. The maximum tested speed - 582 km/h was reached in 2003 [19].

The JR-Maglev vehicles called MLU (appendix E) are based on repulsive forces between superconducting magnets which are mounted on the board of vehicle and coils which are located along the guideway. These coils are powered by ac current so they act as strong electromagnets. The created traveling wave causes that superconducting magnets are attracted and pushed [19]. This principle is demonstrated on Fig. 2.7.

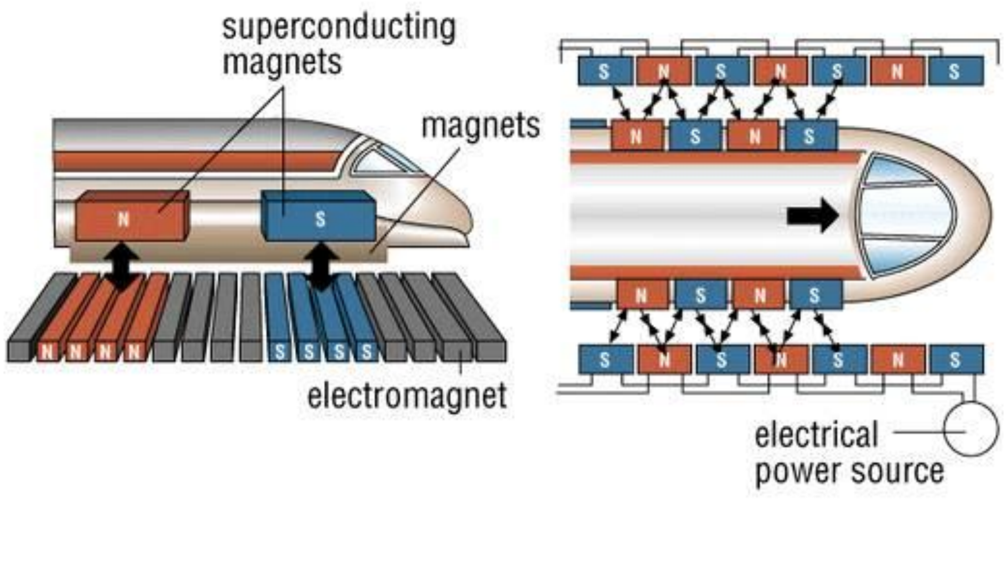

Fig. 2.7: The principle of superconducting Maglev system [24]

Second system is the High-Speed Surface Transportation – HSST, which was developed in 1974. For levitation it uses EMS with short-stator LIM propulsion system. The first commercial line of the HSST system is operating since 2005 and it's called Linimo, illustrated on appendix F. The track is 9 km long, maximum speed is about 100 km/h and it connects suburbs of Nagoya [2].

2.3.3 CHINA

As was mention in previous chapter, in 1999 China signed contraction with Germany for subcontracting of Transrapid system. The construction began in 2001 and was finished in 2002. The first high-speed maglev system for public transportation went into operation in April 2004 in Shanghai (Fig. 2.7). It uses the Transrapid 08 with the electromagnetic levitation system corresponding iron-core long-stator linear synchronous motor in the guide-way. The maximum operation speed is 420 km/h and single journey takes 7.5 minutes [18] [4].

Fig. 2.8: The first high-speed maglev system in Shanghai (TR 08 model) [18]

Research from October 2007 shows that in four years of operation the Shanghai line traveled 4,36 M km and carried 13 M passengers. After Germany and Japan, China became the third country with ground passenger transportation that would reach speeds up to 500 km/h [4].

The Korean Maglev system is also under construction in Changsta, Tangshan and Dalian. In these cities should be test facilities operated with EMS and short-stator linear induction motor propulsion [2].

2.3.4 UNITED STATES

After Germany and Japan, United States also started with research of High Speed Transportation systems. The main discovery was made by Powell and Denby in 1968, who led the research for utilization of superconducting magnets in electro-dynamic suspension. This greatly improved the efficiency of EDS [23]. In the early 1970s, U.S. started the Magplane project, where under the lead of Henry Kolm and Richard Thornton was designed and built the first superconducting magnetically levitated high-speed ground transportation prototype [2].

