F. CASTELLI DEZZA, A. DI GERLANDO, I. VISTOLI

MODELLING AND EXPERIMENTAL APPROACH TO THE DESIGN OF EMS MAGLEV SYSTEMS WITH ELECTROMAGNETIC AND HYBRID LEVITATION DEVICES

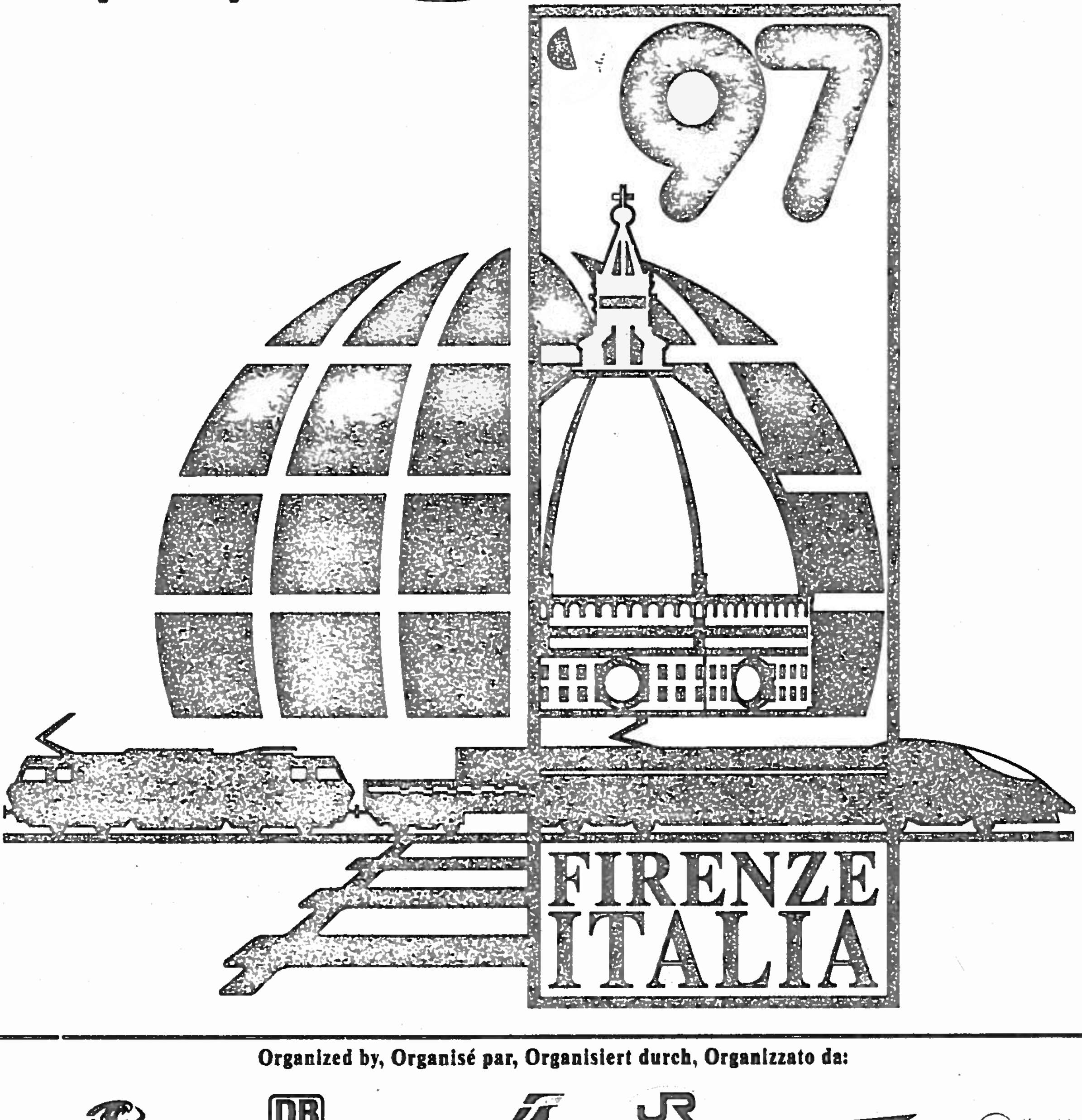
Proceedings of the
World Congress on Railway Research
WCRR'97
Firenze
16-19 Novembre 1997

VOL C

WORLD CONGRESS ON RAILWAY RESEARCH

PROCEEDINGS / ACTES / BERICHTE / ATTI

WCRR



Organized by, Organisé par, Organisiert durch, Organizzato da:

ASSOCIATION OF AMERICAN RAILROADS
BR RESEARCH
DB Deutsche Bahn
FERROVIE DELLO STATO
JR Railway Technical Research Institute
SNCF
Union Internationale des Chemins de fer

With the contribution of, Avec la contribution de, Mit dem Beitrag von, Con il contributo di:

consorzio trevi ETR 500
FiatFerroviaria
TIM Telecom Italia Mobile
FERROVIE DELLO STATO

MODELLING AND EXPERIMENTAL APPROACH TO THE DESIGN OF EMS MAGLEV SYSTEMS WITH ELECTROMAGNETIC AND HYBRID LEVITATION DEVICES

Francesco Castelli Dezza
Assistant Professor
Antonino Di Gerlando
Assistant Professor
Ivo Vistoli
Full Professor

Dipartimento di Elettrotecnica - Politecnico di Milano
Piazza Leonardo da Vinci 32, 20133 Milano, Italy
Telephones: +39 2 239937/12-22-15
Facsimile: +39 2 23993703
E-Mails: (checco, diger, vistoli)@bottani.etec.polimi.it

Abstract

The magnetically levitated transportation systems (MgLev) present the fundamental feature to reach high speeds by eliminating any physical contact between vehicle and guideway, that causes a number of significant problems in the conventional guided transportation systems (wear of contact line and track, pick-up difficulties increasing with speed, high cost maintenance).

Some design problems regarding the on-board levitation-excitation apparatus of Maglev vehicles based on attractive ElectroMagnetic Suspension (EMS) are analysed, by considering systems with purely electromagnetic field excitation (use of windings only) and with hybrid field excitation (presence of both windings and permanent magnets); the different possible configurations of the polar units are examined (single or multiple coils, permanent magnets in the polar bodies or in the levitator yokes), by comparing the main sizing, operating and control characteristics.

Finally, the most important features of a levitating platform prototype are mentioned, constructed c/o the Department of Electrical Engineering of the Politecnico di Milano, aimed to different types of levitation tests.

Key words Maglev Systems, design modelling, parameter analysis

1. Introduction.

The great interest stimulated by Maglev transportation systems all around the world is well known, with involvements in applied research, industrial development and transportation network strategies.

An important aspect of these systems concerns the design optimisation and the control of the on-board inductor subsystems, that accomplish the double function of levitation devices and field excitation apparatus for the propulsion Linear Synchronous Motors (LSM).

The paper describes the results of the studies concerning these subjects, specifically referred to the attractive levitation systems (EMS systems), and as regards the following aspects:

- comparison of the peculiarities of different types of field-levitation polar units;
- description of some characteristics of a prototype constructed c/o our laboratories.

2. Structural topologies and circuit models of the levitation devices

The structural configurations of the analysed levitation devices (in the following called levitators) can be reduces to the three topologies schematised in fig. 1; it is worth to observe that:

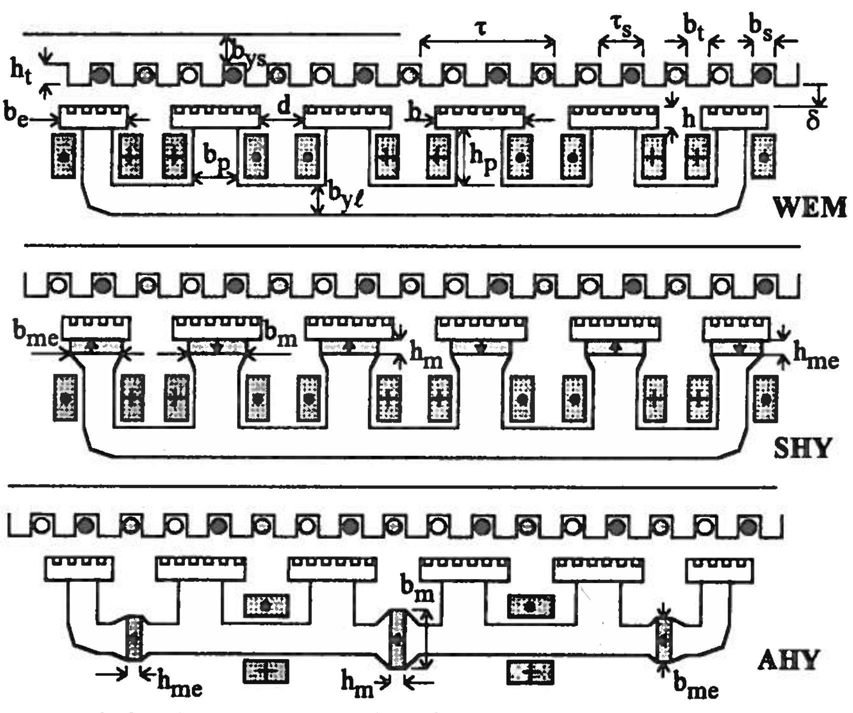


Fig. 1 - *Structure of the 3 types of analysed levitators (PM = permanent magnet):* WEM = *ElectroMagnetic levitator with Windings only*; SHY = *Symmetrical Hybrid levitator (windings + PM);* AHY = *Asymmetrical Hybrid levitator (windings + PM).*

- each component of the system has the same transversal size, equal to ℓ, while the length (in the motion direction) of the external lateral pole shoes ($b_e = \sigma_\delta \bullet b$) is, in general, lower than that of the central pole shoes (with $0.5 \leq \sigma_\delta \leq 1$);
- in the hybrid levitators (including NdFeB permanent magnets (PMs)), the central PMs sizes (h_m , b_m) differ from those of the external PMs (h_{me} , $b_{me} = \sigma_m \bullet b_m$, with $0.5 \leq \sigma_m \leq 1$); the PMs are inserted in suited tightening structures (of non-magnetic nature, not shown in figure), for mechanical protection.

Fig. 2 shows the equivalent magnetic networks, used for the levitation function analysis:

- the m.m.f. m_f includes the constant biasing m.m.f. (M_b) and the regulation m.m.f. (m_r);
- the PMs are modelled by means of their series equivalent circuit (M_m, θ_m);
- all the ferromagnetic branches are supposed unsaturated (for controllability exigencies);
- the presence of the slots is modelled by means of the global Carter's factor k_c (δ);

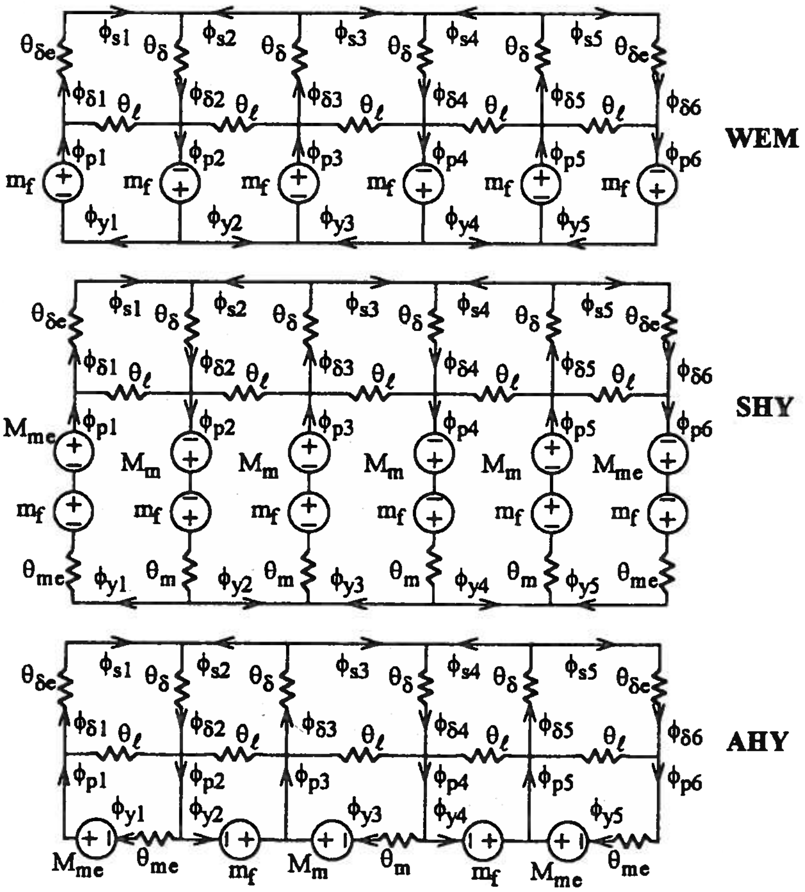


Fig. 2 - *Magnetic networks of the levitators of fig.1, equivalent as regards the levitation function.*

- the interpolar leakage reluctances θ_ℓ are considered as concentrated between the pole shoes;
- the ratio between the air-gap reluctance $\theta_\delta(\delta)$ and θ_ℓ describes the p.u. leakage: $\epsilon_\ell(\delta) = \theta_\delta(\delta)/\theta_\ell$;
- the quantities concerning the lateral, external branches ($_e$) have expressions similar to those of the corresponding central parameters, by using the coefficients σ_δ and σ_m.

