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SIZING AND PERFORMANCE COMPARATIVE ANALYSIS OF FIELD-LEVITATION DEVICES FOR EMS MAGLEV TRANSPORTATION SYSTEMS

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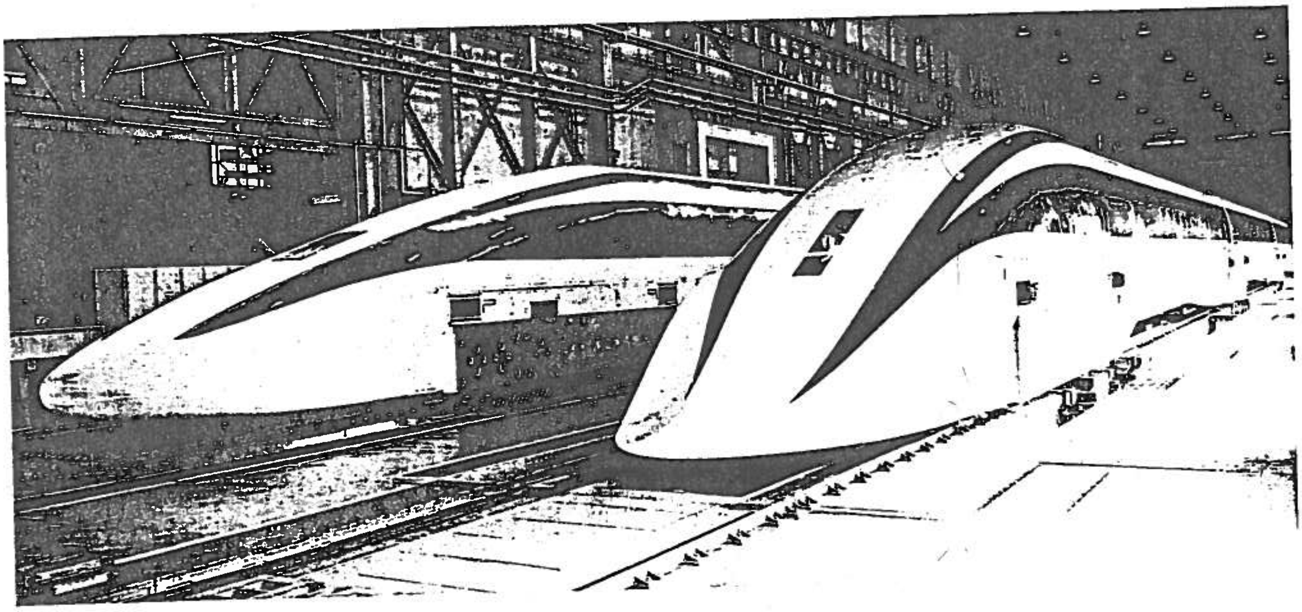

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Sizing and Performance Comparative Analysis of Field-Levitation Devices for EMS Maglev Transportation Systems

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Abstract

Some design aspects regarding the on-board levitation-field apparatus of Maglev vehicles based on attractive ElectroMagnetic Suspension (EMS) are analysed, by considering systems with purely electromagnetic excitation (use of windings only) and with hybrid excitation (presence of both windings and permanent magnets); some 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 their sizing, operating and control characteristics.
Key Words: *Maglev Systems design, parameter analysis.*

1 Introduction

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

An important aspect concerns design and control optimisation of the on-board inductor subsystems: they perform the double function of levitation and of field excitation for the propulsion Linear Synchronous Motors (LSM): the paper describes the results of the studies concerning these subsystems, specifically referred to the attractive levitation EMS systems, and as regards the comparison of different types of field-levitation polar units.

2 Levitator topologies and models

The configurations of the analysed levitation devices (in the following called levitators) can be reduced to the three topologies schematised in fig.1; it is worth to observe that:
- each system component has the same transversal size ℓ, while the length (in the motion direction) of the external side pole shoes ($b_e = \sigma_\delta \cdot b$) is, in general, lower than that of the central pole shoes (usually with $0.5 \le \sigma_\delta \le 1$);
- in the hybrid levitators (including NdFeB permanent magnets (PMs), with $B_r = 1.2$ T), the central PMs sizes (h_m, b_m) differ from the external PM sizes (h_{me}, b_{me}); in particular: $b_{me} = \sigma_m \cdot b_m$, with $0.5 \le \sigma_m \le 1$);
- for mechanical reasons, the PMs are inserted in suited tightening non-magnetic, structures (not shown in fig.1).

