Improved Magnetic Modelling of EMS Maglev Levitators

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Abstract
The paper presents an improved model of the magnetic circuit of two kinds of EMS Maglev levitators (one with coils only and the other one of the hybrid kind, with coils and permanent magnets): this model allows to obtain sensible enhancements both in evaluating the operating quantities, and in the levitation control.
The introduced improvements concern the evaluation of the air-gap quantities (fluxes and forces) and the estimation of the leakage parameters (coil and permanent magnet leakage fluxes):
- the evaluation of the air-gap quantities is performed by means of mathematical expressions, deduced by the analytical investigation of the fields (method of the conformal transformations, in particular the Schwartz and Christoffel transformation); the results of these mathematical expressions have been validated by FEM analyses;
- the evaluation of the leakage parameters is operated on the basis of the actual field distribution, obtained by FEM analyses.

The obtained improvements are shown:
- by evaluating fluxes and forces in different operating conditions, and comparing these values with the results obtained by the classical modelling;
- by showing some levitation tests measurements, discussing the enhancements obtained by the use of the improved modelling.

I Improved Expressions of the Magnetic Quantities

Introduction

The magnetic structure of a Maglev system is characterised by important peculiarities: high air-gap values and great slot openings, that cause significant phenomena of fringing and leakage, multipolar structure of the levitator, with lateral pole shoes different from the central ones, stator winding with a low number of slots/(pole-phase). Considering these features, the classical magnetic circuit modelling is inadequate, for various reasons:
- the air-gap field fringing effect is represented by the Carter's factor, able to take slotting into account only;
- the Carter's factor is rigorously valid only for the evaluation of the flux, not of the force;
- leakage (of coils and permanent magnet particularly) is evaluated in an approximated manner.

The consequence of these lacks is the inaccurate evaluation of the design quantities (fluxes and forces), and thus the need to repeat calculations and to employ FEM methods also during the early stage of the design process. On the other hand, one can observe that:
- the analytical methods are more synthetic of the FEM methods;
- necessarily, the execution of a design requires to start from some mathematical relations; FEM analysis is best suited to be used as a verification tool;
- the use of improved analytical expressions in the model, suited to give a more accurate estimation of fluxes and forces, is advantageous also as concerns the system control, because it allows a more precise evaluation of the state variables.

For these reasons, some improved analytical expressions have been developed, in order to express the air-gap quantities in a simple, quick and accurate manner; at the same time, a mixed geometrical-numerical method has been employed for the calculation of the leakage parameters. In the present paper, the obtained expressions are presented, and the criteria to use them in order to improve the magnet circuit model is illustrated. The paper considers the esapolar levitator of the Transrapid vehicle as the reference system; nevertheless, considering the good results, the given expressions can be used for the design of any magnetic system.

I.1 Genesis of the Improved Expressions

The basic idea is to define correction coefficients representing the ratio among the value assumed by a magnetic quantity in the actual structure, and the value that the same quantity has in a reference structure, called "ideal": in this way, considering any magnetic structure, each quantity can be calculated in a simple and quick manner, as the product of the ideal quantity times the corresponding correction factor; on the basis of this definition, the expressions of the flux and force correction coefficients k_φ and k_F are simply given by:

$$k_\varphi = \frac{\varphi_{act}}{\varphi_{id}} \qquad k_F = \frac{F_{act}}{F_{id}} .$$

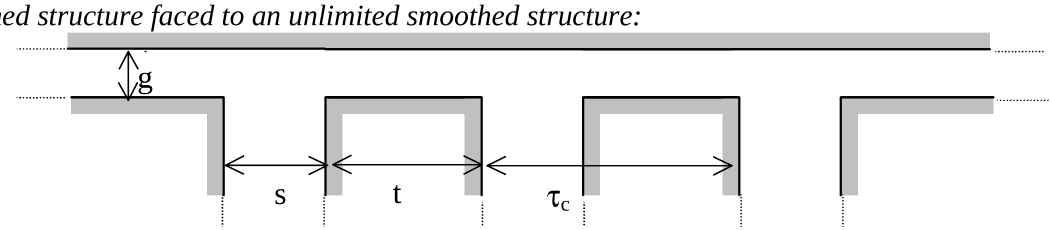
In order to consider reference quantities that result univocally defined, the quantities concerning a uniform magnetic field are assumed as ideal (i.e., the field developing among two unlimited, parallel and smoothed structures); thus, the expressions of the ideal quantities are the following ones:

$$\varphi_{id} = B_{id} \cdot A \qquad F_{id} = \frac{{B_{id}}^2}{2\mu_0} \cdot A \qquad B_{id} = \mu_0 \frac{U}{g} ,$$

where the symbols have the following meaning:
B_{id} = uniform field flux density; U = magnetic voltage among the two ferromagnetic structures; A = considered surface portion; g = air-gap among the two structures.
As regards the "actual" quantities, the aim to obtain closed-form expressions of the correction coefficients leads to search for field analytical solutions: here the conformal transformation method is adopted, in particular the Schwarz and Christoffel transformation.
The procedure for obtaining the correction coefficients is described in detail in [1]; here, just the analytical expressions of these coefficients are given, for the considered configurations.

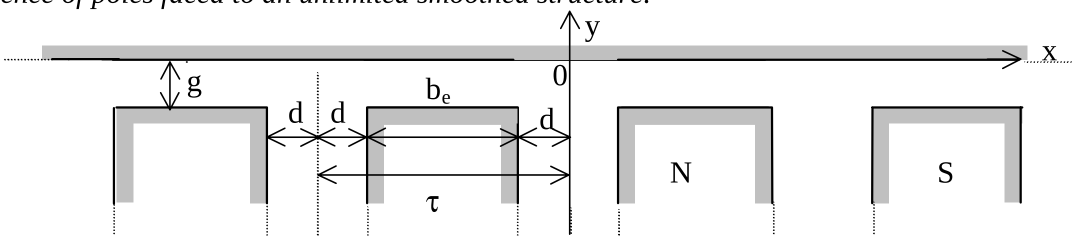
I.2 Considered Cases and Expressions

A1: toothed structure faced to an unlimited smoothed structure:



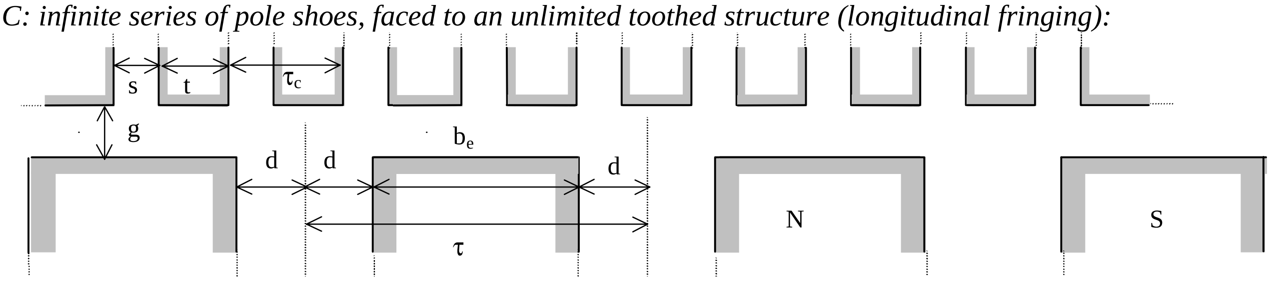
$$k_{\varphi.S} = 1 - \frac{s}{\tau_c} \cdot \frac{2}{\pi} \left\{ atan\left(\frac{s}{2g}\right) - \frac{g}{s} \cdot \ln\left[1 + \left(\frac{s}{2g}\right)^2\right] \right\} \qquad k_{F.S} = 1 - \frac{s}{\tau_c} \cdot \frac{2}{\pi} \cdot atan\left(\frac{s}{2g}\right)$$

A2: sequence of poles faced to an unlimited smoothed structure:



$$k_{\varphi.P} = 1 + \frac{2}{\pi} \cdot \frac{g}{b_e} \left\{ 2\frac{d}{g} atan\left(\frac{g}{d}\right) + \ln \frac{1 + \left(\frac{d}{g}\right)^2}{4} \right\} \qquad k_{F.P} = 1 + 2\frac{d}{b_e} \cdot \left\{ 1 - \frac{2}{\pi} \cdot \mathrm{atan}\left(\frac{d}{g}\right) \cdot \left[1 + \left(\frac{g}{d}\right)^2\right] \right\}$$

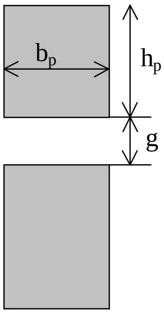
C: infinite series of pole shoes, faced to an unlimited toothed structure (longitudinal fringing):



In the case of a toothed structure faced to a series of pole shoes, the correction coefficients are simply the product of the single coefficients of the two non-smoothed structures (toothed and pole shoe structures), as like as each of them were faced to a smoothed surface; therefore:

$$k_{\varphi.S+P} = k_{\varphi.S} \cdot k_{\varphi.P}, \qquad k_{F.S+P} = k_{F.S} \cdot k_{F.P}.$$

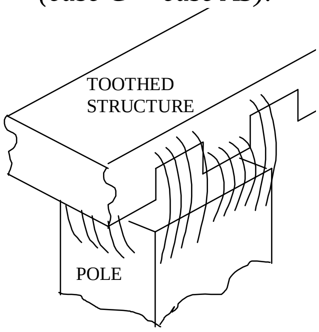
A3: faced plates of finite size (transversal fringing):



$$k_{\varphi T} = 1 + \frac{2}{\pi}\frac{g}{b_p}\left[1 + \ln\left(\frac{\pi}{4g}\left(2h_p + g\right)\right)\right]$$

$$k_{FT} = 1 + \frac{2}{\pi}\frac{g}{b_p}$$

R: longitudinal + transversal fringing (case C + case A3):



In general

$$k = k_{S+P} + (k_T - 1) \cdot t/\tau_c,$$

thus

$$k_\varphi = k_{\varphi.S+P} + (k_{\varphi.T} - 1) \cdot t/\tau_c,$$

$$k_F = k_{F.S+P} + (k_{F.T} - 1) \cdot t/\tau_c$$

In the following, the expressions that some magnetic quantities assume in the classical and in the improved evaluation method are shown, because the comparison among these expressions allows two series of remarks about the errors of the classical formulas and the value to attribute to the ideal flux density B_i.