3. Design analysis of the levitators

Reference is made to Table I (the data concern a system with maximum speed $v_M = 500$ km/h).

By adopting the same air gap flux density ($B_{\delta n}$) under all the poles, with the values of Table I, the following limit conditions occur, depending on σ_δ : $\sigma_\delta = 0.5 \rightarrow B_{\delta n} = 0.501$ T; $\sigma_\delta = 1 \rightarrow B_{\delta n} = 0.458$ T.

Table I - *Data of a EMS Maglev system, considered for the comparative analysis of different levitators.*

polar pitch: τ [mm]	300	transversal dimension (per side): ℓ [mm]	240
stator tooth width: b_t [mm]	58	stator slot width: b_s [mm]	42
stator tooth height: h_t [mm]	43	nominal geometric air-gap: δ_n [mm]	10
central pole shoe extension: b [mm]	200	pole shoe height: h_e [mm]	28
linear generator slot pitch: τ_{sg} [mm]	28.6	linear generator slot width: b_{sg} [mm]	8.6
levitation rated force (1 levitator) $F_{\delta n}$ [kN]	24	lev. force without payload (1 lev.) $F_{\delta o}$ [kN]	18

It is useful to introduce the quantity $p_e = p_e(\sigma_\delta) = 4 + 2 \cdot \sigma_\delta$, that can be called "number of effective poles" of the levitator: both the levitation force and the propulsion force are proportional to this quantity.

As regards the choice of σ_δ in the range $0.5 \leq \sigma_\delta \leq 1$, it can be shown that the stator (ϕ_s) and levitator (ϕ_y) yoke fluxes significantly depend on σ_δ : the choice $\sigma_\delta = 1$ makes equal all the air-gap fluxes, with "pair poles" distribution: this requires a weighty sizing of the yokes ($b_{y\,l}$ and b_{ys}), particularly heavy for the stator, due to its extension; on the contrary, the choice $\sigma_\delta = 0.5$ is the best one as regards the yokes.

Table II shows the ratio $\rho_s(\sigma_\delta) = b_{ys}(\sigma_\delta)/b_{ys}(0.5)$, between the stator yoke width for a generic σ_δ and the value of this width for $\sigma_\delta = 0.5$ (σ_δ represents also the ratio of the ferromagnetic masses).

The unacceptable increase for $\sigma_\delta = 1$ (+83 %) is confirmed, while in the case of the Transrapid prototypes (Emsland, Germany: $\sigma_\delta \approx 0.75$) this increase is roughly halved.

Table II - *Ratio* $\rho_s(\sigma_\delta) = b_{ys}(\sigma_\delta)/b_{ys}(0.5)$ *between the width (mass) of the stator yoke as a function of* σ_δ *and the minimum width (mass) (for* $\sigma_\delta = 0.5$*).*

σ_δ	0.50	0.55	0.60	0.65	0.70	0.75	0.80	0.85	0.90	0.95	1
$\rho_s(\sigma_\delta)$	1	1.09	1.18	1.26	1.35	1.43	1.51	1.59	1.67	1.75	1.83

In the following, the elements that make the difference among the various levitator types are analysed.

3.1. The electromagnetic levitator equipped with windings only (WEM)

By solving the magnetic network WEM of fig.2, it can be shown that the m.m.f.s M_{fn}, necessary to sustain the nominal fluxes in that network, are equal (their absolute value is $M_{fn} = \theta_{\delta n} \cdot \phi_{\delta n}$).

As regards the operation during variations of the air-gap width, as known an EMS levitator is inherently unstable, thus it requires current controlled power supplies (with quick response), air-gap transducers (with suited dynamic features) and control regulators.

The m.m.f. $m_f(t)$ produced around each pole consists of the following contributions:

- M_b is a constant biasing m.m.f., that produces the flux necessary to generate an average levitation force equal to the weight to be supported by the levitator;
- $m_r(t)$ is the m.m.f. regulation component, aimed to the stabilisation and, above all, directed to compensate the disturbing forces, mainly generated by the guideway asperities during the vehicle running.

The amplitude of the m.m.f. $m_r(t)$ depends on the asperities and on the chosen control law: once assured the essential objective to avoid any contact between vehicle and guideway (occurrence that can be prevented mainly by an accurate construction of the guideway), the best strategy consists of controlling the currents in order to produce an instantaneous levitating force equal to the vehicle weight force; in such a way, the levitator runs in the motion direction without any vertical displacement, thus without transmitting vibrations to the vehicle body and to the passengers. This strategy, that minimises the control power too, can be called control with "constant levitating force": it can be applied also to the other types of levitators; in the WEM EMS topology it coincides also with the control with "constant air-gap flux".