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Fig.2 shows the equivalent magnetic networks of the systems of fig.1, used for the levitation analysis:
- the field 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 parameters (M_m, Θ_m);
- all the ferromagnetic branches are supposed unsaturated for control exigencies ($\mu_{fe} \to \infty$ is presumed);
- the presence of the slots is taken into account by means of the resultant Carter's factor $k_c = k_c(\delta)$;
- the interpolar leakage reluctances Θ_ℓ are considered as concentrated between the pole shoes;
- the ratio between the airgap reluctance $\Theta_\delta = \Theta_\delta(\delta)$ and Θ_ℓ describes the p.u. leakage: $\varepsilon_\ell = \varepsilon_\ell(\delta) = \Theta_\delta(\delta)/\Theta_\ell$;
- the quantities concerning the side, 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 1 (the data concern a system with maximum speed $v_M = 500$ km/h).

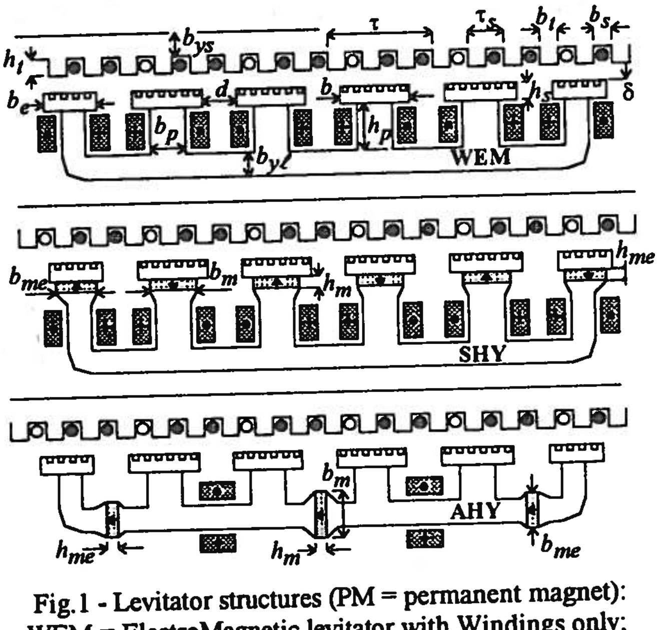

Fig.1 - Levitator structures (PM = permanent magnet):
WEM = ElectroMagnetic levitator with Windings only;
SHY = Symmetrical Hybrid levitator (windings + PM);
AHY = Asymmetrical Hybrid levitator (windings + PM).

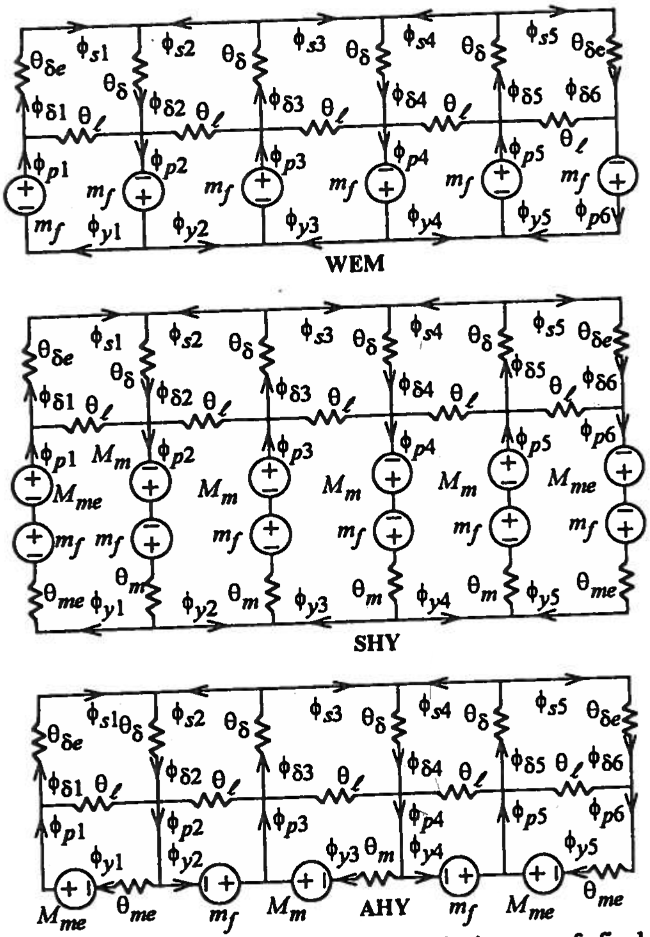

Fig.2 - Magnetic networks of the levitators of fig.1, equivalent as regards the levitation function.

By adopting the same nominal airgap flux density ($B_{\delta n}$) under all the pole shoes, with the data of Table 1, the following limit conditions occur, depending on the value of σ_δ: $\sigma_\delta = 0.5 \rightarrow B_{\delta n} = 0.501$ T; $\sigma_\delta = 1 \rightarrow B_{\delta n} = 0.458$ T.

Table 1. Data of the considered EMS Maglev system.