I.3 Classical and Improved Expressions of the Magnetic Quantities

Flux density to be used.

In the classical analysis of the magnetic structures, fluxes and forces are evaluated on the basis of the air-gap flux density B_δ, defined as the average flux density under the pole, i.e. the ratio among the air-gap actual flux over the pole shoe geometrical cross section: $B_\delta = \phi / A_{geom}$. Here, the use of another quantity is proposed, the ideal flux density B_i (the flux density in an air-gap among two smoothed, unlimited structures).

	Classical Method	Improved Method
Link among air-gap flux density and magnetic voltage drop	$B_\delta = \mu_0 \frac{U_\delta}{\delta \cdot k_{Carter}}$ (1)	$B_i = \mu_0 \frac{U_\delta}{\delta}$ (2)
Flux	$\phi = B_\delta \cdot A_{geom}$ (3)	$\phi = B_i \cdot A_{geom} \cdot k_\varphi$ (4)
	$\phi = \frac{1}{k_{Carter}} \cdot \mu_0 A_{geom} \frac{U_\delta}{\delta}$ (5)	$\phi = k_\varphi \cdot \mu_0 A_{geom} \frac{U_\delta}{\delta}$ (6)
Force	$F = \frac{1}{2\mu_0} B_\delta^2 A_{geom}$ (7)	$F = \frac{1}{2\mu_0} B_i^2 \cdot A_{geom} \cdot k_F$ (8)
	$F = \frac{1}{k_{Carter}^2} \cdot \frac{\mu_0 A_{geom}}{2}\left(\frac{U_\delta}{\delta}\right)^2$ (9)	$F = k_F \frac{\mu_0 A_{geom}}{2}\left(\frac{U_\delta}{\delta}\right)^2$ (10)

Expressions of the air-gap reluctance (obtained by the ratio among air-gap magnetic voltage drop and flux):

classical method: $$\theta_\delta = \frac{U_\delta}{\phi_\delta} = \frac{B_\delta}{\mu_0} \cdot \delta \cdot k_{Carter} \cdot \frac{1}{B_\delta \cdot A_{geom}} = \frac{\delta \cdot k_{Carter}}{\mu_0 \cdot A_{geom}}; \qquad (11)$$

improved method: $$\theta_\delta = \frac{U_\delta}{\phi_\delta} = \frac{B_i}{\mu_0} \cdot \delta \cdot \frac{1}{B_i \cdot A_{geom} \cdot k_\varphi} = \frac{\delta}{\mu_0 \cdot A_{geom} \cdot k_\varphi}. \qquad (12)$$

I.4 Errors of the Classical Formulas

The FEM test of the correction coefficients has shown the correctness of the analytical expressions proposed for such coefficients [1]: thus, expressions (4), (6), (8), (10) are assumed correct (expression (2) is correct, because it is a definition). In the following, some remarks are proposed, about the accuracy of the classical expressions.

(I) Eq.(3) $\phi = B_\delta \cdot A_{geom}$ is correct by definition, because B_δ represents the average flux density under the pole, i.e. the ratio among the actual air-gap flux and the geometrical pole shoe cross section: $B_\delta = \phi / A_{geom}$.

(II) The expression (1) $B_\delta = \mu_0 \frac{U_\delta}{\delta \cdot k_{Carter}}$ is inaccurate. In fact, by using (3), (4), (2) one obtains:

$B_\delta = \frac{\phi}{A_{geom}} = \frac{B_i A_{geom} k_\varphi}{A_{geom}} = B_i k_\varphi = \mu_0 \frac{U_\delta}{\delta} k_\varphi$; this expression must be considered correct, because (3), (4), (2) are correct; thus, the validity of (1) implies that $1/k_{Carter} = k_\varphi$.

In case of an unlimited toothed structure faced to an unlimited smoothed structure, the coefficient k_φ (that becomes $k_{\varphi s}$ of the case A1) appears to have an analytical expression that is the reciprocal of the Carter' s factor, i.e.: $1/k_{Carter} = k_{\varphi_s}$; this fact seems to confirm the validity of (1), but in the general case of polar shoes faced to a toothed structure, k_φ takes into account also the fringing effect due to the finite extension of the pole shoe (in analytical terms, the k_φ here considered is given by $k_\varphi = k_{\varphi_s} \cdot k_{\varphi_p}$, see parag.3.2 and 3.3); thus, it follows $1/k_{Carter} \neq k_\varphi$; therefore, (1) is not verified in the general case, or, at least, it is inaccurate.[1]

(III) Also the expression (5) $\phi = \mu_0 A_{geom} \cdot (U_\delta / (k_{Carter} \cdot \delta))$ is inaccurate, as a consequence of (II).

(IV) The expression (7) $F = \left(B_\delta^2 / (2\mu_0)\right) \cdot A_{geom}$ is not valid in general, but it is correct only in case of uniform flux density distribution. In fact, it follows from the expression $F = \int_{A_{geom}} B^2 / (2\mu_0) \cdot dA$, and the simplification of the integral operator is allowed only if the flux density distribution is roughly uniform (because in this case we have $\int_{A_{geom}} B^2 dA = B^2 \int_{A_{geom}} dA = B^2 A_{geom}$). If this condition is not verified, we can in any case assume $F = \left(B*^2 / (2\mu_0)\right) \cdot A_{geom}$, but $B*$ must be interpreted as a flux density equivalent as regards the force effects, i.e. $B* = \sqrt{\frac{1}{A_{geom}} \int_{A_{geom}} B^2 dA}$; thus, we can use (7), but only if B_δ is substituted by $B*$ (in general, it is incorrect consider B_δ instead of $B*$, because the flux density B_δ is an average value as regards the flux: $B_\delta = \frac{\phi}{A_{geom}} = \frac{1}{A_{geom}} \cdot \int_{A_{geom}} B \cdot dA$).

N.B.: on the basis of the previous considerations, it follows that the error of the classical method is to assume the flux density as uniform even if it is not the case, or (alternatively), in using the same flux density B_δ, valid for the flux, also for the force evaluation. In almost all the traditional magnetic structures, the geometrical sizes are proportioned in such a way that these distinctions are not relevant, thus justifying the general use of the relations; on the contrary, in systems with particular proportions (such as the Maglev levitator) these phenomena are evident and the error in the force calculation can be important (performed comparisons have shown that the error can become roughly 30%).

(V) The expression (9) $F = \frac{1}{k_{Carter}^2} \frac{\mu_0 A_{geom}}{2} \left(\frac{U_\delta}{\delta}\right)^2$ is incorrect, as a consequence of (IV) and (II).

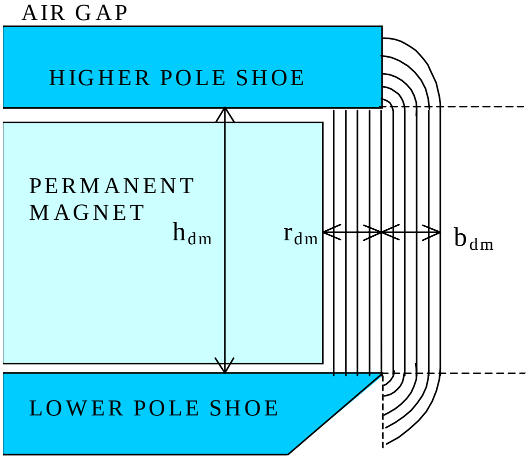
I.5 The Leakage Calculation Procedure

In the classical method, the leakage calculation is performed by assuming a given flux distribution, and obtaining some expressions based on length and cross section of the corresponding flux tubes. The method here considered is the same, but it is based on the actual flux distribution, obtained by FEM field analyses; FEM analysis allows also to validate the method, because it is possible to calculate magnetic voltage drops and fluxes, thus obtaining a numerical evaluation of the leakage reluctances by making their ratio.

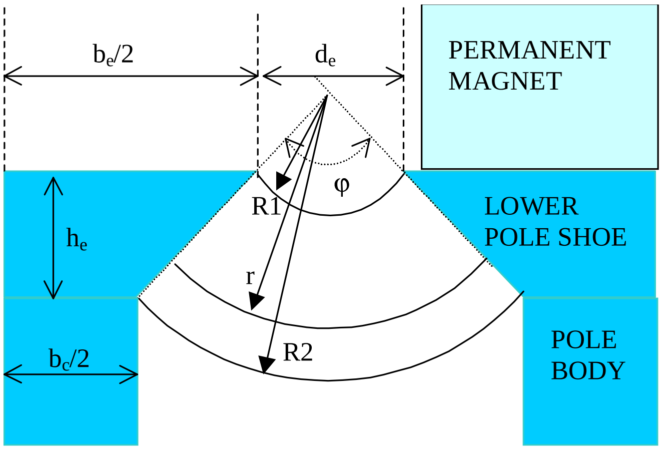
In the following, the procedure for the calculation of the geometrical leakage reluctances is illustrated, for the magnet and for the lower pole shoes.

