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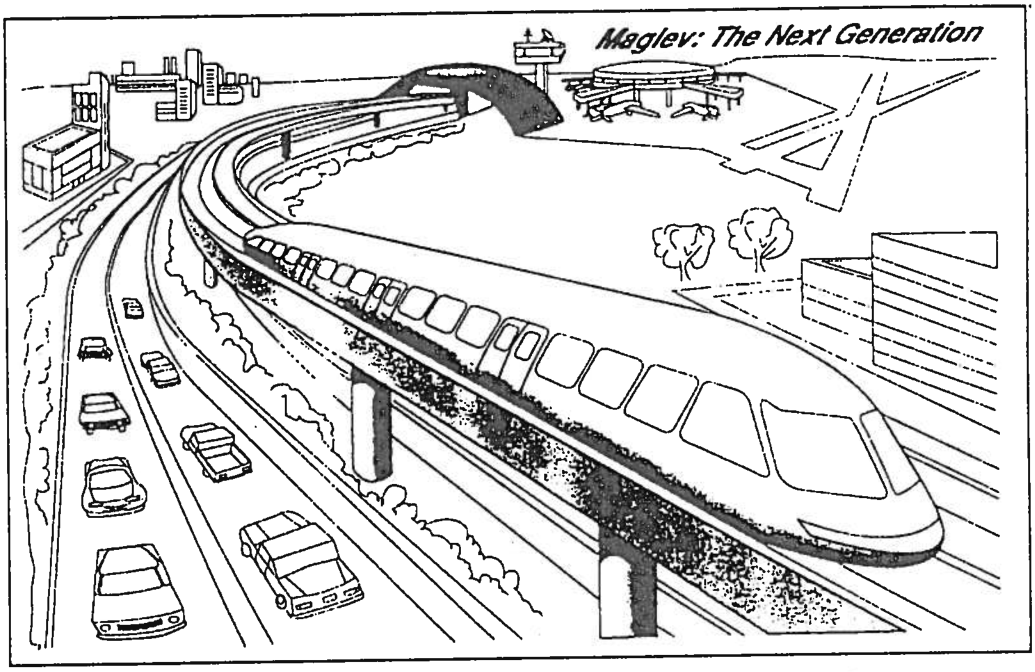
MAGLEV '93
13th INTERNATIONAL CONFERENCE ON MAGNETICALLY LEVITATED SYSTEMS AND LINEAR DRIVES

ARGONNE NATIONAL LABORATORY
ARGONNE, ILLINOIS, USA, 19-21 MAGGIO 1993

CONF - 930550



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MAY 19-21, 1993

Federal Railroad Administration

U.S. Army Corps of Engineers

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Design Problems of Linear on Board Generators in EMS MAGLEV Transportation Systems

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Abstract - The power needed for feeding the on board apparatus in the EMS MAGLEV systems is obtained by linear synchronous generators arranged in the field poles of the LSM.

In the present paper some operation aspects of these machines are studied, with the aim to analyze their design criteria: different topics are examined, in particular the interaction with the LSM operation, the winding configurations and a possible modular arrangement of the generation-conversion units.

I. INTRODUCTION

In the EMS Maglev vehicles equipped with long stator linear synchronous motor (LSM), the feeding of the excitation and guidance windings, together with that of the auxiliary services, requires an adequate level of the on board available power, that must be generated during the motion of the vehicle.
Among the different possibilities, till now only the solution consisting of a linear synchronous generator (LSG) has been studied and experimented: it is an electrical machine capable to obtain A.C. energy from the harmonic magnetic fields produced by the currents circulating in the LSM armature windings. This energy, suitably converted, is subsequently used for recharging the batteries and feeding the on board loads.

II. CALCULATION OF THE ELEMENTARY E.M.F.

The LSG, arranged in the LSM pole-pieces, is obtained by inserting suitable windings, sensitive to the harmonic m.m.f.s produced by the LSM armature currents. For studying the LSG, some simplifying hypotheses are assumed, that allow a handy design oriented analysis:

- the LSG armature currents are considered perfectly sinusoidal;
- the effects of the harmonic m.m.f.s are studied neglecting the presence of the teeth, except for the use of Carter's factors;
- the Fourier series of the m.m.f. waveforms is operated by assuming periodic shapes;
- the end effects are neglected.