From the coil structure point of view, two types of WEM EMS levitators can be distinguished:

- single winding levitator (WEM1), excited with a regulated current with a non zero average value;
- separated winding levitator (WEM2), with a biasing winding (carrying a constant current) and a regulation winding (galvanically separated by the previous one).

The adoption of a WEM2 levitator type has the main advantage of a separate, significantly reduced, sizing both of the biasing power supply (with minimum needs of dynamic response) and of the regulation power supply, that is requested to generate quickly variable, small amplitude currents (virtually zero, in case of an ideal guideway without asperities).

On the other hand, the advantages of this separation are paid with an increase of the copper mass of the coils and with a corresponding increase of the levitation losses. Usually a Maglev system operates with air-gap oscillations in the range $0.5{\bullet}\delta_n \le \delta \le 1.5{\bullet}\delta_n$, while in stationary conditions the air-gap is maximum, normally $\delta_M = 2{\bullet}\delta_n$. The analysis shows that the regulation m.m.f., virtually zero for $\delta = \delta_n$, increases less than linearly with the increase of δ, and it is maximum in the lift-off process (for $\delta_M = 2 \bullet \delta_n = 20$ mm → $m_r = 0.81 \bullet M_b$).

3.2. The symmetrical hybrid electromagnetic levitator (SHY)

The PM design parameters are χ (ratio between the rated working PM flux density B_{PMn} and its remanence B_r) and ρ_{fn} (active biasing field contribution M_{fn} , fraction of the rated air-gap magnetic voltage $U_{\delta n}$ due to the winding): their choice (both in the range (0-1)) defines PM cross section area and height.

It can be shown that all the PMs of a SHY system have the same height (proportional to $(1-\rho_{fn})$), while the cross section area of the external PMs is lower than those of the central PMs (according to a factor $\sigma_m \approx \sigma_\delta$). Moreover, with $\chi = 0.5$ the PM mass is minimum (maximum energy product condition).

The operation analysis as a function of the air-gap width shows that the external pole fluxes remain roughly equal σ_m times the central fluxes, and that the last ones maintain themselves balanced.

The m.m.f. variation Δm_f necessary to obtain a desired variation $\Delta\phi_\delta$ of the air-gap flux (and therefore of the levitating force F_δ) is higher in a SHY system than in the WEM one, because in the former Δm_f must overcome the PM internal reluctance; this effect seem to reduce the advantage of the SHY system (i.e. the possibility to produce a stationary levitation force ideally with zero biasing currents).

Conversely, if the control technique with "constant air-gap flux" is supposed to be used, the previous conclusions are too much pessimistic: in fact, it can be shown that in the SHY system the regulation m.m.f. needed to maintain the flux ϕ_δ at the rated value $\phi_{\delta n}$ is practically the same of the WEM system.

This apparent paradox can be explained considering that, if ϕ_δ is constant, when the air-gap increases there is no practical magnetic voltage variation across the PM internal reluctance (θ_m), but only an increase of magnetic voltage at the air-gap: this is the only contribution that the winding regulation m.m.f. is required to supply. In conclusion, with the vehicle at nominal payload, as regards the regulation with "constant air-gap flux" around the nominal air-gap, the SHY system is very similar to the WEM system, with the additional advantage of a great reduction of the biasing winding losses.

Again at rated payload, a different comparison concerns the air-gap increase allowed by the use of a SHY levitator: in the SHY case, the adoption of a m.m.f. biasing M $_b$ equal to that of the WEM case allows to increase the air-gap up to $\delta_{na} = 21.6$ mm, more than doubled compared with the WEM case.

On the basis of the previous analysis, the opportunity to adopt values $\chi > 0.5$ and/or $\rho_{fn} > 0$ does not appear justified: to this aim it is worth to consider the system in the zero air-gap limit condition. In this situation the air-gap flux ($\phi_{\delta co}$) equals the PM remanence flux: neglecting the saturation effects, the flux $\phi_{\delta co}$ becomes significantly higher than $\phi_{\delta n}$, and the same occurs for the contact force $F_{\delta co}$ (in our case $\varphi_{\delta co} = \phi_{\delta co} / \phi_{\delta n} \approx 2.14$ and $f_{\delta co} = F_{\delta co} / F_{\delta n} \approx 4.60$): a so high value of the contact force $F_{\delta co}$ is extremely dangerous because, in case of fault of the winding current control, a violent collision between vehicle and guideway can occur ("gluing" event), with risks for the running safety and for the PM integrity.