[1] By the way, it must be noted that the relation $1/k_{Carter} = k_{\varphi_s}$, even if correct just in a particular case, demonstrates the congruence among the developed theory and the classical expressions.

Magnet Leakage Reluctance.
In the following, it is supposed that each pole shoe structure has a permanent magnet included between a higher pole shoe, faced to the air-gap, and a lower pole shoe, connected to the pole body.



Model of the magnet self-leakage.



Model of the leakage among the lower pole shoes.

As regards the leakage modelling, the field lines are supposed straight line segments, parallel to the permanent magnet edge, joined with the pole shoe edges by circumference arcs; both the pole shoe edges are considered inclined of an angle equal to $\pi/2$ radians with respect to the horizontal. Thus, the following quantities are defined:

- r_{dm} = magnet indentation with respect to the pole shoes;
- b_{dm} = extension of the magnet leakage flux tubes;
- h_{dm} = height of the leakage tubes = distance between pole shoes.

With the previous assumptions, the leakage permeance (per transversal unit length) is expressed by:

$$\lambda_{dm} \approx 2\mu_0\left(\frac{r_{dm}}{h_{dm}} + \int_0^{b_{dm}} \frac{dx}{h_{dm} + \pi x}\right) = 2\mu_0\left(\frac{r_{dm}}{h_{dm}} + \frac{1}{\pi} ln\left(1 + \pi\frac{b_{dm}}{h_{dm}}\right)\right) .$$

Leakage Reluctance among the lower pole shoes.
The lower pole shoes have trapezoidal shape, with major base equal to the width b_e of the higher pole shoes, and minor base equal to the width b_c of the pole bodies. The flux lines are schematised as circumference arcs perpendicular to the inclined sides. Called R_1 and R_2 the radius of the two extreme arcs, r the generic radius and φ the angle formed by the two inclined surfaces, the leakage permeance (per unit transversal length) is expressed by:

$$\lambda_{di} = \mu_0 \int_{R_1}^{R_2} \frac{dr}{r \cdot \varphi} = \frac{\mu_0}{\varphi} ln\left(\frac{R_2}{R_1}\right).$$

From simple geometrical relations, one obtains that

$$\frac{(b_e - b_c)/2}{h_e} = tan\frac{\varphi}{2}, \quad \text{from which} \quad \varphi = 2 \cdot atan\left(\frac{b_e - b_c}{2h_e}\right);$$

$$R_1 = \frac{d_e}{2}\frac{1}{sen(\varphi/2)}, \qquad R_2 = \left(\frac{d_e}{2} + \frac{b_e - b_c}{2}\right)\frac{1}{sen(\varphi/2)} \quad \text{and then} \quad \frac{R_2}{R_1} = 1 + \frac{b_e - b_c}{d_e},$$

where d_e is the longitudinal distance among two higher pole shoes.
Thus, the permeance expression results

$$\lambda_{di} = \mu_0 \frac{ln\left(1 + \frac{b_e - b_c}{d_e}\right)}{2 \cdot atan\left(\frac{b_e - b_c}{2h_e}\right)}.$$

II. The Enhancements Obtained with the Improved Model

Introduction

On the basis of the previously described improved model, the design of two types of EMS Maglev levitators has been performed, one with coils only, the other of the hybrid kind, with coils and permanent magnets [5]. Referring to the results of this design, the evident enhancements introduced by the improved model will be shown. To this aim, the results of the following comparisons are reported:

- values of fluxes and forces (for different air-gap values), evaluated according to the two models and by means of FEM analyses;
- levitation test oscillogrammes performed on the same system, represented with the two models.

II.1 Comparison of Fluxes and Forces

The designed levitators ([5]), object of the calculations, are shown in fig.1a and 2a. The classical models are reported in fig. 1b and 2b, and the corresponding improved models in fig.1c and 2c. In the classical model, the air-gap reluctances are evaluated by the expression (11), while in the improved model, the expression (12) is used.

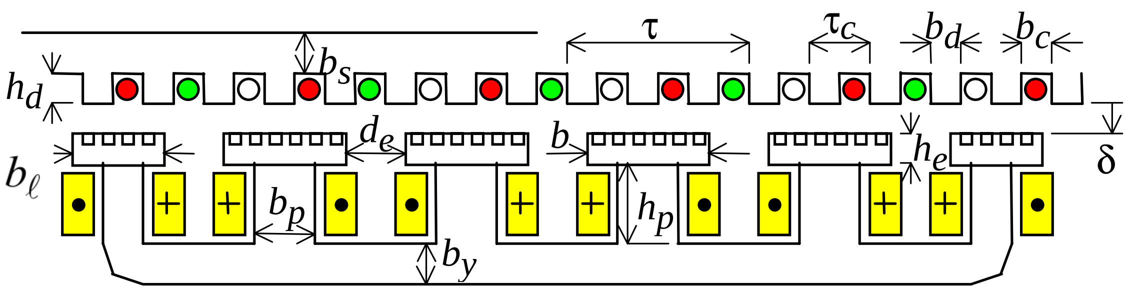


Fig. 1a: schematic of the levitator with coils only.

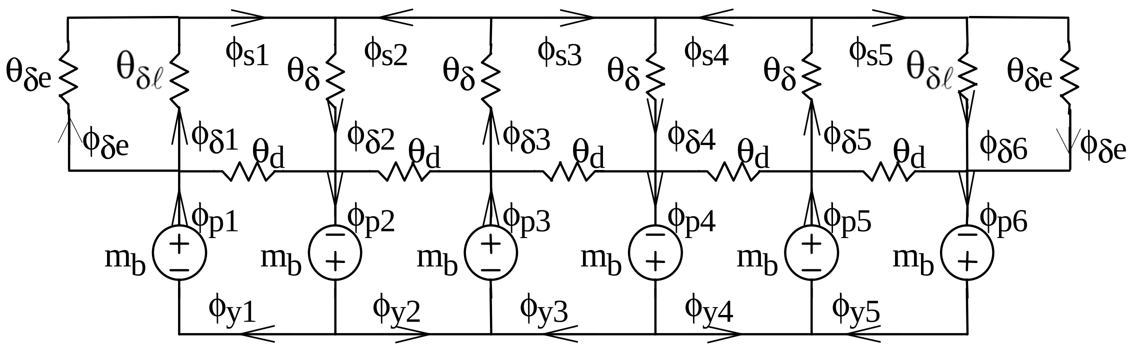


Fig. 1b: classical model for the network of the levitator with coils only.

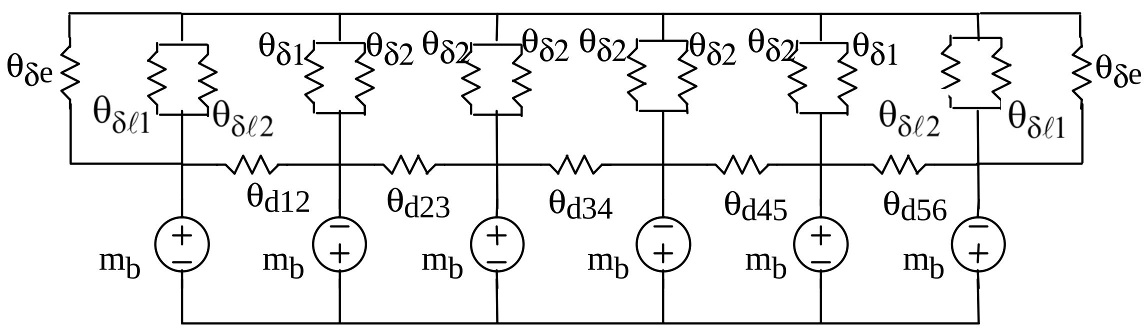


Fig. 1c: improved model for the network of the levitator with coils only.

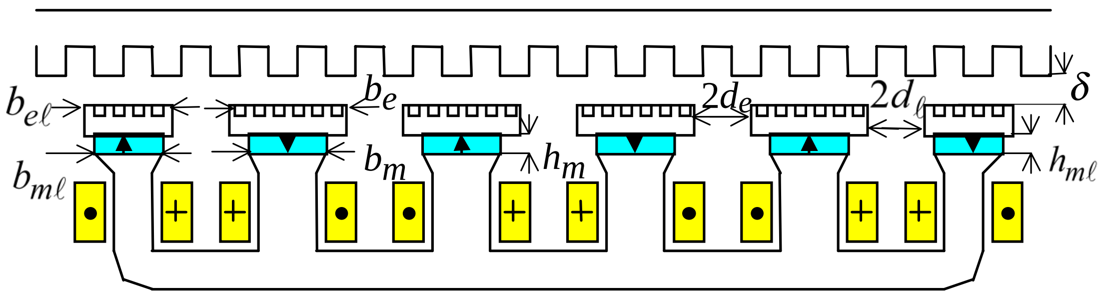


Fig. 2a: schematic of the hybrid levitator with permanent magnets and coils.