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

The analysis of the rated operation is common to all the different configurations: to this aim, it is useful to call

$$p_e = 4 + 2 \cdot \sigma_\delta \tag{1}$$

the "number of effective poles" of the levitator: both the thrust and the levitation force are proportional to this quantity; in particular, the rated levitation force equals:

$$F_{\delta n} = p_e \cdot \left(B_{\delta n}^2 / (2 \cdot \mu_0)\right) \cdot A_\delta \ , \tag{2}$$

with A_δ airgap area of the central poles. As regards the influence of σ_δ, defined $\phi_{\delta n} = B_{\delta n} \cdot A_\delta$, the stator yoke fluxes

$$\phi_{s1n} = \phi_{s3n} = \phi_{s5n} = \sigma_\delta \cdot \phi_{\delta n}$$
$$\phi_{s2n} = \phi_{s4n} = (1 - \sigma_\delta) \cdot \phi_{\delta n} \tag{3}$$

significantly depend on σ_δ: as shown in fig.3, the choice $\sigma_\delta = 1$ makes equal all the air-gap fluxes, with "pair poles" distribution: this requires a weighty yoke sizing, particularly heavy for the stator (b_{ys}), due to its extension; on the contrary, $\sigma_\delta = 0.5$ is the best choice as regards the yokes. Similar dependence on σ_δ occurs also for the levitator yoke fluxes, affected by the interpolar leakage fluxes too.
Table 2 shows the ratio $\rho_s(\sigma_\delta) = b_{ys}(\sigma_\delta)/b_{ys}(0.5)$, between a generic stator yoke width and the width for $\sigma_\delta = 0.5$ (ρ_s gives also the ferromagnetic masses ratio): the unacceptable increase for $\sigma_\delta = 1$ (+83 %) is confirmed, while in the case of the Transrapid prototypes (Emsland, Germany) this increase is roughly halved ($\sigma_\delta \approx 0.75 \rightarrow \rho_s \approx 1.43$).
In the following, the different levitators are analysed.

Table 2. 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	0.60	0.70	0.80	0.90	1
$\rho_s(\sigma_\delta)$	1	1.18	1.35	1.51	1.67	1.83

3.1 The wounded electromagnetic levitator (WEM)

By solving the network WEM of fig.2, it follows that the m.m.f.s M_{fn}, necessary to sustain the nominal fluxes in that network, are equal each other (with value $M_{fn} = \theta_{\delta n} \cdot \phi_{\delta n}$, where $\theta_{\delta n}$ is the central rated airgap reluctance). As regards the generic operation, defined

$$\phi_\delta = m_f / \theta_\delta(\delta) \ , \tag{4}$$

the solution of the WEM network of fig.2 gives:

$$\phi_{\delta 1} = \phi_{\delta 6} = \phi_{\delta e} = \sigma_\delta \cdot \phi_\delta \tag{5}$$
$$\phi_{\delta 2} = \phi_{\delta 3} = \phi_{\delta 4} = \phi_{\delta 5} = \phi_\delta \tag{6}$$
$$\phi_{s1} = \phi_{s3} = \phi_{s5} = \sigma_\delta \cdot \phi_\delta \tag{7}$$
$$\phi_{s2} = \phi_{s4} = (1 - \sigma_\delta) \cdot \phi_\delta \tag{8}$$
$$\phi_{p1} = \phi_{p6} = (1 + 2 \cdot \varepsilon_\ell / \sigma_\delta) \cdot \sigma_\delta \cdot \phi_\delta \tag{9}$$
$$\phi_{p2} = \phi_{p3} = \phi_{p4} = \phi_{p5} = (1 + 4 \cdot \varepsilon_\ell) \cdot \phi_\delta \tag{10}$$

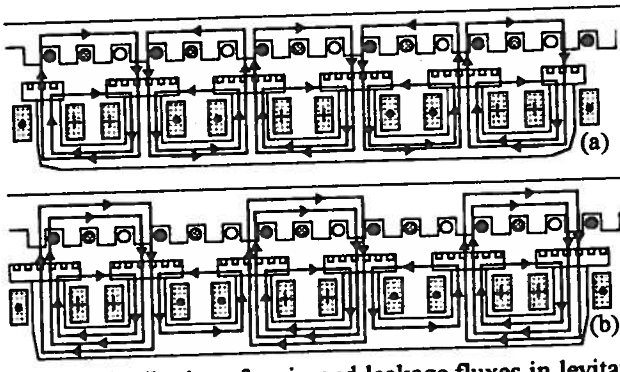

Fig.3 - Distribution of main and leakage fluxes in levitator and stator magnetic branches: a): $\sigma_\delta = 0.5$; b): $\sigma_\delta = 1$.

$$\phi_{y1} = \phi_{y3} = \phi_{y5} = \left(1 + 2 \cdot \varepsilon_\ell / \sigma_\delta\right) \cdot \sigma_\delta \cdot \phi_\delta \qquad (11)$$

$$\phi_{y2} = \phi_{y4} = \left(1 - \sigma_\delta + 2 \cdot \varepsilon_\ell\right) \cdot \phi_\delta \quad . \qquad (12)$$