In the following, all the quantities concerning the LSG construction and operation will be marked with the superscript ′.

Named v the synchronous speed, the speeds of the LSM armature harmonic m.m.f.s (measured in an armature reference frame) equal:

$$v_n = v/n = 2\cdot f\cdot \tau/n = 2\cdot f\cdot \tau_n \ , \qquad (1)$$

with n harmonic order, f feeding frequency, τ_n polar pitch of the n-th harmonic m.m.f..

Considerations regarding manufacture and operation aspects lead to construct a LSM armature winding characterized by unity values both of the N° q of slots per pole per phase and of the N° u of conductors in the slot; then all the harmonic m.m.f.s are tooth harmonics and their winding factors equal unity.
The harmonic orders of the LSM m.m.f.s equal:

$$n = 1 + 6\cdot k \ , \qquad k = \pm 1, \pm 2, \pm 3, \ldots ; \qquad (2)$$

from eq.(2), the positive values of n (7, 13, 19,...) correspond to harmonic m.m.f.s running in the same direction of the fundamental m.m.f., while the negative values (-5, -11, -17,...) correspond to harmonic m.m.f.s running in the opposite direction.
From (1), (2), the speed of the n-th m.m.f., measured with respect to the vehicle, equal:

$$v'_n = \frac{v}{n} - v = v\cdot\left(\frac{1-n}{n}\right) \ ; \qquad (3)$$

then the frequencies of the e.m.f.s induced in the armature of the LSG are given by:

$$f'_n = \left|\frac{v'_n}{2\cdot\tau_n}\right| = f\cdot|1-n| = 6\cdot f\cdot|k| \ . \qquad (4)$$

Eq.(4) shows the interesting result that the LSG "sees" the harmonic m.m.f.s, two by two, with the same frequency, multiple of a factor $|1-n|$ with respect to LSM feeding frequency. In particular, both the 5-th and the 7-th harmonic m.m.f.s induce e.m.f.s with frequency $f' = f'_5 = f'_7 = 6\cdot f$; the 11-th and 13-th harmonic m.m.f.s produce $f'_{11} = f'_{13} = 12\cdot f = 2\cdot f'$, and similarly for the higher harmonics.
Neglecting the presence of the teeth, the amplitude of the flux density due to the n-th harmonic m.m.f. is given by:

$$B_{nM} = \mu_0\cdot\frac{M_{nM}}{\delta} = \frac{\mu_0}{\delta}\ \frac{3\cdot\sqrt{2}}{\pi}\cdot\frac{I}{|n|} \ , \qquad (5)$$

and the corresponding flux per pole equals:

$$\Phi_n = \frac{2}{\pi}\cdot B_{nM}\cdot\tau_n\cdot\ell_c = \mu_0\cdot\frac{6\cdot\sqrt{2}}{\pi^2}\cdot\frac{\tau\cdot\ell_c}{\delta}\cdot\frac{I}{n^2} \ , \qquad (6)$$

with ℓ_c transversal width of the LSM (1 side).
Lastly, the e.m.f. induced in each of the 2 conductors forming a full pitch turn equals:

$$e'_n = \frac{\pi}{\sqrt{2}}\cdot f'_n\cdot\Phi_n = \frac{6\cdot\mu_0}{\pi}\cdot\frac{\tau\cdot\ell_c}{\delta}\cdot f\cdot I\cdot\frac{|1-n|}{n^2} \ . \qquad (7)$$

Observing eq.s (4) and (7), one can conclude that it is sufficient to study the LSG operation and design referring to the 5-th and 7-th harmonic m.m.f.s only.

Generally the phase harmonic e.m.f. equals:

$$E'_n = k'_{wn}\cdot U'\cdot e'_n \ , \qquad (8)$$

where k'_{wn} and U' are the winding factor and the number of conductors in series per phase.
From eq.(7), given the LSM and its operating conditions, the e.m.f. e'_n is determined: then, the choices regarding the LSG can affect the value of the other factors of eq.(8) only.

Manuscript received March 6, 1993.
Work supported by the Italian Research National Council (CNR) PFT2 Project; Contract N°92.01972.PF74.

III. CHOICE PROBLEMS OF LSG WINDINGS

A very important choice concerns the value of the coil pitch τ': to show its influence let consider fig.1. Named β the electrical angle between the magnetic axes of LSM inductor and armature, fig.1 refers to two particular operating conditions:

- alignment between magnetic axes of LSM inductor and armature (corresponding to $\beta=0$);
- time instant in which the current in the phase A of the LSM has the maximum value.