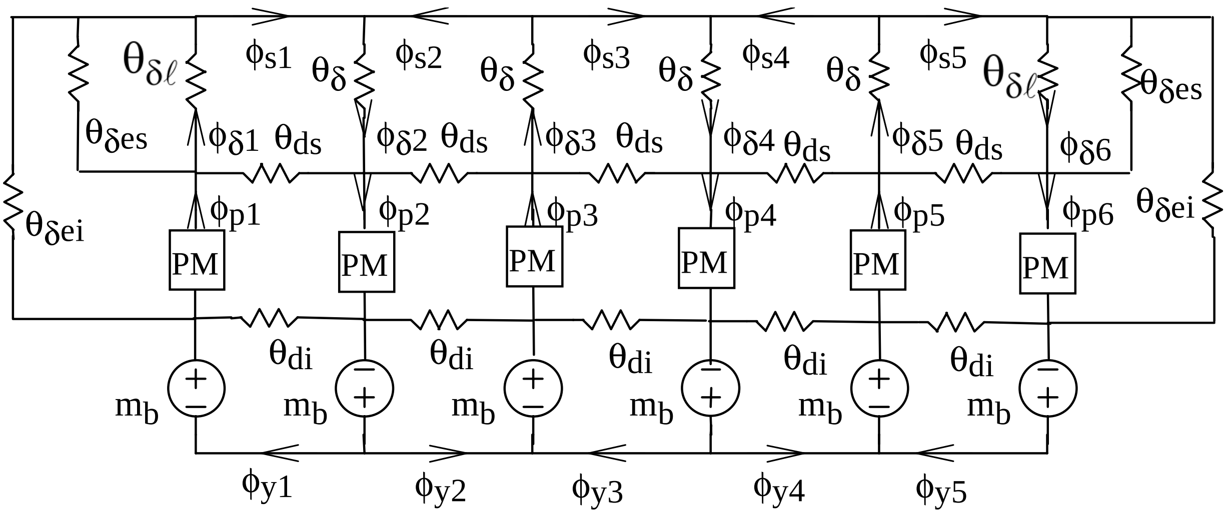


Fig. 2b: classical model for the network of the hybrid levitator with coils and permanent magnets.

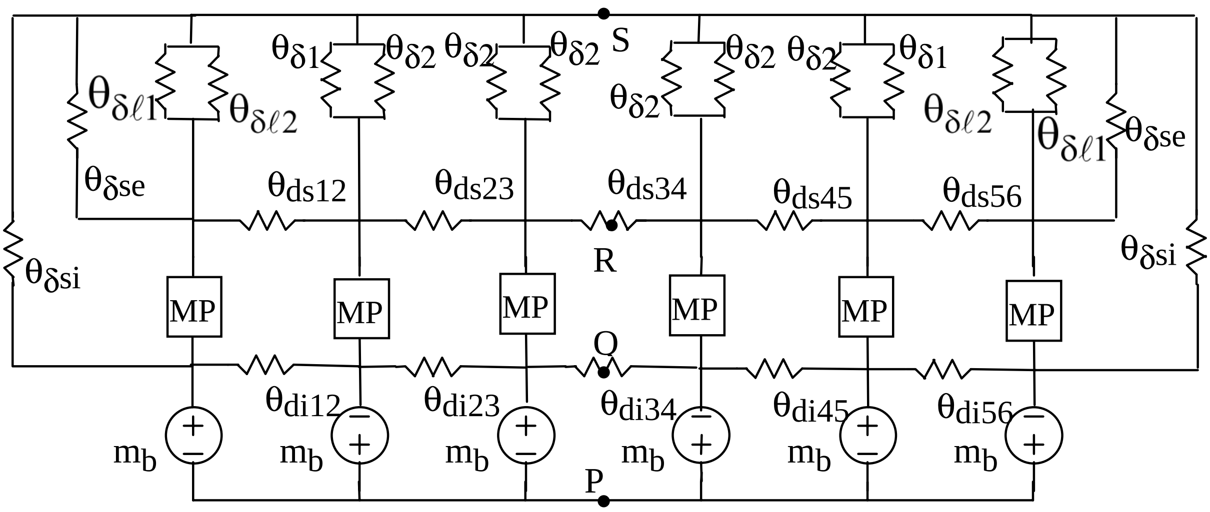


Fig. 2c: improved model for the network of the hybrid levitator with coils and permanent magnets.

classical method:

$$\theta_\delta = \frac{U_\delta}{\phi_\delta} = \frac{B_\delta}{\mu_0} \cdot \delta \cdot k_{Carter} \frac{1}{B_\delta \cdot A_{geom}} = \frac{\delta \cdot k_{Carter}}{\mu_0 \cdot A_{geom}}; \tag{11}$$

improved method:

$$\theta_\delta = \frac{U_\delta}{\phi_\delta} = \frac{B_i}{\mu_0} \cdot \delta \cdot \frac{1}{B_i \cdot A_{geom} \cdot k_\varphi} = \frac{\delta}{\mu_0 \cdot A_{geom} \cdot k_\varphi} \tag{12}$$

Considering that the performed FEM simulations are of 2D kind, also the analytical calculation is referred to this condition, thus neglecting the transversal dimension and the related correction coefficients; in fact, it must be noted that the reported values are per unit transversal length.

As regards the FEM analyses, the flux in each branch is evaluated simply as the difference among the vector potential values on the lines that delimit the same branch, while the acting force over an object is evaluated as the integral of the Maxwell tensor along a close line including the object itself.

The considered air-gap values are the rated air-gap (4 mm), the lifting air-gap (equal to twice the rated one), and a very reduced air-gap (0.3 mm), chosen to simulate the " gluing" condition (condition that occurs when the levitator under the track tends to be attracted till to the contact against the track itself). For all the air-gap values, a value of m.m.f. has been adopted capable to generate the rated levitation force (equal to the vehicle weight); this m.m.f. has been evaluated by means of FEM analyses, and it is indicated in p.u., in the first column, referred to a reference m.m.f. equal to 1970 A; in case of an electromagnetic levitator with coils only, this is the m.m.f. value necessary to produce the rated levitation force with rated air-gap (the adoption of this reference value allows to directly show the ratio among the m.m.f.s – and thus the Joule losses – of the hybrid levitator with permanent magnets, compared with that with coils only). In the case of hybrid levitator with permanent magnets, also the operating conditions with zero coil currents have been analysed.
In the following, the results of the performed comparisons are discussed, by showing:

– the ratio among the analytically evaluated quantities and the FEM results;
– the actual values of the evaluated quantities, according to the three methods (classical, improved, FEM).

II.1.1 Electromagnetic Levitator with Coils Only

Fluxes with Rated Air-Gap

Table II.1.1.1: ratio among analytically and FEM evaluated fluxes, in conditions of rated air-gap.

mmf = 0	STATOR YOKE			AIR-GAP			POLES			LEVITAT. YOKE			EXT.
	1	2	3	4	5	6	7	8	9	10	11	12	13
CLASS.	0.787	0.995	0.798	0.767	0.866	0.874	0.812	0.888	0.897	0.812	0.995	0.831	1.000
IMPROV.	1.004	0.941	1.000	1.005	0.980	0.977	1.004	0.983	0.982	1.004	0.954	1.001	1.000

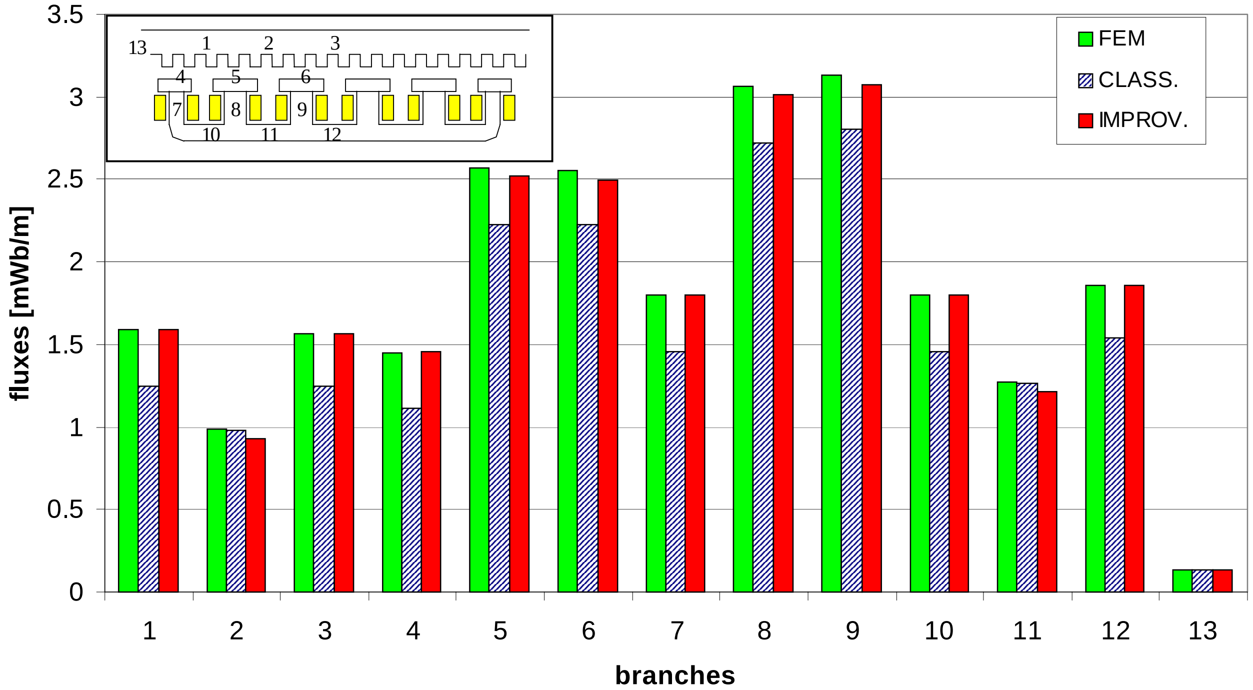


Fig. II.1.1.1: actual values of the fluxes evaluated with the three methods, with rated air-gap.