But unlike Japan or Germany, U.S. doesn't possess a test facility for HST, so there are two current projects – General Atomics and MagneMotion aiming to install an operational system at Brooklyn Polytechnic University and at Old Dominion University [23].

Nowadays there are maglev activities in Pennsylvania – General Atomics system, which uses EDS with permanent magnets and long-stator LSM, or in Florida – Maglev 2000 using the same system [23].

System	Location	Country	Propulsion type	Suspension type	Status
Transrapid	Emsland	Germany	Long-stator LSM	EMS	Test facility
	Shanghai	China	Long-stator LSM	EMS	In operation
MLU	Yamanashi	Japan	Air-core long-stator LSM	EDS	Test facility
HSST	Nagoya	Japan	Short-stator LIM	EMS	Test facility
Linimo	Nagoya	Japan	Short-stator LIM	EMS	In operation
Korean Maglev	Daejeon	South Korea	Short-stator LIM	EMS	Test facility
	Changsta	China	Short-stator LIM	EMS	Test facility
	Tangshan	China	Short-stator LIM	EMS	Test facility under construction
	Dalian	China	Wheels and PM	EDS with PM	Test facility under construction
MagneMotion	Massachusetts	USA	Long-stator LSM	EMS with PM	Test facility
General Atomics	Pennsylvania	USA	Long-stator LSM	EDS with PM	Test facility
American Maglev	Virginia, Georgia	USA	Short-stator LIM	EMS	Test facility
Maglev 2000	Florida	USA	Long-stator LSM	EDS	In research

Tab. 2.1: Maglev activities to 2009 [2]

Also in other countries there have been proposals of maglev transportation system, for example Denmark, Switzerland, United Kingdom, India, and so on. But all these projects are still in research part or were rejected (detailed overview at Tab. 2.1)

The main reason for rejection of maglev system is economical. So far the mentioned models are expensive and complex. So lots of universities are trying to come with new concept, which could solve this problem. For example are described two models – SupraTrans and Inductrack.

SupraTrans project

SupraTrans system is based on superconducting levitation. It consists of superconducting materials levitating in the static magnetic field created by permanent magnets placed in guideway. The High-Temperature Superconductors create self-stabilizing system, which stabilize lateral and vertical position of the vehicle in the magnetic track. That is the advantage of this system – it doesn't need an electronic control to keep a constant distance between the vehicle and the track like it is needed with magnetic levitation system. As propulsion is use the double-sided linear induction motor. So far there has been built a model which is 1,3 meters long and it has been tested on 7 meters long track (dimension were chosen so that it can fit in laboratory). Further plans are to implement electrical cooling system without need of cryogenic liquids and wireless power supply of the vehicle – by solving these problems the SupraTrans system could be operated with speeds around 200 km/h. [21]

Inductrack project

This concept is finding simpler and less expensive possibility for HST systems. It works on principle of Halbach array of permanent magnets (already described in chap….), this arrangement of PM's is mounted on the train and it provides necessary levitation forces. With the moving vehicle the magnetic field from PM induces repelling currents in a close-packed array of shorted conducting coils in the track. As a drive system could be realize by special drive coils with levitation coils which are pulsed in synchronism with field of PM's or could be used the linear induction motor propulsion system. The Inductrack project was funded by NASA – they wanted to implement a sloping maglev track for launching large rockets [22].

CONCLUSION

The aim of this thesis was to become acquainted with principles of linear motors and their utilization for maglev trains. There were mentioned two main kinds – the linear synchronous and the linear induction motors. Comparing to torque motors they have lower power-factor and deal with the edge and the end effect, these difficulties are partly handled by several structural options (for example tubular linear motors). Linear motors product linear thrust without any conversion and their construction is low profile so they are eligible for magnetically levitated vehicles.