Thus, the flux distribution imposed in the rated condition is maintained also in a generic situation, and all the fluxes can be expressed in term of central airgap fluxes ϕ_δ; as regard the levitation force, we can write:

$$F_\delta = p_e \cdot \frac{\phi_\delta^2}{2 \cdot \mu_0 \cdot A_\delta} \qquad (13)$$

and developing:

$$F_\delta = p_e \cdot \frac{\mu_0}{2} \cdot A_\delta \cdot \frac{m_f^2}{\left(k_c(\delta) \cdot \delta\right)^2} \quad . \qquad (14)$$

It should be noted that the value of the Carter's factor k_c and its variation with the airgap (fig.4) greatly affects both the fluxes (through θ_δ) and the levitation force.

As known, an EMS levitator is inherently unstable: hence it requires current controlled power supplies (with quick response), airgap transducers (with suited dynamic features) and control regulators; thus, the m.m.f. $m_f(t)$ produced around each pole consists of the following terms:

- 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 unevenness during the vehicle running.

The amplitude of the m.m.f. $m_r(t)$ depends on the unevenness 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 field 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 and SHY EMS topologies it coincides also with the control with "constant airgap flux" (see (13)).

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

- single winding levitator (WEM1): each pole is excited with a regulated current with a nonzero average value;

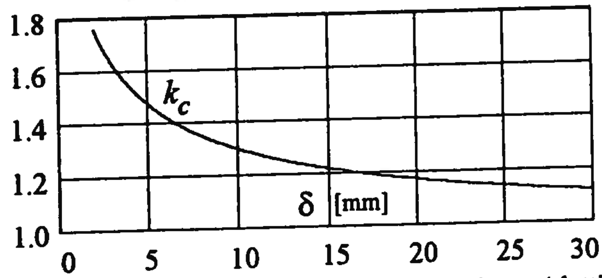

Fig.4 - Carter's factor as a function of the airgap (slotting data of Table 1).

- separated winding levitator (WEM2): each pole has a biasing winding (carrying a constant current) and a regulation winding (isolated by the previous one).

The adoption of a WEM2 levitator type has the main advantage of a separate, significantly reduced, sizing of both 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 ideal smoothed guideway). 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: the ratio σ_{cu} between the WEM2 and WEM1 copper masses and losses depends on the ratio $M_{rpu} = M_r / M_b$ between the rms regulation m.m.f. and the biasing m.m.f. (see fig.5):

$$\sigma_{cu} = \frac{1 + M_{rpu}}{\sqrt{1 + M_{rpu}^2}} . \qquad (15)$$

Usually a Maglev system operates with airgap oscillations in the range $0.5 \cdot \delta_n \le \delta \le 1.5 \cdot \delta_n$, while in rest conditions (stops at the stations) the air-gap is maximum, normally $\delta_M = 2 \cdot \delta_n$. The analysis shows that the regulation m.m.f., virtually zero for $\delta = \delta_n$, increases less than linearly with the increase of δ (thanks to the decrease of k_c), and it is maximum in the lift-off process (for $\delta_M = 2 \cdot \delta_n = 20$ mm $\rightarrow m_r = 0.81 \cdot M_b$).

3.2 The symmetrical hybrid levitator (SHY)

The PM design parameters are:

- the PM working ratio χ ($\chi = B_{PMn} / B_r$, with B_{PMn} rated working PM flux density and B_r its remanence);
- the field active ratio ρ_{fn}, ($\rho_{fn} = M_{fn} / U_{\delta n}$, with M_{fn} rated active m.m.f., fraction of the rated airgap magnetic drop $U_{\delta n}$; $U_{\delta n}$ is due to the active biasing and to the PM).

The choice of χ and ρ_{fn} (both in the range (0-1)) defines PM cross section area and height.

The design analysis of the SHY network of fig.2 in rated conditions shows that all the PMs have the same height, while the cross section area of the central PMs (A_m) is higher than that of the external PMs (A_{me}):

$$h_m = h_{me} = \delta_n \cdot \left(1 - \rho_{fn}\right) \cdot \frac{k_{cn} \cdot \mu_r}{1 - \chi} \cdot \frac{B_{\delta n}}{B_r} \qquad (16)$$

$$A_m = A_\delta \cdot \frac{1 + 4 \cdot \varepsilon_{\ell n}}{\chi} \cdot \frac{B_{\delta n}}{B_r} \qquad (17)$$