Fluxes with Lifting Air-Gap

Table II.1.1.2: ratio among analytically and FEM evaluated fluxes, with lifting air-gap.

mmf = 1,837 p.u.	STATOR YOKE			AIR-GAP			POLES			LEVITAT. YOKE			EXT.
	1	2	3	4	5	6	7	8	9	10	11	12	13
CLASS.	0.726	1.120	0.741	0.693	0.842	0.854	0.761	0.865	0.877	0.761	1.041	0.786	0.925
IMPROV.	0.997	0.999	0.988	1.009	0.998	0.991	0.984	0.979	0.973	0.984	0.971	0.974	0.925

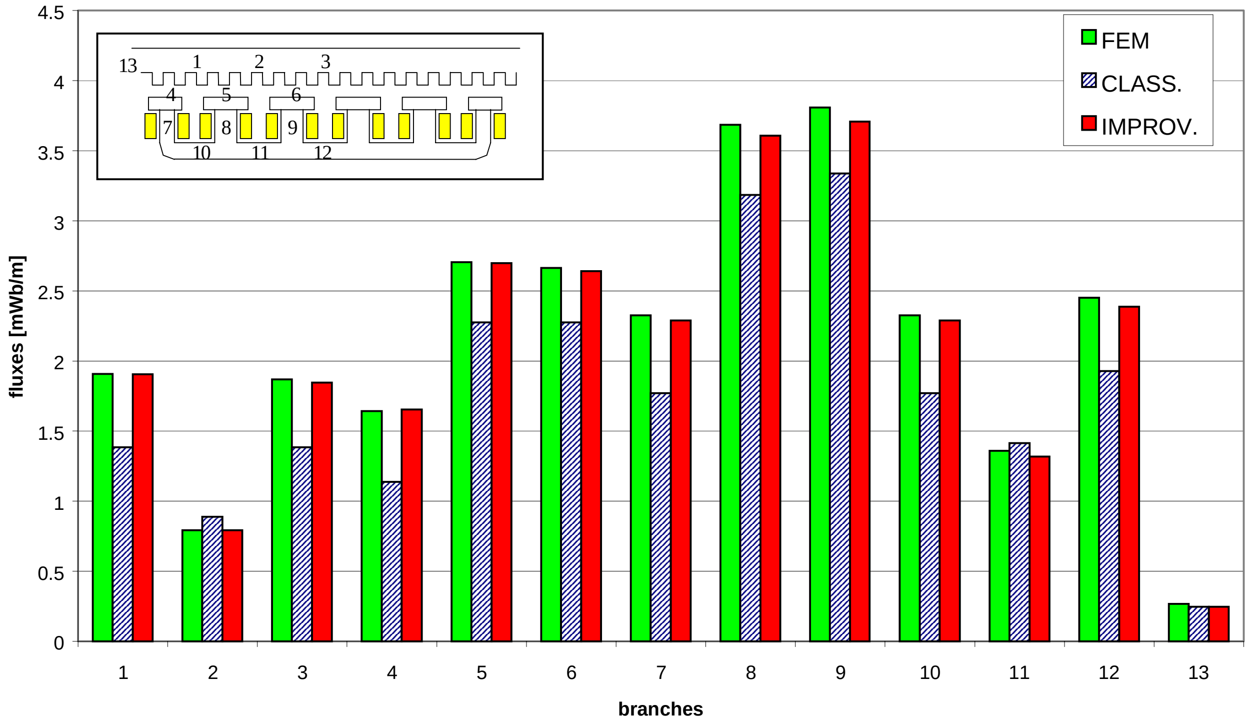


Fig. II.1.1.2: actual values of the fluxes evaluated with the three methods, with lifting air-gap.

Fluxes with Gluing Air-Gap

Table II.1.1.3: ratio among analytically and FEM evaluated fluxes, with gluing air-gap.

mmf = 0,086 p.u.	STATOR YOKE			AIR-GAP			POLES			LEVITAT. YOKE			EXT.
	1	2	3	4	5	6	7	8	9	10	11	12	13
CLASS.	0.956	0.962	0.955	0.953	0.959	0.959	0.957	0.961	0.961	0.957	0.966	0.958	1.091
IMPROV.	1.017	0.973	1.013	1.015	0.995	0.994	1.017	0.997	0.996	1.017	0.977	1.015	1.091

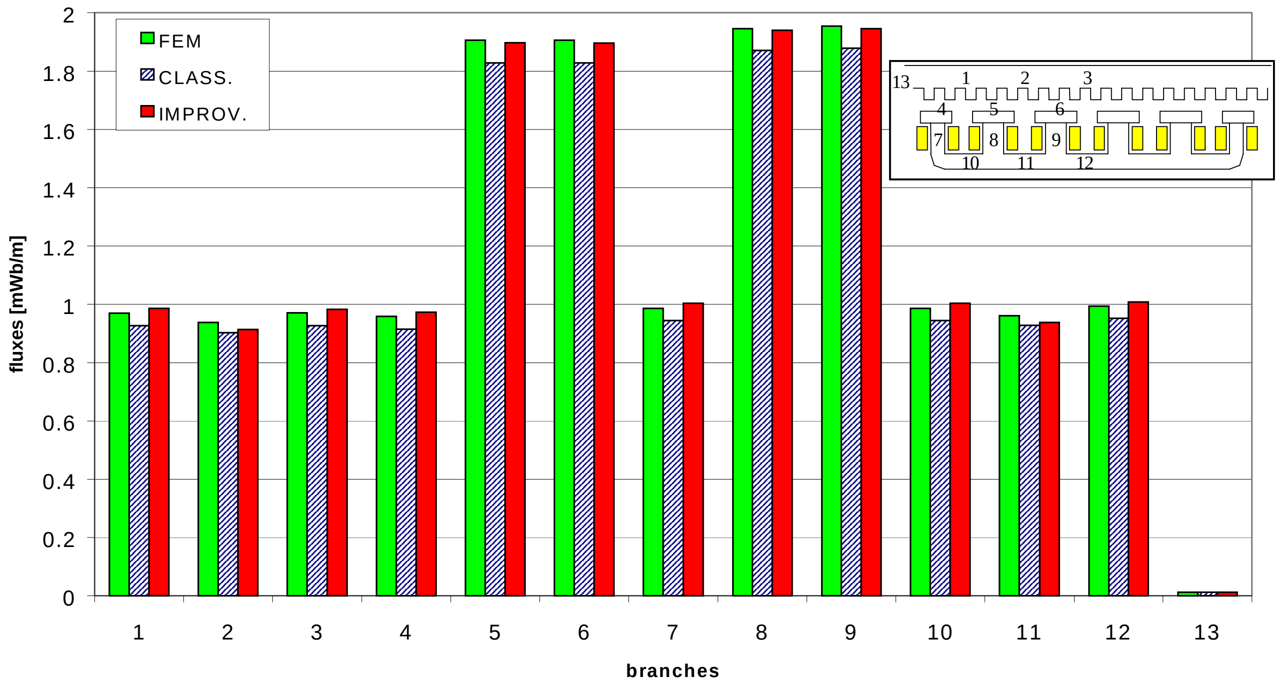


Fig. II.1.1.3: actual values of the fluxes evaluated with the three methods, with gluing air-gap.

Force

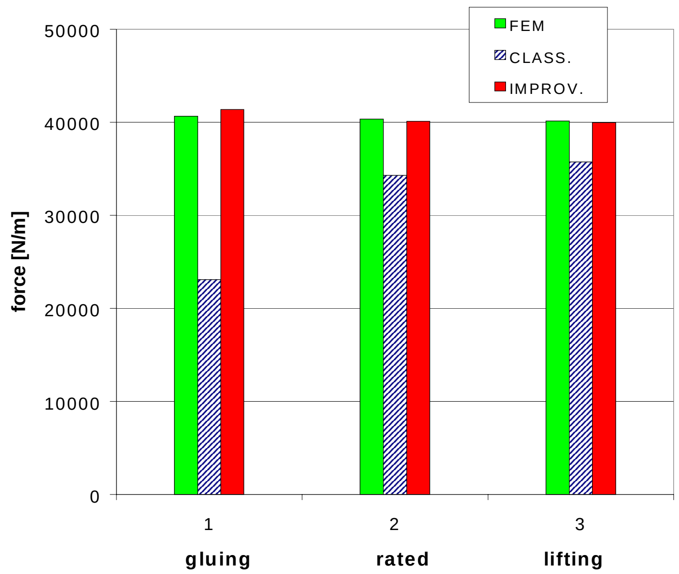


Fig. II.1.1.4: actual values of the forces, evaluated with the three methods.

Table II.1.1.4: actual values of the forces, and p.u. values, referred to the FEM results.