The 1-st condition will be removed in the following, showing the effects of angles $\beta\neq 0$. The 2-nd condition allows to represent easily the air-gap m.m.f. diagram and its fundamental, 5-th and 7-th harmonics: in any case the conclusions drawn for the e.m.f.s e'_5 and e'_7 have general validity, because these e.m.f.s have constant amplitude and same frequency.
The presence of only one turn having pitch τ', in symmetric position with respect to the field pole axis, allows to easily show the phasor composition of the two elementary e.m.f.s (e'_n) to give the turn e.m.f. (E'_{tn}).
Observing in fig.1 the disposition of the 5-th and 7-th harmonic m.m.f.s with respect to the LSG turn, one can deduce that the harmonic turn e.m.f.s (E'_{t5} and E'_{t7}) are two phasors opposed each other (the central halfwaves of the corresponding m.m.f.s are opposed).
The amplitude of each turn harmonic e.m.f. E'_{tn} depends on the value of τ': if we adopt a value τ' equal to the polar pitch τ_n of the n-th harmonic m.m.f., the turn e.m.f. equals the scalar sum of the e.m.f.s e'_n, because these e.m.f.s are in phase; of course, the choice of exploiting both the harmonics leads to adopt a coil pitch τ' within these limits:

$$\tau_7 < \tau' < \tau_5 \quad . \qquad (9)$$

From this, one obtains the phasor diagrams of fig.2: the phase angles γ_5 and γ_7 of the figure can be calculated by means of the following expression, for n=-5 and n=7:

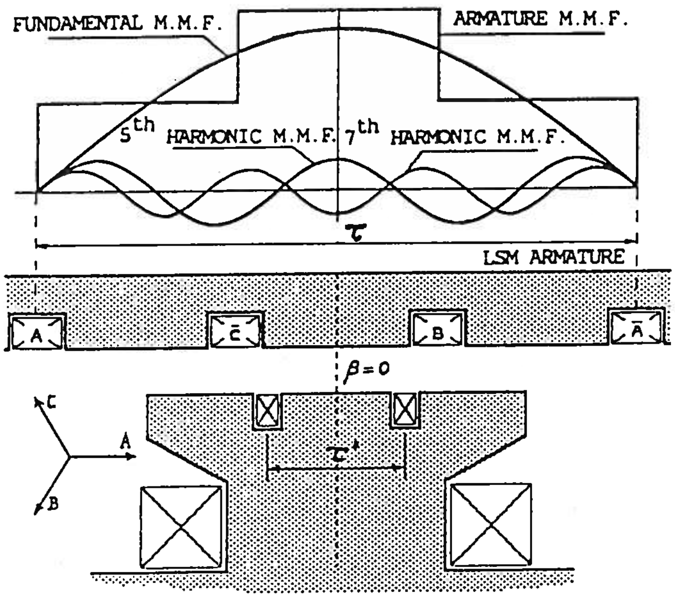


Fig.1. Alignment condition between the axes of the LSM armature m.m.f. and 1 LSG coil ($\beta=0$).

$$\gamma_n = \pi \cdot \frac{n}{|n|} \cdot \left(\frac{\tau' - \tau_n}{\tau_n} \right) \quad . \qquad (10)$$

By calculating the polar pitch factors ($k'_{\tau n}=E'_{tn}/(2\cdot e'_n)$), some particular values can be obtained, shown in Table I:

Table I
Polar pitch factor $k'_{\tau n}$ as a function of τ'/τ

τ'/τ	1/7	1/5	2/7
$k'_{\tau 5}$	0.901	1	0.782
$k'_{\tau 7}$	1	0.809	0

From Table I one can observe that:

- a coil pitch τ' equal to the polar pitch of the 7-th harmonic m.m.f. produces the maximum 7-th harmonic turn e.m.f. and reduces the 5-th harmonic e.m.f., and vice-versa;
- a pitch τ' equal to the double of the 7-th harmonic polar pitch cancels the corresponding e.m.f., heavily reducing also the 5-th harmonic e.m.f..