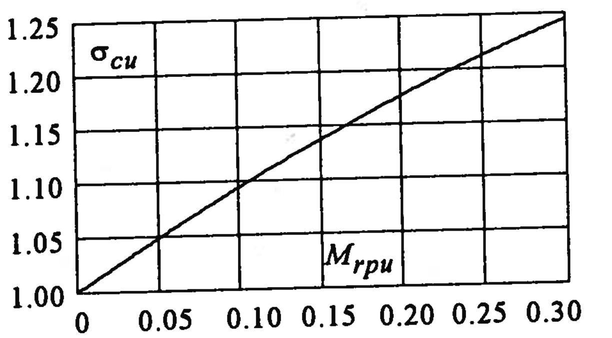

Fig.5 - Ratio σ_{cu} between the WEM2 and WEM1 copper masses and losses as a function of the ratio $M_{rpu} = M_r / M_b$ between the rms regulation m.m.f. and the biasing m.m.f..

$$\sigma_m = A_{me}/A_m = \frac{1+(2/\sigma_\delta)\cdot\varepsilon_{\ell n}}{1+4\cdot\varepsilon_{\ell n}}\cdot\sigma_\delta \;; \tag{18}$$

$\mu_r = B_r/(\mu_0 \cdot H_c) \approx 1.06$ is the PM p.u. reversible permeability, $k_{cn} = k_c(\delta_n) \approx 1.29$, $\varepsilon_{\ell n} = \varepsilon_\ell(\delta_n) \approx 0.02$ ($\rightarrow \sigma_m \approx \sigma_\delta$).
The product $h_m \cdot A_m$ is proportional to the PM mass: it results minimum for $\chi = \chi_{opt} = 0.5$ (condition corresponding to that of the PM maximum energy product).
Table 3 shows the PM mass ratio, defined as $\sigma_{PM} = M_{PM}(\chi)/M_{PM}(\chi_{opt})$: the PM mass increases for $\chi > \chi_{opt}$ (the increase is limited for χ values not too far from χ_{opt}).

Table 3. Ratio $\sigma_{PM} = M_{PM}(\chi)/M_{PM}(\chi_{opt})$ of the PM mass, as a function of the working factor χ ($\chi_{opt} = 0.5$).

χ	0.50	0.55	0.60	0.65	0.70	0.75	0.80
σ_{PM}	1	1.010	1.042	1.099	1.190	1.333	1.563

Defined the following quantities:

$$\phi_\delta = \frac{m_f + M_m}{(1+4\cdot\varepsilon_\ell)\cdot\theta_m + \theta_\delta} \tag{19}$$

$$\phi_{\delta e} = \sigma_\delta \cdot \phi_\delta \cdot \eta_\theta(\delta) \tag{20}$$

$$\eta_\theta(\delta) = \frac{(1+4\cdot\varepsilon_\ell)+\theta_\delta/\theta_m}{(\sigma_\delta/\sigma_m + 2\cdot\varepsilon_\ell/\sigma_m)+\theta_\delta/\theta_m} \tag{21}$$

the general fluxes distribution in the SHY levitator is:

$$\phi_{\delta 1} = \phi_{\delta 6} = \phi_{\delta e} \;,\;\; \phi_{\delta 2} = \phi_{\delta 3} = \phi_{\delta 4} = \phi_{\delta 5} = \phi_\delta \tag{22}$$

$$\phi_{s1} = \phi_{s3} = \phi_{s5} = \phi_{\delta e} \;,\;\; \phi_{s2} = \phi_{s4} = \phi_\delta - \phi_{\delta e} \tag{23}$$

$$\phi_{y1} = \phi_{y3} = \phi_{y5} = \phi_{\delta e}\cdot(1+2\cdot\varepsilon_\ell/\sigma_\delta) \tag{24}$$

$$\phi_{y2} = \phi_{y4} = \phi_\delta\cdot(1+4\cdot\varepsilon_\ell) - \phi_{\delta e}\cdot(1+2\cdot\varepsilon_\ell/\sigma_\delta) \tag{25}$$

$$\phi_{p1} = \phi_{p6} = \phi_{\delta e}\cdot(1+2\cdot\varepsilon_\ell/\sigma_\delta) \tag{26}$$

$$\phi_{p2} = \phi_{p3} = \phi_{p4} = \phi_{p5} = \phi_\delta\cdot(1+4\cdot\varepsilon_\ell) \;\; ; \tag{27}$$

the levitation force equals:

$$F_\delta = \frac{4+2\cdot\sigma_\delta\cdot\eta_\theta^2}{2\cdot\mu_0\cdot A_\delta}\cdot\phi_\delta^2 \,. \tag{28}$$

Thanks to the fact that, in practice, $\eta_\theta \approx 1$ is always true, (20) and (28) become the same as (5) and (13) respectively. Thus, the central pole fluxes are always balanced; the external fluxes are roughly σ_δ times the former; the force equals p_e times that under each central airgap: so, as the dependence on the flux distribution, WEM and SHY systems are similar.
On the other hand, (19) shows that the m.m.f. variation Δm_f necessary to obtain a desired variation $\Delta\phi_\delta$ of the airgap 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 θ_m:

$$\left(\frac{\partial\phi_\delta}{\partial m_f}\right)_{SHY} = \frac{\theta_\delta}{\theta_\delta + (1+4\cdot\varepsilon_\ell)\cdot\theta_m}\cdot\left(\frac{\partial\phi_\delta}{\partial m_f}\right)_{WEM} \,. \tag{29}$$