	GLUING	RATED	LIFTING
FORCES (p. u. transversal length) [N/m]			
FEM	40633	40333	40117
CLASS.	23083	34283	35733
IMPROV.	41350	40083	39967
RATIO, referred to FEM values			
CLASS.	0.568	0.850	0.891
IMPROV.	1.018	0.994	0.996

It can be noted that the improved method allows a sensibly better estimation of the fluxes and of the forces in all the branches and in all the examined conditions.
It should be observed the very high error (above 40%) of the classical method in the force evaluation. This is due to the fact that in this case the employed expression $F = \frac{1}{2\mu_0}\frac{\varphi^2}{A_{esp}}$ becomes invalid: this expression makes sense only if the flux density has uniform distribution; for very reduced air-gaps, the flux crosses the air-gap practically towards the teeth, the field is very distorted, thus the previous expression cannot be used. The error can be reduced if the cross section A_{esp} of the pole shoe is multiplied by the ratio b_d / τ_c (b_d = tooth width; τ_c = slot pitch), in such a way to obtain a cross section more similar to the actual flux cross section. This expedient has a small value, above all because the error remains high: in the examined case, we have $b_d / \tau_c = ½$, thus the force becomes twice; therefore, referring to the table II.1.1.4, the showed ratio doubles (0.568·2 = 1.136), and the error remains of 13 – 15 % roughly. Moreover, there are no criteria to establish when to use the section A_{esp} or the section $A_{esp} \cdot b_d / \tau_c$.
On the basis of these considerations, a possible question could concern the reason why the classical expression of the force is commonly used without problems. In fact, the expression is generally acceptable, because rarely the field is highly non-uniform: usually, in case of small air-gap (induction motors) the slots are half closed or closed, while in case of open slots (alternators), the air-gaps are higher: in both the cases, the field distribution can be considered uniform enough, and the classical expression is acceptable; after all, the same Table II.1.1.4 shows that, in case of rated and lifting air-gap, the errors of the classical expression are more reduced. On the contrary, the problem arises in this particular situation, because the slots are open and the air-gap tends to zero.
Another remark concerns the fact that the amount of the error of the classical method changes with the air-gap: in the force evaluation, the error decreases with the increase of the air-gap, while the opposite occurs in the calculation of the flux, i.e., when the air-gap increases, the same happens for the error (in any case, the considered error is the relative one, referred to the FEM solution, as can be observed in Tables II.1.1).
As regards the fluxes, this behaviour can be explained by considering that, when the air-gap decreases, the fringing effect due to the pole shoes tends to vanish, while the only remaining important effect is the fringing due to the slotting, correctly modelled by k_{Carter} (remember that $k_{Carter} = 1/k_{\varphi S}$, and that $k_{\varphi S}$ corresponds to the factor k_φ in the case of toothed structure faced to a smoothed structure, i.e. without pole shoes).
As regards the force, the reduction of the error for increasing air-gap can be explained with the reduction of the field non uniformity, to which the validity of the expression used for the force evaluation is correlated.

II.1.2 Hybrid Electromagnetic Levitator with Permanent Magnets

Fluxes with Rated Air-Gap

Table II.1.2.1: ratio among analytical and FEM evaluated fluxes, in conditions of rated air-gap.

mmf = 0	STATOR YOKE			AIR-GAP			POLES			LEVITAT. YOKE			EXT.
	1	2	3	4	5	6	7	8	9	10	11	12	13
CLAS.	0,893	0,975	0,899	0,887	0,933	0,937	0,903	0,943	0,947	0,903	0,983	0,912	1,110
IMPR.	1,007	0,970	1,005	1,008	0,989	0,988	1,006	0,990	0,989	1,006	0,973	1,005	0,964

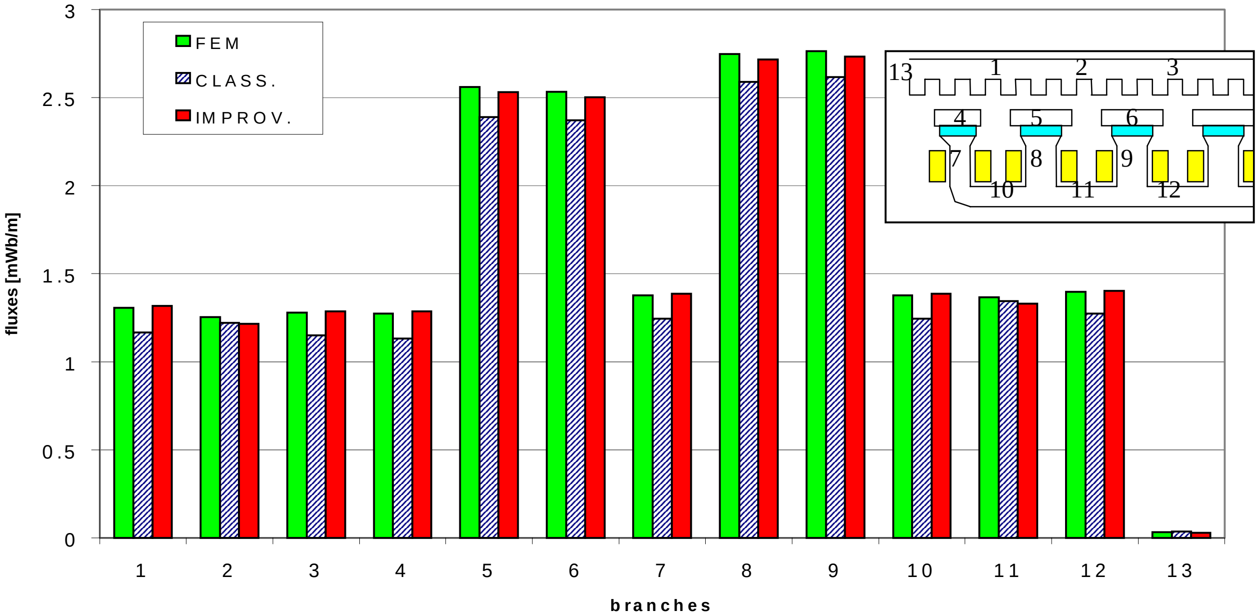


Fig. II.1.2.1: actual values of the fluxes evaluated with the three methods, rated air-gap conditions, mmf = 0.

Fluxes with Lifting Air-Gap

Table II.1.2.2: ratio among analytically and FEM evaluated fluxes, with lifting air-gap.

mmf (p.u)		STATOR YOKE			AIR-GAP			POLES			LEVITAT. YOKE			EXT.
		1	2	3	4	5	6	7	8	9	10	11	12	13
0	CLAS.	0,826	1,005	0,840	0,822	0,908	0,917	0,829	0,905	0,913	0,829	0,986	0,848	0,906
	IMPR.	1,020	0,994	1,016	1,032	1,008	1,005	0,995	0,983	0,979	0,995	0,968	0,989	0,782
1,117	CLAS.	0,829	1,030	0,842	0,804	0,908	0,918	0,864	0,940	0,952	0,864	1,039	0,888	1,045
	IMPR.	1,008	1,008	1,005	1,010	1,008	1,006	1,009	1,011	1,011	1,009	1,014	1,009	0,990

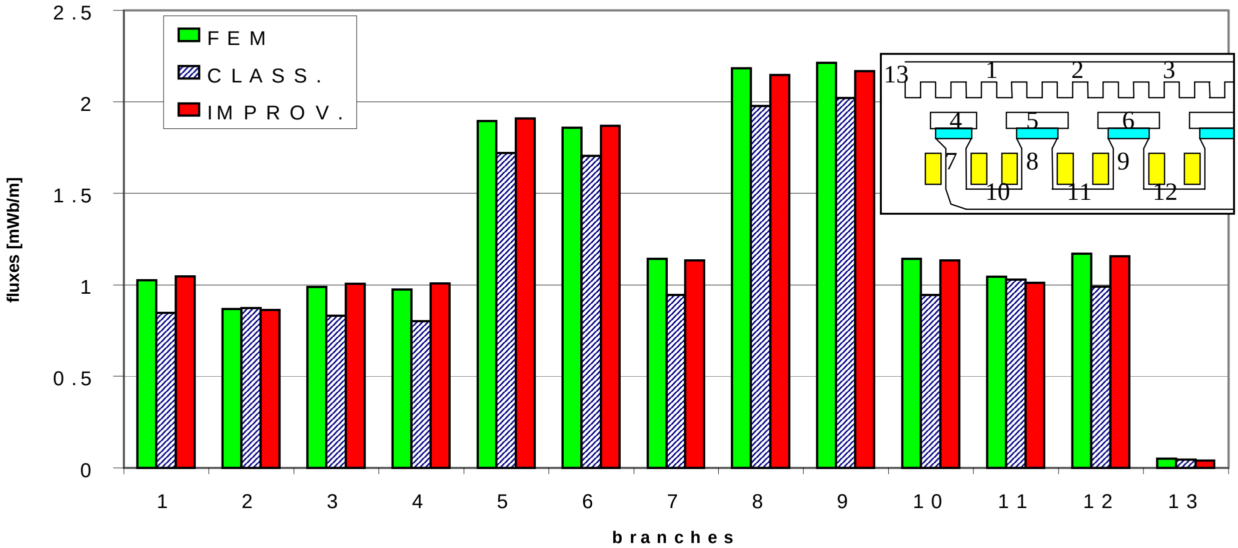


Fig. II.1.2.2a: actual values of the fluxes evaluated with the three methods: lifting air-gap and mmf = 0.

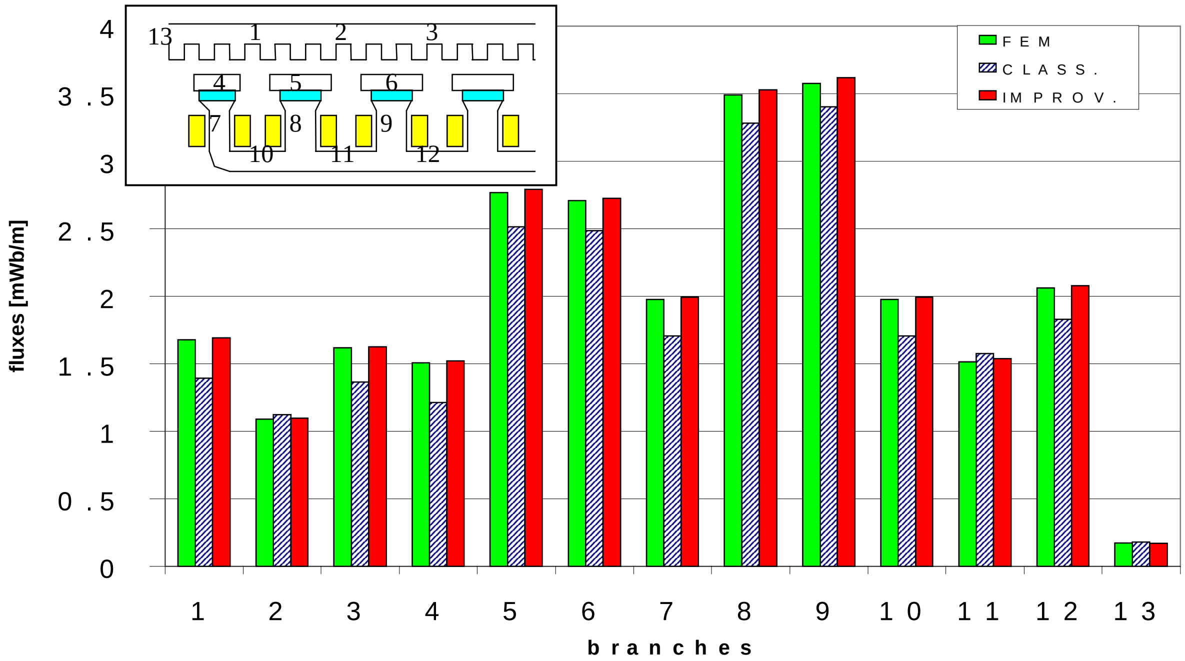


Fig. II.1.2.2b: actual values of the fluxes evaluated with the three methods: lifting air-gap; mmf = 1.117 p.u.