Considering the same configuration of fig.1 for $\beta>0$, one can realize that the 5-th and 7-th harmonic e.m.f.s are not opposed each other any more: this fact because, during the variation of β, the displacement angle β_n of the two harmonic m.m.f.s is different:

$$\beta_n = |n|\cdot\beta \quad . \qquad (11)$$

Then, the phase displacement between the 5-th and 7-th harmonic e.m.f.s equals:

$$\Delta\beta = \pi + \beta_7 - \beta_5 = \pi + 2\cdot\beta \quad , \qquad (12)$$

as shown in the phasor diagram of fig.3.
It is worth to notice that in fig.3 E'_5 and E'_7 indicate the winding e.m.f.s of one phase, considering that the angle β produces the same displacement both on the turn e.m.f. (E'_{tn}) and on the winding e.m.f. (E'_n).
From fig.3 one obtains the following expression for the amplitude of the winding e.m.f. E', resultant of the e.m.f.s E'_5 and E'_7:

$$E'=\sqrt{(E'_5)^2+(E'_7)^2+2\cdot(E'_5)\cdot(E'_7)\cdot\cos(\Delta\beta)} \quad . \qquad (13)$$

Before analyzing the different winding structures, it is worth to do some remarks regarding the choice between three-phase or single-phase armature winding:

- considering that there are no loads directly connected to the LSG terminals, the number of phases is not a constraint a priori;
- a three-phase generator produces, at the D.C. side of the rectifier, a harmonic pollution level that is lower compared with that of a single-phase generator;

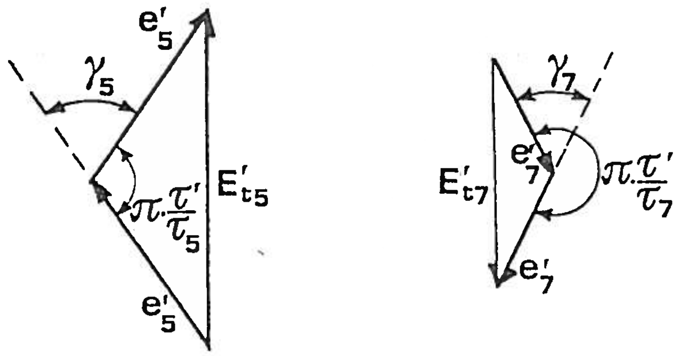


Fig.2. Phasor diagrams of the 5-th and 7-th harmonic e.m.f.s induced in the turn of fig.1.

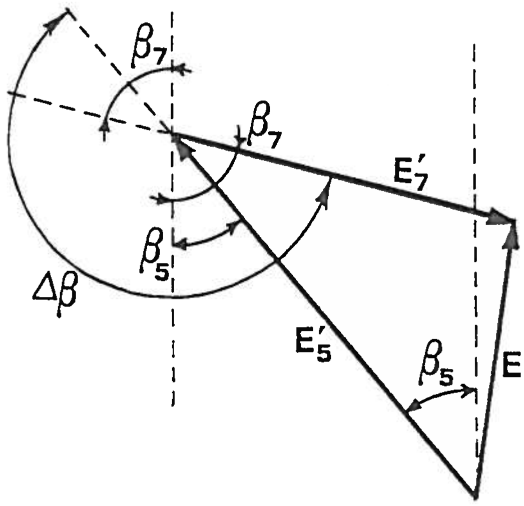


Fig.3. Sum of 5-th and 7-th harmonic e.m.f.s.

- on the other hand, the room requested by a three-phase winding is higher than that of a single-phase winding, and it can be difficult to arrange it in the LSM pole-pieces.

Moreover, in case of a three-phase LSG the two terns of e.m.f.s (due to the 5-th and 7-th harmonic m.m.f.s, running in opposite directions) have opposite cyclic sequence: then, in the harmonic composition there is an effect similar to that shown in fig.4.
The dissymmetry level depends on the ratio between the 7-th and 5-th harmonic e.m.f.s amplitudes and on the angle β (see eq.(12)).
In the choice of the coil pitch τ' for 3-phase LSG windings it is necessary to consider that:
- a value of τ' within the limits of eq.(9) is not acceptable for the dissimmetry: as a matter of fact, even if the LSG does not feed any 3-phase load, it would transfer the dissimmetry to the D.C. side of the rectifiers, producing there high levels of harmonics which are non-characteristic and, what is more, depend on the operating conditions;
- a pitch τ' that cancels the 7-th harmonic e.m.f. eliminates the dissimmetry, but implies a severe reduction of the 5-th harmonic e.m.f. (see 3-rd column of Table I).