This remark makes the SHY levitator behaviour quite critic, showing that its features are less convenient than those estimated just on the basis of the rated conditions. A first remedy, again with $\rho_{fn} = 0$, is possible by adopting a value $\chi > 0.5$: the increase of χ implies the growth of the PM height, with a reduction of the remanence flux, i.e. of $\phi_{\delta co}$. Nevertheless, the increase of χ causes the growth of the PM mass too; moreover, it is impossible to obtain a "gluing" force lower than the rated levitating force: Table III shows some values of χ and of the PM masses ratio σ_{MP}, as a function of the p.u. "gluing" force $f_{\delta co}$.

Table III - *Values of the needed PM values of* $\chi = B_{MPn} / B_r$ *and of* $\sigma_{PM} = M_{MP}(\chi) / M_{MP}(0.5)$, *as a function of the desired values of the p.u. "gluing" force* $f_{\delta co} = F_{\delta co} / F_{\delta n}$ *(for* $\rho_{fn} = 0$).

$f_{\delta co}$	4	3.75	3.5	3.25	3.00	2.75	2.50	2.25	2.00	1.75
χ	0.536	0.554	0.573	0.595	0.619	0.646	0.678	0.715	0.758	0.810
σ_{PM}	1.005	1.012	1.022	1.037	1.060	1.094	1.145	1.226	1.363	1.627

The PM mass increase when reducing $f_{\delta co}$, at first small, is more important when a reduction of $f_{\delta co}$ below 3 is desired: in particular, the condition that seems to be more reasonably acceptable is that with $f_{\delta co} = 1.75$ ($\rightarrow \chi = \chi_c = 0.810$), because, in case of empty vehicle (worst case, with $F_{weight} = 0.75 \bullet F_{\delta n}$), it corresponds to a resultant force on the vehicle having the same amplitude of the full payload force. Apart from the force sign, this situation is equivalent to that of a vehicle equipped with WEM type levitators, when a failure of the winding supply system occurs (with the currents reaching the zero level), thus causing the fall of the vehicle under its own weight.

On the other hand, the design choice $f_{\delta co} = 1.75$, even if interesting, implies a high PM mass increase ($\sigma_{MP} \approx 1.63$): this oversizing, technically feasible, is quite significant and could result unacceptable from the economical point of view, due to the NdFeB high cost (nowadays equal to 1 M£it/kg roughly).

Thus, it is better to adopt an active biasing contribution ($\rho_{fn} > 0$): among all the possible values for ρ_{fn} , it is interesting that value ρ_{fnc} that, with $\chi = \chi_c = 0.810$, allows to maintain unvaried the PM mass compared those of the case $\chi = 0.5$; in the examined case, this condition leads to $\rho_{fnc} = 0.384$.

Among the advantages of a partial active current biasing of a SHY levitator there is also the fact that, in case of failure of the power supply (probably corresponding to a zero level reaching of the winding currents), the system almost surely tends towards the fall instead of towards the "gluing" contact, because a significant fraction of the levitating force disappears.

3.3. The asymmetrical hybrid electromagnetic levitator (AHY)

Also as regards this topology (see fig.s 1 and 2 AHY), it is necessary to define the sizing criteria of the 3 PMs and of the 2 coils in such a way that, at rated conditions, the air-gap fluxes produce the rated levitating force: the procedure, similar to that of the SHY case, leads to show that in the AHY levitator all the PM cross sections have the same value, being different the heights; moreover, the rated biasing m.m.f. M_{fn} of each winding of the levitator AHY is twice that of each winding of the WEM case.

The analysis in generic conditions shows that the fluxes in the four central poles and the corresponding air-gap fluxes are not balanced, but there is just an operating symmetry with respect to the central axis of the levitator: thus, there are stator and levitator yoke branches that, in certain conditions, are magnetically more loaded than others. The most critical situation is that occurring during the lift-off process; moreover, the "gluing" phenomenon must be definitely avoided, because in these condition the levitator could never be detached from the guideway by electromagnetic means: we have verified that, fortunately, for $\sigma_\delta = 0.5$ (the best sizing choice) this occurrence is impossible.