Fluxes with Gluing Air-Gap

Table II.1.2.3: ratio among analytically and FEM evaluated fluxes, with gluing air-gap.

mmf (p.u)		STATOR YOKE 1	2	3	AIR-GAP 4	5	6	POLES 7	8	9	LEVITAT. YOKE 10	11	12	EXT. 13
0	CLAS.	0,994	0,993	0,994	0,993	0,994	0,993	0,996	0,996	0,996	0,996	0,996	0,996	1,383
	IMPR.	1,000	0,994	0,999	0,999	0,997	0,997	1,001	0,999	0,999	1,001	0,997	1,001	1,307
-1,280	CLAS.	1,022	0,972	1,019	1,047	0,990	0,989	0,959	0,929	0,915	0,959	0,915	0,915	1,222
	IMPR.	1,029	0,973	1,026	1,053	0,993	0,993	0,967	0,933	0,918	0,967	0,916	0,924	1,224

N.B.: in this case the mmf is negative, because it must apply a demagnitizing effect.

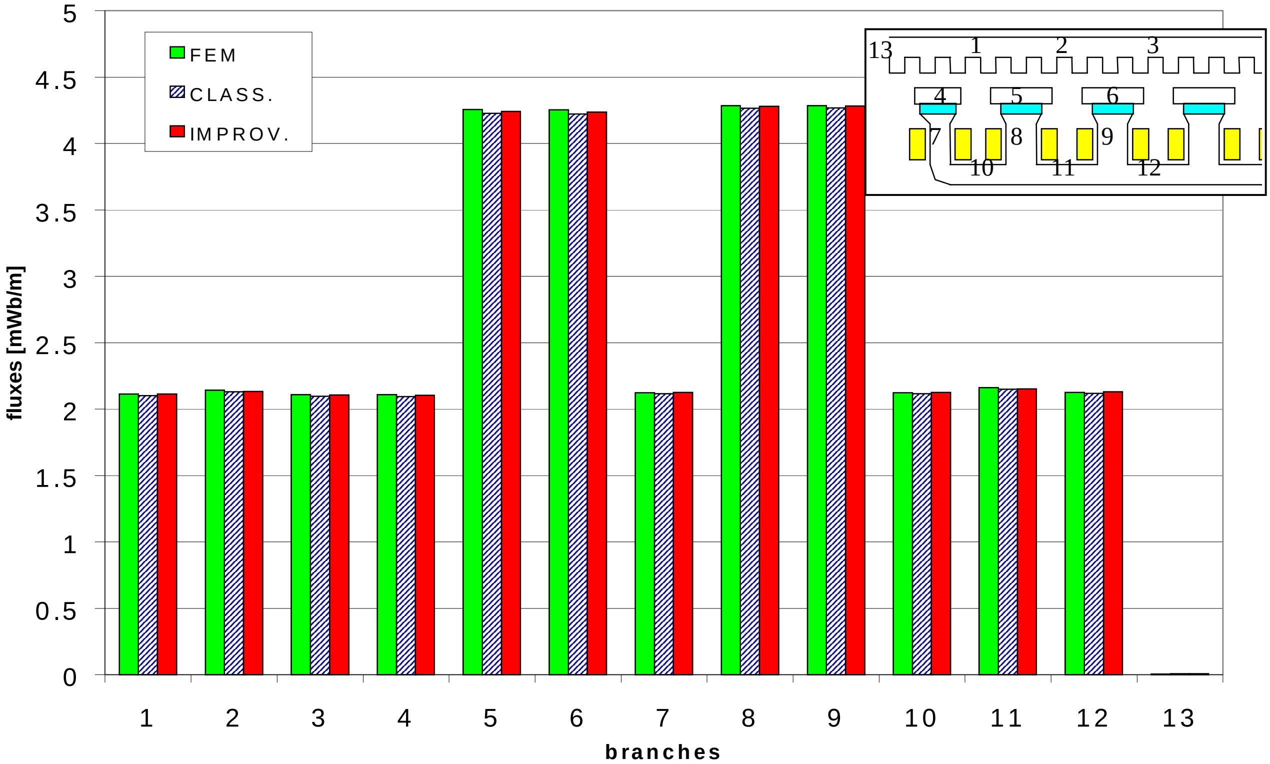


Fig. II.1.2.3a: actual values of the fluxes evaluated with the three methods, with gluing air-gap and mmf = 0.

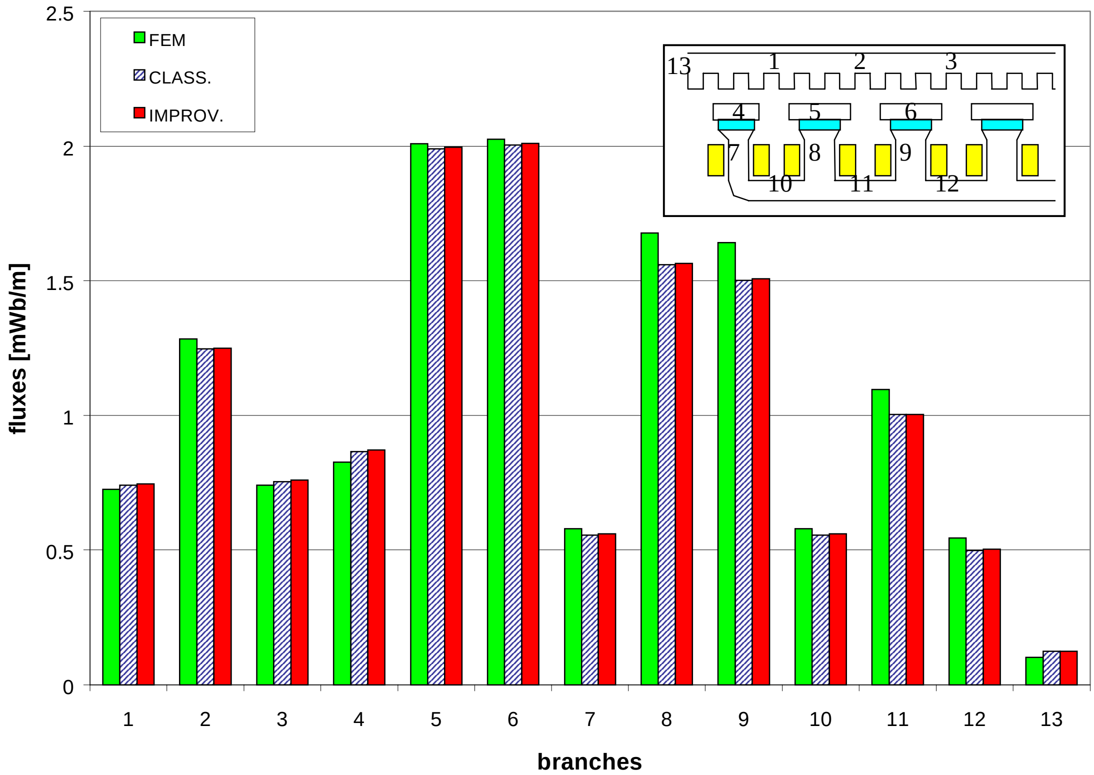


Fig. II.1.2.3b: actual values of the fluxes evaluated with the three methods: gluing air-gap, mmf = –1.28 (p.u.).

Force

Table II.1.2.4: actual forces and ratio among analytical and FEM values.