In any case, the possible compromise choice, consisting in allowing a limited level of dissimmetry, does not eliminate the construction difficulties, due also to the problems of end winding crossings.

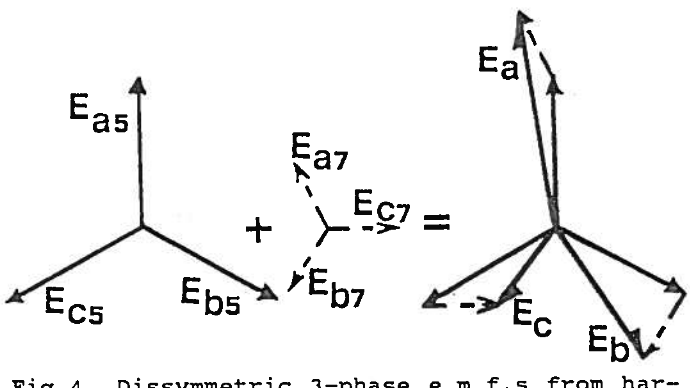


Fig.4. Dissymmetric 3-phase e.m.f.s from harmonic terns of opposite cyclic sequence.

IV. ANALYSIS OF SINGLE-PHASE WINDINGS

In the following the analysis of single-phase windings will be performed: these windings are intrinsecally easier to be constructed compared with three-phase windings.

The LSG is characterized by the presence of some active conductors, distributed along the air-gap surface of the LSM field poles: the choices of the number of these conductors, of their disposition in each field pole and of their series and parallel connections are conditioned by several elements:
- phase e.m.f. amplitude and its sensitiveness to the LSM operating conditions;
- construction problems of the windings;
- number of converters necessary for a good operation of the system, both in normal conditions and in case of partial failure (problem of the reserve);
- harmonic pollution of the rectified voltage.

The amplitude of the phase e.m.f. constitutes an important element for the choice: nevertheless, being equal the induced e.m.f., the configurations that better satisfy also the other exigences are to be preferred.
Given a single-phase winding with p' poles, q' slot per pole, u' conductors per slot, U' conductors connected in series ($U'=u'\cdot q'\cdot p'$), the winding factor (k'_{wn}) that appears in eq.(8) can be expressed as a product between a distribution factor (k'_{dn}) multiplied by a polar pitch factor ($k'_{\tau n}$).
For a structure uniformly toothed, the two factors have the following expressions:

$$k'_{dn}=\frac{\sin\left(\frac{\pi}{2}\cdot\frac{\tau'}{\tau_n}\right)}{q'\cdot\sin\left(\frac{\pi}{2\cdot q'}\cdot\frac{\tau'}{\tau_n}\right)}\ ;\ k'_{\tau n}=\frac{\sin\left(p'\cdot\frac{\gamma_n}{2}\right)}{p'\cdot\sin\left(\frac{\gamma_n}{2}\right)}\ ,\qquad (14)$$

with γ_n given again by eq.(10).
As regards the expressions for the harmonic elementary e.m.f.s (e'_n), the phase e.m.f.s (E'_n), the phase displacement between the harmonics ($\Delta\beta$) and their resultant (E'), eq.s (7), (8), (12), (13) are still valid.

In order to perform a homogeneous analysis of the different winding configurations, the following comparison conditions are considered:
- reference is made to the theoretical no-load values of the rectified voltage (E'_{od}) instead of the RMS values of the phase e.m.f. (E'); as known, for single-phase rectifiers we have:

$$E'_{od}=\frac{2\cdot\sqrt{2}}{\pi}\cdot E'\ ;\qquad (15)$$

- the same total number of conductors U', disposed in each field pole, is adopted.

The first hypothesis allows to extend the comparison also to those cases in which there are more than one winding portions within each field pole, and the series connection of these portions is made at the D.C. side of the rectifiers; the second condition allows a comparison being equal the number of active conductors, and it is intended in a generalized sense, even in case of more than one winding portion disposed within each LSM field pole.
The only elements that can be modified in order to obtain different values of E'_{od} are the following:
- the subdivision of the winding;

- the winding factor, by the choice of p′, q′, τ′.