There are two systems of magnetic levitation used in transportation – electromagnetic suspension (attractive levitation) and electrodynamic suspension (repulsive levitation). Both of these systems could use LIM or LSM propulsion system, but usually we deal with EMS system using LIM propulsion (for shorter distances with low speed) and EDS system using LSM propulsion. However, this has not to be rule – for example German Transrapid system uses EMS with LSM propulsion suspension.

Many countries are interested in implementation of HSGT, unfortunately in present days there is only one operating high speed maglev system in Shanghai (not considering the low-speed maglev system Linimo in Japan). Expansion of maglev trains is limited by high cost and complexity. The Transrapid system uses EMS which is inherently unstable, for this reason the control system for electromagnets has to fulfill demanding standards, on the other hand, the Japanese JR-Maglev system uses superconducting magnets so for operation of this system the cryogenic cooling system is necessary. Because of this matter there is effort for cheaper structural solution, for example the Inductrack project which substitutes superconductors with Halbach array of permanent magnets.

Despite these problems the Maglev trains are perspective developing successors of the conventional railway systems.

REFERENCES

[1] Handbook of electric motors. Second Edition. New York: Taylor & Francis Group, LLC, 2004. ISBN 978-0-8247-4105-1.)

[2] Hellinger, R.; Mnich, P., "Linear Motor-Powered Transportation: History, Present Status, and Future Outlook," Proceedings of the IEEE , vol.97, no.11, pp.1892,1900, Nov. 2009 doi:10.1109/JPROC.2009.2030249 Dostupné z: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5280196&isnumber=5297592

[3] MAYER, Daniel. Elektrodynamika v energetice. 1. vyd. Praha: BEN, 2005. ISBN 80-7300-164-0.

[4] Luguang Yan, "The Linear Motor Powered Transportation Development and Application in China," Proceedings of the IEEE , vol.97, no.11, pp.1872,1880, Nov. 2009, doi: 10.1109/JPROC.2009.2030245 Dostupné z: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5290110&isnumber=5297592

[5] Sen, P.C., "On linear synchronous motor (LSM) for high speed propulsion," Magnetics, IEEE Transactions on , vol.11, no.5, pp.1484,1486, Sep 1975, doi: 10.1109/TMAG.1975.1058873 Dostupné z: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=1058873&isnumber=22815

[6] BARTOŠ, V., J. ČERVENÝ, J. HRUŠKA, A. KOTLANOVÁ a B. SKALA. Elektrické stroje. Plzeň: Západočeská univerzita v Plzni, 2011. ISBN 978-80-7043-444-4.

[7] McLean, G. W., "Review of recent progress in linear motors," Electric Power Applications, IEE Proceedings B , vol.135, no.6, pp.380,416, November 1988, doi: 10.1049/ip-b:19880042 Dostupné z: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=4648722&isnumber=314

[8] BARTOŠ, Václav. Teorie elektrických strojů. Plzeň: Západočeská univerzita v Plzni, 2006. ISBN 80-7043-509-7.

[9] Levi, Enrico, "Linear synchronous motors for high-speed ground transportation," Magnetics, IEEE Transactions on , vol.9, no.3, pp.242,248, Sep 1973, doi: 10.1109/TMAG.1973.1067639 Dostupné z: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=1067639&isnumber=22921

[10] Kefeng Huang; Huaishu Li; Shuai Li, "Research actuality and trend in development of tubular permanent magnetism linear motors," Artificial Intelligence, Management Science and Electronic Commerce (AIMSEC), 2011 2nd International Conference on , vol., no., pp.5726,5729, 8-10 Aug. 2011 doi: 10.1109/AIMSEC.2011.6010011 Dostupné z: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6010011&isnumber=6009617

[11] Luhai Zheng; Jianxun Jin; Youguang Guo; Haiyan Lu; Jianguo Zhu, "Design and electromagnetic analysis of a HTS linear synchronous motor," Applied Superconductivity and Electromagnetic Devices, 2009. ASEMD 2009. International Conference on , vol., no., pp.5,10, 25-27 Sept. 2009 doi: 10.1109/ASEMD.2009.5306705 Dostupné z: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5306705&isnumber=5306603

[12] JACEK, Gieras, Zbigniew PIECH a Bronislaw TOMCZUK. Linear Synchronous Motors: Transportation and Automation Systems. 2. vyd. New York: Taylor & Francis Group, 2012. ISBN 978143984221.