	LIFTING AIR-GAP		RATED	GLUING AIR-GAP	
ACTUAL FORCES (per unit length)					
FEM	18733	40333	38667	202000	44850
CLASS.	19750	42650	38383	122900	26167
IMPROV.	18883	40767	38500	204000	43500
RATIO among analytical and FEM values					
CLASS.	1.054	1.057	0.993	0.608	0.583
IMPROV.	1.008	1.011	0.996	1.010	0.970

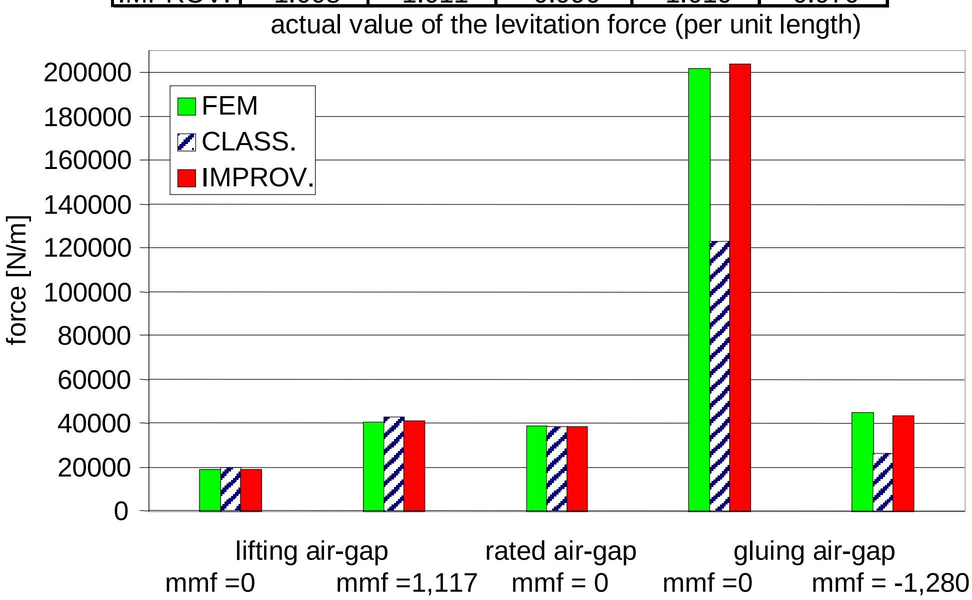
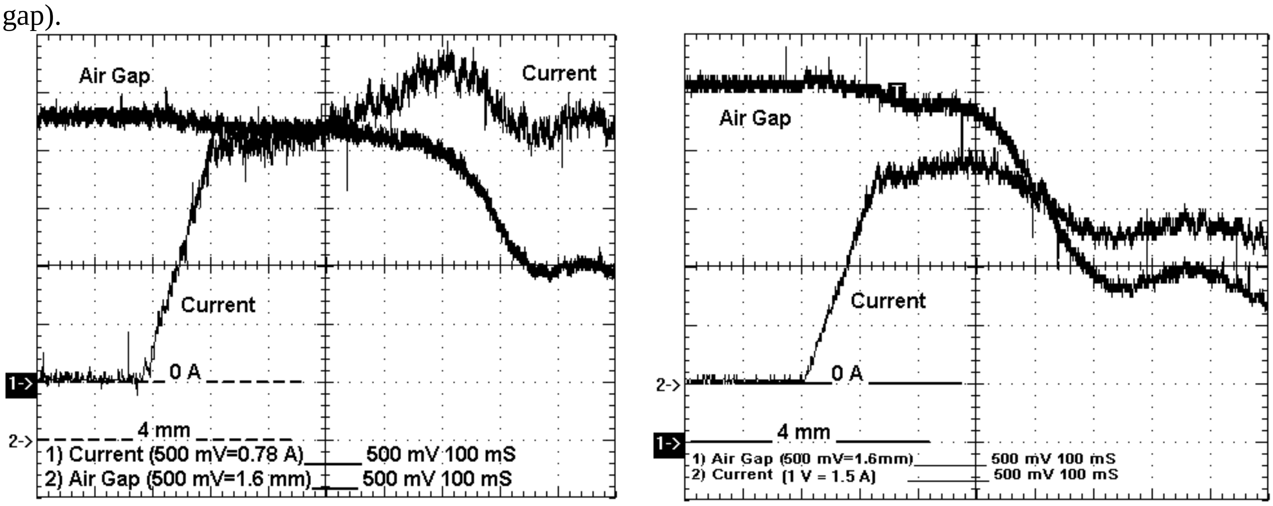


Fig. II.1.2.4: values of the forces, evaluated with the three methods.

Also in this case, in general, the improved method allows a really better estimation of fluxes and forces.
Some particular remarks are required for the case of very reduced air-gap (gluing air-gap).
One can observe that the fluxes are quite correctly estimated also by the classical method: this happens not only for the same reason already explained as regards the electromagnetic levitator with coils only (weak influence of the fringing due to the pole shoes), but above all because when the air-gap tends to zero, the same thing happens to the air-gap reluctances, and the values of the fluxes are substantially determined by the magnet equivalent reluctances; these reluctances are evaluated in the same manner in the two methods, thus it is reasonable to obtain similar results.
On the contrary, in case of rated and lifting air-gap, where the air-gap reluctances are important, the improved method estimates the fluxes more better (this shows that the proposed coefficients are more correct than the Carter factor only).
Again in case of gluing air-gap, as like as for the electromagnetic levitator with coils only, the error connected with the use of the classical method in the force evaluation is very high: the same remarks made in the case of levitator with coils only can be applied.
At this point, a spontaneous question could be the following: in gluing conditions, why does the classical method evaluate correctly the fluxes but the force shows great error levels? The reason is simply connected to the employed calculation method: the fluxes are evaluated by circuit solving the magnetic network; thus starting from correct expressions of the reluctances, correct results can be obtained. The force is evaluated with an expression that is incorrect in these conditions, hence the results are wrong.
A last remark regards the fact that the classical method causes higher errors in case of a levitator with coils only, rather than in the levitator with the magnets: this can be explained with the fact that in the levitator with the magnets the correction coefficients have a very lower importance in the evaluation of the quantities. In fact, the permeability of the magnet is close to that of the air: thus, the presence of the magnet corresponds to an additional air-gap, that reduces the importance of the mechanical air-gap, and therefore the influence of the air-gap reluctances (to which the correction coefficients are associated); the consequence is that fluxes and forces are less influenced from the correction coefficients.

II.2 Levitation Tests

Several levitation tests have been performed by using a simplified platform (the magnetic structure has two poles instead of six, and no permanent magnets are inserted).
The usefulness of the improved model to the aim of the control can be demonstrated by comparing the oscillogrammes of the figures shown in the following. Both these figures refer to a lifting process conducted as follows: at first the magnetic structure flux is increased up to the lifting value (the value required to produce the rated force, with lifting air-gap); as soon as the rising flux ramp is concluded, the ramp of the air-gap reduction starts: the air-gap is decreased from the initial value (lifting value) to the rated one (operating air-gap).



a *b*

Fig. 3: measured air-gap and current waveforms during the complete lifting transient, obtained with the simplified (a) and improved (b) models.

Fig.3a refers to the test in which the classical model is employed. The following features can be observed:

- above all, the inaccuracy of the model: at the end of the lifting process (i.e. with rated air-gap) the current should be lower than the initial value (corresponding to the final value of the current ramp), because, with a lower air-gap, it is required a lower m.m.f. in order to obtain the same force. On the contrary, one can note that the final and the initial values are roughly equal: clearly, this means that the link flux-current expressed by the model is significantly different from the real one;
- indeed because of the inaccuracy, the levitation can start only after that the current has raised, and in fact the air-gap starts to decrease only when the current has reached a suited threshold.

Fig.3b refers to the same conditions of fig.3a, but with the improved model. Here the link flux-current is better represented, and in fact the final current value is lower than the initial value, and indeed this fact allows to shorten the current transient (the time interval concerning the current raising is limited) and thus reducing also the air-gap answer delay: the introduction of the improved model has allowed the elimination of the anomaly concerning the current behaviour.

III Conclusions

In the present paper, a method for the improved modelling of the magnetic structure of EMS Maglev system levitation devices has been described: levitators with esapolar structure have been considered, both equipped with coils only and of the hybrid kind, equipped with control coils and biasing permanent magnets.
The improvement of the magnetic circuit model is obtained by using correction coefficients, deduced by the conformal transformation theory: these coefficients, that represent a generalization of the well known Carter's factor, take into account the distorting effect of the air-gap field, due to the simultaneous presence of the faced magnetic "holes", corresponding to the stator slots and to the levitator interpolar zones. Considered the different effect that the field distortion generated by the magnetic "holes" produces on the flux distribution and on the levitation force value, the above mentioned coefficients are different for the calculation of the fluxes and of the forces.
Also the interpolar leakage reluctances and the self-leakage reluctances of the permanent magnets have been evaluated, thus obtaining magnetic network structures for the analysis of several operating condition with rated load: air-gap with rated value, at lifting and at the incipient gluing condition.
Several numerical simulations, based on FEM analyses and on the use of classical and improved magnetic networks, have shown the higher accuracy of the improved approach compared with the classical one: in fact, the results of the improved circuit simulation are very close to those of the FEM analysis; of course, differently from the simulation time required by FEM analysis, the circuit analysis is extremely quicker, and it is more suited to be employed both during the design stage and for the dynamical analysis of the levitation systems.
The use of the improved modelling instead of the classical one has been evaluated also by means of suited levitation tests: the implementation of the improved model in the system control evidenced the possibility to enhance the system answer during the lifting stage, reducing the duration of this process.

References

1. A. Di Gerlando, G. Foglia, "Improved Analytical Evaluation of Air Gap Fluxes and Forces of Ferromagnetic Smoothed and Toothed Structures and Pole Shoes", in International Journal COMPEL, n° 19, 2000.
2. F. Castelli Dezza, A. Di Gerlando, G. Foglia, "Field-Circuit Integrated Methodologies for Design and Modelling of Permanent Magnet Levitation Devices for Maglev Transportation Systems", in International Journal COMPEL, n° 19, 2000.
3. F. Castelli Dezza, A. Di Gerlando, G. Foglia, "Theoretical Studies and Experimental Activities on EMS Levitation Devices for Maglev Levitation Systems", in MAGLEV 2000, Proceedings of the 16th International Conference on magnetically levitated systems and linear drives, June 7-10 2000, Rio De Janeiro, Brazil, pag. 213-218.
4. G. Foglia, "Theoretical and Experimental Analysis of Excitation and Levitation Devices in EMS Maglev Systems", Ph. D. Thesis c/o Politecnico di Milano, XIII Cycle, February 2001.
5. F. Castelli Dezza, A. Di Gerlando, G. Foglia, "Design of Scaled Prototypes of EMS Maglev Levitators, Based on an Improved Magnetic Modelling", accepted for publication in MAGLEV 2002 Proceedings.