This effect seems to reduce the main 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 airgap flux" is supposed to be used, the previous remark is too pessimistic: in fact, in the SHY system the regulation m.m.f. requested 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 airgap increases there is no practical magnetic drop variation across the PM internal reluctance (θ_m), but only an increase of magnetic drop at the airgap: this is the only contribution that the winding regulation m.m.f. is required to supply.
In conclusion, as regards the regulation with "constant airgap flux" in rated conditions, 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, another comparison concerns the airgap increase allowed by a SHY levitator in case of an active biasing m.m.f.: called δ_{na} the new increased rated airgap in the SHY system, biased with the same m.m.f. M_{fnWEM} of the WEM levitator, the following equation, concerning the rated airgap flux, applies:

$$\frac{M_{fnWEM} + M_m}{(1+4\cdot\varepsilon_\ell(\delta_{na}))\cdot\theta_m + \theta_\delta(\delta_{na})} = \frac{M_{fnWEM}}{\theta_\delta(\delta_n)} \,, \tag{30}$$

whose solution gives an airgap of δ_{na} = 21.6 mm, more than doubled compared with the WEM case.

Coming back to the initial rated airgap, on the basis of the previous analysis, the opportunity to adopt values $\chi > \chi_{opt} = 0.5$ and/or $\rho_{fn} > 0$ does not appear justified: to this aim it is worth to consider the zero airgap limit condition (contact between levitator and stator). In this situation, neglecting the saturation effects, the contact airgap flux $\phi_{\delta co}$ ideally equals the PM remanence flux and becomes significantly higher than $\phi_{\delta n}$; the same occurs for the contact force $F_{\delta co}$; thus, observing that:

$$\phi_{\delta co} = \phi_{\delta(\delta=0,\, m_f=0)} = M_m/\theta_m = B_r\cdot A_m \,, \tag{31}$$

$$\phi_{\delta n} = B_{\delta n}\cdot A_\delta = \frac{B_{MPn}\cdot A_m}{1+4\cdot\varepsilon_{\ell n}} = \chi\cdot\frac{B_r\cdot A_m}{1+4\cdot\varepsilon_{\ell n}} \,, \tag{32}$$

it follows (quantities expressed in p.u.):

$$\varphi_{\delta co} = \phi_{\delta co}/\phi_{\delta n} = (1+4\cdot\varepsilon_{\ell n})/\chi \,, \tag{33}$$

$$f_{\delta co} = F_{\delta co}/F_{\delta n} = \varphi_{\delta co}^2 = (1+4\cdot\varepsilon_{\ell n})^2/\chi^2 \,. \tag{34}$$

In our case: $\varphi_{\delta co} \approx 2.14$ and $f_{\delta co} \approx 4.60$: even if partially limited by saturation effects, 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 running safety and 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 $\varphi_{\delta co}$ and of $f_{\delta co}$, as shown by (33) and (34).
On the other hand, the increase of χ causes the growth of the PM mass too; when reducing $f_{\delta co}$, this mass increase (proportional to σ_{PM}), at first small for high values of $f_{\delta co}$, becomes important when a reduction of $f_{\delta co}$ below 2.5 is desired; anyway, it is impossible to obtain a "gluing" force lower than $F_{\delta n}$ ($\chi \rightarrow 1 \;\Rightarrow\; f_{\delta co} \rightarrow (1+4\cdot\varepsilon_{\ell n})^2$).
Fig.6 shows the p.u. gluing force ($f_{\delta co} = F_{\delta co}/F_{\delta n}$) and the

PM mass ratio σ_{PM}, as a function of the PM working ratio χ, in a limited range of interest of χ.
The condition that seems to be more reasonably acceptable (as shown in fig.6) is that with $f_{\delta co}$ = 1.75: from (34), one obtains: $\chi = \chi_c = 0.810$. In fact, in case of empty vehicle (worst case, with $F_{weight} = 0.75 \cdot F_{\delta n}$), $f_{\delta co}$ = 1.75 implies 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 acceptable as regards the gluing effect, implies a high PM mass increase ($\sigma_{PM} \approx 1.63$): this oversizing, technically feasible, is significant and could result unacceptable for economical reasons, considering the NdFeB high cost.
Thus, it is better to introduce an active biasing contribution ($\rho_{fn} = M_{fn}/U_{\delta n} > 0$): among all the possible values for ρ_{fn}, it is convenient to choose the value ρ_{fnc} that, with $\chi = \chi_c = 0.810$, allows to maintain unvaried the PM mass compared with that of the case $\chi_{opt} = 0.5$; by (16), (17), the following condition must be imposed:

$$\left(1-\rho_{fnc}\right)/\left[\chi_c \cdot (1-\chi_c)\right] = 1/\left[\chi_{opt} \cdot \left(1-\chi_{opt}\right)\right], \quad (35)$$

whose solution is: $\rho_{fnc} = 1 - 4 \cdot \chi_c \cdot (1-\chi_c)$; in the examined case, it follows: $\rho_{fnc} = 0.384$.