[13] Meissnerův efekt. In: Zdeněk Moravec: Blog a web o chemii, elektronice a programování [online]. 2013 [cit. 2013-04-19]. Dostupné z: Meissnerův efekt

[14] Investigations into the electrical properties of particular metals at different temperatures led to the identification of superconductivity and the exploration of possible applications. In: Bore of studies [online]. 2007 [cit. 2013-04-19]. Dostupné z: http://www.boredofstudies.org/wiki/Investigations_into_the_electrical_properties_of_particular_metals_at_different_temperatures_led_to_the_identification_of_superconductivity_and_the_exploration_of_possible_applications.

[15] WILDI, Theodor. Electrical Machines, Drives, and Power Systems. Third Edition. New Jersey: Prentice-Hall, Inc., 1997. ISBN 0-13-571333-1.

[16] MAYER, Daniel. Nové možnosti magnetické levitace v dopravě?. ELEKTRO: Odborný časopis pro elektrotechniku [online]. 2003, č. 12 [cit. 2013-04-19]. Dostupné z: http://www.odbornecasopisy.cz/index.php?id_document=25632

[17] Maglev Technology. In: The Enteprise Center [online]. 2008 [cit. 2013-04-19]. Dostupné z: http://www.theenterprisectr.org/high-speed-ground-transportation/maglev-technology.html

[18] Transrapid [online]. 2010 [cit. 2013-05-29]. Dostupné z: http://www.transrapid.de/cgi/en/basics.prg?session=51c93ca251a528d6_197674

[19] Maglev [online]. 2010 [cit. 2013-05-29]. Dostupné z: http://www.rtri.or.jp/rd/division/rd79/yamanashi/english/maglev_frame_E.html

[20] Transrapid. In: Wikipedia: the free encyclopedia [online]. San Francisco (CA): Wikimedia Foundation, 2001- [cit. 2013-05-29]. Dostupné z: http://en.wikipedia.org/wiki/Transrapid

[21] Schultz, L. ; de Haas, O.; and more authors; Superconductively levitated transport system - the SupraTrans project, June 2005 [cit. 2012-05-29]. Dostupné z: http://80.ieeexplore.ieee.org.dialog.cvut.cz/xpl/articleDetails.jsp?tp=&arnumber=1440126&queryText%3DSuperconductively+Levitated+Transport++System%E2%80%94The+SupraTrans+Projec

[22] POST, Richard F. a Dmitry DYUTOV. The Inductrack: A Simpler Approach to Magnetic Levitation. 1999.

[23] Thornton, R.D., "Efficient and Affordable Maglev Opportunities in the United States," Proceedings of the IEEE , vol.97, no.11, pp.1901,1921, Nov. 2009 doi: 10.1109/JPROC.2009.2030251 Dostupné z: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5297599&isnumber=5297592

[24] Randolph Miller's Introduction to Superconductors. Western Oregon University [online]. 2011 [cit. 2013-06-03]. Dostupné z: http://www.wou.edu/~rmiller09/superconductivity/

LIST OF APPENDIX

APPENDIX

Appendix A: The Transrapid 04 presented in 1973 [18]

Appendix B: The Transrapid 05 presented in 1979 [18]

Appendix C: The Transrapid 06 presented in 1983 [18]

Appendix D: The latest model Transrapid 09 presented in 2007 [18]

Appendix E: The latest superconducting maglev system MLX01 and older version MLU002 N [19]

Appendix F: The low-speed Linimo system [2]