4. Comparison between dimensional and operating data of different levitators

Table IV shows the comparison among some dimensional and operating quantities, in the following common conditions: winding current density: $S = 4$ A/mm^2; copper fill factor: $\alpha_{cu} = 0.3$; air-gap oscillations during the vehicle travel: $\Delta\delta = 0.5 \bullet \delta_n$; iron core flux density: $B_{fe} = 1.2$ T in the WEM and SHY types; $B_{fe} = 1.3$ T in the AHY type (in the lift-off condition). It follows that:

- the WEM2 case has masses and losses higher than those of WEM1, but with separated regulation;
- the SHY-a levitator is more light, the PM mass is minimised, has low losses, but it shows very high values of "gluing" force and of winding losses necessary to detach the levitator from the stator;
- the SHY-b levitator has a lower "gluing" force and its rated losses are not significantly increased, but the PM mass and the "detach" losses are too high;

- the SHY-c levitator maintains limited the "gluing" force and the "detach" losses and minimises the PM mass, by means of a not excessive increase of the rated and lift-off losses: among the three considered SHY solutions, this appears to be the best one;
- the AHY levitator has the disadvantage of a magnetic oversizing of guideway and levitator, in order to prevent risks of saturation in the most unbalanced flux distribution condition; on the other hand, the rated and lift-off losses are very limited, together with the PM mass, and there is no "gluing" risk.

Table IV - *Comparison among different levitators with* $\sigma_\delta = 0.5$; $\delta_n = 10$ mm; $F_{\delta n} = 24$ kN
SHY-a: $\chi = 0.5$, $\rho_{fn} = 0$; SHY-b: $\chi = 0.810$, $\rho_{fn} = 0$; SHY-c: $\chi = 0.810$, $\rho_{fn} = 0.384$

Parameter (for 1 levitator) / **Levitator**	**WEM1**	**WEM2**	**SHY-a**	**SHY-b**	**SHY-c**	**AHY**
guideway Iron core mass [kg]	220.5	220.5	220.5	220.5	220.5	318.5
levitator Iron core mass [kg]	230.5	241	200	202	208	343
rated biasing m.m.f. (per pole) [A]	5170	5170	0	0	1985	10340
rated biasing winding losses [W]	2415	2515	0	0	725	710
rated winding losses (bias. + regul.) [W]	2620	3240	775	935	1290	750
overall copper mass [kg]	69.5	86.0	20.5	25.0	34.0	19.0
PM mass [kg]	0	0	18.25	29.65	18.25	11.09
total mass of one levitator [kg]	300	327	239	257	260	373
lift-off winding losses (from $\delta = 2 \cdot \delta_n$) [W]	7890	8195	6060	7315	8735	2750
(limit "gluing" force)/($F_{\delta n}$) [p.u.]	0	0	4.60	1.75	1.75	0.92
detach winding losses (from $\delta = 0$) [W]	0	0	9255	11170	3070	0

5. The levitator prototype and the programme of experimental activities

From the described studies, valid elements have been obtained to start an experimental investigation. Thus, the design and construction of a levitating platform has been made, now being completed (fig. 3):

- the platform fixed part supports the stator ferromagnetic core, laminated and toothed;
- the platform mobile part has four magnetically independent pole pairs.

The nominal air-gap has been fixed at 8 mm, with variations contained within ± 4 mm.

During the first experimental tests, the air-gap measurement is based, according to a preliminary strategy, on the use of TV cameras, equipped with corresponding acquisition boards; different solutions will be tested, also concerning the winding connection and feeding and as regards the control techniques.