Finally, 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 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 airgap fluxes (balanced in the central pole shoes) produce the rated levitating force: the procedure, similar to that of the

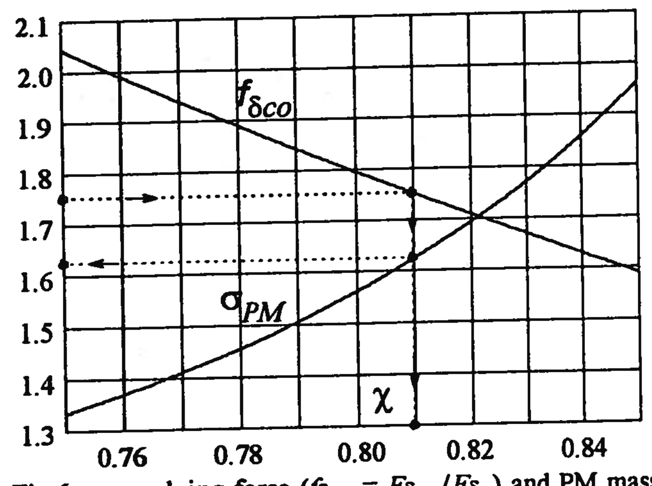

Fig.6 - p.u. gluing force ($f_{\delta co} = F_{\delta co}/F_{\delta n}$) and PM mass factor σ_{PM} ($\sigma_{PM} = M_{PM}(\chi)/M_{PM}(\chi_{opt})$), as a function of the PM working ratio ($\chi = B_{MPn}/B_r$); $\chi_{opt} = 0.5$.

SHY case, leads to the following design results:

$$A_m = A_{me} = A_\delta \cdot \left(B_{\delta n}/B_r\right) \cdot \left(\sigma_\delta + 2 \cdot \varepsilon_{\ell n}\right)/\chi \quad (36)$$

$$h_m = \delta_n \cdot 2 \cdot \left(B_{\delta n}/B_r\right) \cdot \left(\mu_r \cdot k_{cn}\right)/(1-\chi) \quad (37)$$

$$h_{me} = \delta_n \cdot \left(1 + \frac{1+2\cdot\varepsilon_{\ell n}/\sigma_\delta}{1+2\cdot\varepsilon_{\ell n}}\right) \cdot \frac{\mu_r \cdot k_{cn}}{1-\chi} \cdot \frac{B_{\delta n}}{B_r} \quad (38)$$

$$M_{fn} = 2 \cdot \left(B_{\delta n}/\mu_0\right) \cdot k_{cn} \cdot \delta_n = 2 \cdot U_{\delta n} \ . \quad (39)$$

Thus, 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.
As regards generic operating conditions, defined the following auxiliary reluctances:

$$\theta_{\delta\ell} = \theta_{\delta\ell}(\delta) = \frac{\theta_\delta(\delta)}{1+4\cdot\varepsilon_\ell(\delta)} \quad (40)$$

$$\theta_{\delta e\ell} = \theta_{\delta e\ell}(\delta) = \frac{\theta_{\delta e}(\delta)}{1+2\cdot\varepsilon_\ell(\delta)} = \frac{\theta_\delta(\delta)/\sigma_\delta}{1+2\cdot\varepsilon_\ell(\delta)} \quad (41)$$

$$\theta_e = \theta_e(\delta) = \theta_{me} + \theta_{\delta e\ell}\,, \quad (42)$$

the solution of the network AHY of fig.2 gives:

$$\phi_{y2} = \phi_{y4} = \frac{\left(\theta_{\delta\ell}+\theta_e\right)\cdot\left(\theta_m + 2\cdot\theta_{\delta\ell}\right)\cdot m_f/\theta_{\delta\ell}}{\theta_{\delta\ell}\cdot\theta_m + 2\cdot\theta_e\cdot\theta_m + 2\cdot\theta_{\delta\ell}\cdot\theta_e} + \quad (43)$$
$$- \frac{\left(\theta_{\delta\ell}+\theta_e\right)\cdot M_m + \left(\theta_m + 2\cdot\theta_{\delta\ell}\right)\cdot M_{me}}{\theta_{\delta\ell}\cdot\theta_m + 2\cdot\theta_e\cdot\theta_m + 2\cdot\theta_{\delta\ell}\cdot\theta_e}$$

$$\phi_{y1} = \phi_{y5} = \frac{M_{me}}{\theta_{\delta\ell}+\theta_e} - \frac{\theta_{\delta\ell}}{\theta_{\delta\ell}+\theta_e}\cdot\phi_{y2} \quad (44)$$

$$\phi_{y3} = \frac{M_m}{\theta_m + 2\cdot\theta_{\delta\ell}} - \frac{2\cdot\theta_{\delta\ell}}{\theta_m + 2\cdot\theta_{\delta\ell}}\cdot\phi_{y2} \quad (45)$$

$$\phi_{p1} = \phi_{p6} = \phi_{y1} \quad (46)$$

$$\phi_{p2} = \phi_{p5} = \phi_{y1} + \phi_{y2} \ ; \ \phi_{p3} = \phi_{p4} = \phi_{y2} + \phi_{y3} \quad (47)$$

$$\phi_{\delta 1} = \phi_{\delta 6} = \phi_{p1}/\left(1+2\cdot\varepsilon_\ell/\sigma_\delta\right) \quad (48)$$

$$\phi_{\delta 2} = \phi_{\delta 5} = \frac{\phi_{p2}}{1+4\cdot\varepsilon_\ell}\ ; \ \phi_{\delta 3} = \phi_{\delta 4} = \frac{\phi_{p3}}{1+4\cdot\varepsilon_\ell} \quad (49)$$

$$\phi_{s1} = \phi_{s5} = \phi_{\delta 1} \quad (50)$$

$$\phi_{s2} = \phi_{s4} = \phi_{\delta 2} - \phi_{s1} \ ; \ \phi_{s3} = \phi_{\delta 3} - \phi_{s2} \quad (51)$$

$$F_\delta = \frac{1}{2\cdot\mu_0\cdot A_\delta}\cdot 2\cdot\left(\phi_{\delta 1}^2 + \phi_{\delta 2}^2 + \phi_{\delta 3}^2\right) \ . \quad (52)$$

Thus, the four central pole and airgap fluxes are unbalanced: there is just an operating symmetry with respect to the levitator central axis; then, due to this flux unbalance, (52) shows that the "constant levitation force" control does not correspond to the "constant airgap flux" control.
Moreover, 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, that affects the yoke sizing.
Moreover, the "gluing" phenomenon must be definitely avoided, because in this condition the levitator could never be detached from the guideway by electromagnetic means (the active m.m.f.s would act in virtually zero-reluctance magnetic loops): fortunately, for $\sigma_\delta = 0.5$ (the best sizing choice) this situation never occurs.

4 Comparison between sizing and operating data of the levitators

Table 5 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: $\alpha_{cu} = 0.3$; airgap oscillations during the vehicle travel: $\Delta\delta = \pm 0.5 \cdot \delta_n$; 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 worst condition, i.e. at the lift-off process).

Table 5. Comparison among different levitators: $\sigma_\delta = 0.5$; $\delta_n = 10$ mm; $F_{\delta n} = 24$ kN; SHY-a: $\chi = 0.5$, $\rho_{fn} = 0$; SHY-b: $\chi = 0.810$, $\rho_{fn} = 0$; SHY-c: $\chi = 0.810$, $\rho_{fn} = 0.384$

Levitator type / Parameter (1 levitator)	WEM 1	WEM 2	SHY a	SHY b	SHY c	AHY
guideway Fe mass [kg]	221	221	221	221	221	319
levitator Fe mass [kg]	231	241	200	202	208	343
bias. m.m.f. M_{bn} [kA]	5.17	5.17	0	0	1.99	10.3
rated biasing loss [kW]	2.42	2.52	0	0	0.73	0.71
rated total loss [kW]	2.62	3.24	0.78	0.94	1.29	0.75
tot. winding M_{Cu} [kg]	69.5	86.0	20.5	25.0	34.0	19.0
total M_{PM} (1 lev.) [kg]	0	0	18.3	29.7	18.3	11.1
levitator tot. mass [kg]	300	327	239	257	260	373
lift-off loss ($2 \cdot \delta_n$) [kW]	7.89	8.20	6.06	7.32	8.74	2.75
gluing force/$F_{\delta n}$ [p.u.]	0	0	4.60	1.75	1.75	0.92
detach loss (δ=0) [kW]	0	0	9.26	11.2	3.07	0

The results of Table 5 show that:
- the WEM2 case has masses and losses higher than those of WEM1, but it allows separated regulation;
- the SHY-a levitator is more light, the PM mass is minimised, it has low losses, but it shows very high values of "gluing" force and of winding losses due to the currents 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, paid with 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 guideway and levitator magnetic oversizing, in order to prevent risks of saturation in unbalanced flux 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.

5 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 sizing and operating features of the Maglev system.
The studies will continue, both as regards theoretical analysis of the levitator topologies, and concerning experimental tests on levitator prototypes.

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