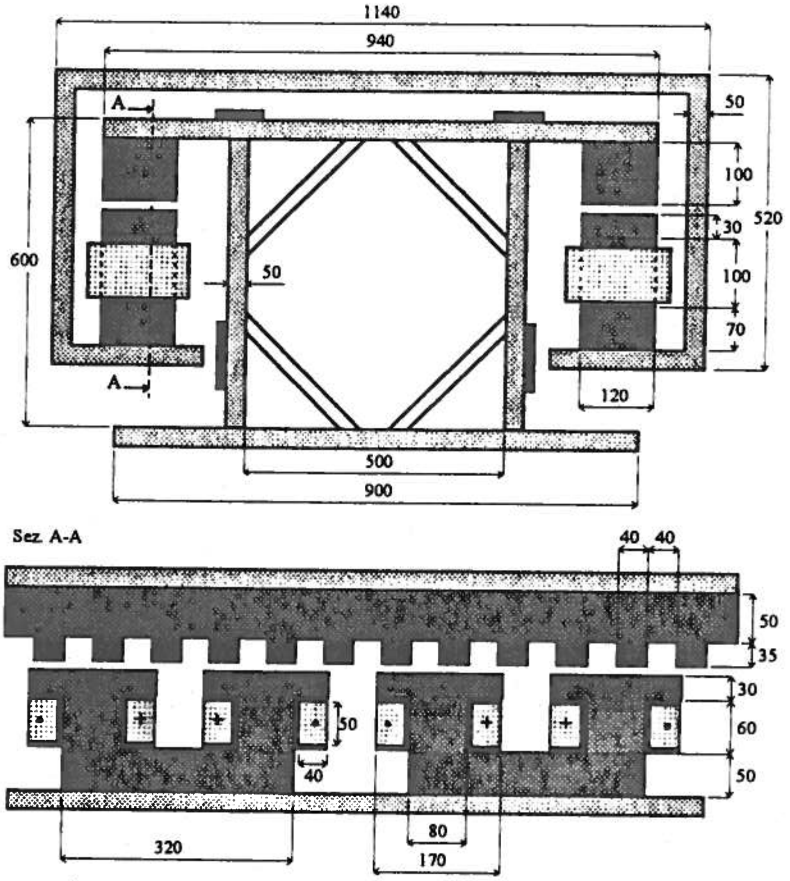


Fig. 3 - *Longitudinal view and lateral section view (A-A) of the constructed levitating platform.*

Subsequently, the development of further experiences will be performed, thanks to the modularity and expandability features of the system; among the possible tests, the following ones will be considered:

- analysis of the system behaviour when combined levitation and propulsion forces occur;
- tests on contactless on-board energy transmission systems.

Conclusions

In this paper, three types of levitators for EMS Maglev transportation systems have been described and analysed, equipped with windings only or with windings and permanent magnets, in a symmetrical and asymmetrical disposition: the core, windings and permanent magnets sizing has been analysed, by examining the parameter influence on the dimensional and operating features of the Maglev system.

Finally, the experimental activities now in progress have been briefly mentioned.

The studies will continue, both as regards the theoretical analysis of the described levitator topologies and/or of new structures, and concerning the experimental tests.

BIBLIOGRAPHY

[1] A. Di Gerlando, M. Galasso: "Feeding Problems in Maglev Systems"; Proceedings of the 1st National Workshop on Electrical Drives with Linear Motors; Milano, Italy, 1992 (in Italian).

[2] A. Di Gerlando, I. Vistoli, M. Galasso: "Comparative Analysis of EDS and EMS Maglev Systems", Maglev'93, 13 th International Conference on Magnetically Levitated Systems and Linear Drives, Argonne National Laboratory, Illinois, USA, 1993.

[3] A. Di Gerlando, I. Vistoli: "Design Problems of Linear On Board Generators in EMS Maglev Transportation Systems", Maglev'93, 13 th International Conference on Magnetically Levitated Systems and Linear Drives, Argonne National Laboratory, Illinois, USA, 1993.

[4] A. Di Gerlando, I. Vistoli: "Design Analysis of Linear on-board Generators for EMS Maglev Vehicles"; Proceedings of the 1st PFT2 National Conference, sponsored by the Italian National Research Council (CNR), Rome, Italy, September 1993 (in Italian).

[5] A. Di Gerlando, S. Fortuna, I. Vistoli: "Armature Current Unbalance Detection using On-board Probe Windings for the Stator On-line Diagnostics of EMS Maglev Systems", Int.Conf. on Magnetically Levitated Systems (Maglev), Bremen, Germany, 1995.

[6] A. Di Gerlando, S. Fortuna, I. Vistoli: "Design Oriented Analytical Modelling of Linear Synchronous On-Board Generators for EMS Maglev Systems", Conference "Electrimacs '96", Saint Nazaire, France, 1996, pp.793-800.

[7] A. Di Gerlando, S. Fortuna: "Design and Experimental Analysis of On-Board Probe Windings for the Stator On-Line Diagnostics of EMS Maglev Systems", ICEM '96, Vigo, Spain, 1996.

[8] A. Di Gerlando, S. Fortuna, I. Vistoli: "Analysis of On-Board Induced Windings for Power Generation and Diagnostics in EMS Maglev Transportation Systems Equipped with Long Stator Linear Synchronous Motors"; Proceedings of the 2nd National Workshop on Electrical Drives with Linear Motors; Pisa, 1996 (in Italian).

[9] C. Fossati, E. Piccagli: "Design Problems of the Inductors in EMS Maglev Systems"; Proceedings of the 2nd National Workshop on Electrical Drives with Linear Motors; Pisa, 1996 (in Italian).