The maximum allowed N° of poles of the LSG winding is limited by the length of the field pole (roughly equal to $2\cdot\tau/3$): the analysis showed that it is practically impossible to adopt a p′ value more than 4, also in order not to reduce the pitch τ′ excessively.

By observing the 1-st eq. of (14), one can realize that the highest values of the winding factor can be obtained for q′=1, because the distribution factor becomes unity.

By studying different kinds of windings the following general characteristics have been deduced:

- in the range of practical interest of the LSM angle β (60° ≤ β ≤ 120°), during the increasing of the coil pitch τ′, at first the function $E_{od}(\beta,\tau')$ increases, then decreases, with a maximum occurring for a τ′ value depending on the winding type;
- the voltage E'_{od} is an even function, with respect to the position $\beta=\pi/2$ (equal to the angle for which the maximum occurs).

In order to estimate the characteristics of the different winding types, it is necessary to make reference to the data of a real EMS MAGLEV system. To this end, starting from some constructed prototypes (e.g. the Transrapid 06, studied in Emsland, Germany), a general design of the LSM has been performed: to the corresponding main data, shown in Table II, the subsequent results will be referred.

Table II
General data of the LSM considered for the study of the LSG of an EMS MAGLEV system

Operation data:	
maximum speed	v = 415 km/h
maximum inverter frequency	f = 225 Hz
maximum thrust	F_x = 40 kN
rated armature current	I = 635 A $_{RMS}$
air gap flux density	B_f = 0.63 T
Construction data:	
mass of the vehicle	$M = 1.2\cdot10^5$ kg
Total N° of poles (per side)	p = 102
N° of poles of each magnetic unit	p_u = 6
air gap	δ = 10 mm
field pole transversal length	ℓ_e = 220 mm
polar pitch	τ = 255 mm

In fig.5 the schemes of some studied windings are shown, together with their synthetic description: an analysis of their characteristics helps to conveniently choose one of the types. For now, just the winding disposed within one LSM field pole will be considered.

In fig.6 the amplitudes of the no-load rectified voltage E'_{od} are shown, as a function of the angle β, for the 6 cases of fig.5; in Table III the values of the ratio τ′/τ are shown, corresponding (for $\beta=\pi/2$) to the maximum of the rectified voltage, together with the value of this maximum ($E'_{od(max)}$).

Table III
Values of the ratio τ′/τ corresponding to the maximum of the no-load rectified voltage E'_{od}, for $\beta = \pi/2$ and for the 6 cases of fig.s 5, 6 (Total number of conductors: U′=8).

CASE N°	1	2	3	4	5	6
τ′/τ	.167	.173	.173	.127	.155	.171
$E'_{od(max)}$ [V]	3.07	4.23	4.19	3.47	4.30	4.82

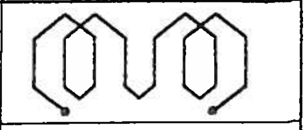
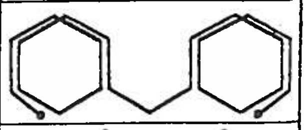
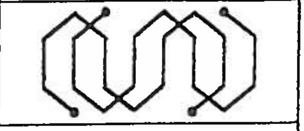
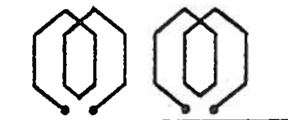
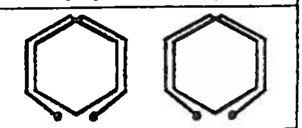
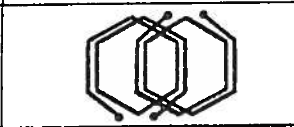
TYPE OF SINGLE-PHASE WINDING	WINDING SCHEME
CASE 1 SINGLE EXTENDED WINDING p′=4 ; q′=2 ; u′=1 ONE RECTIFIER	
CASE 2 SINGLE EXTENDED WINDING p′=4 ; q′=1 ; u′=2 ONE RECTIFIER	
CASE 3 DOUBLE EXTENDED WINDING 2 x (p′=4 ; q′=1 ; u′=1) TWO RECTIFIERS	
CASE 4 DOUBLE WINDING WITH 2 COILS 2 x (p′=2 ; q′=2 ; u′=1) TWO RECTIFIERS	
CASE 5 DOUBLE WINDING WITH 2 COILS 2 x (p′=2 ; q′=1 ; u′=2) TWO RECTIFIERS	
CASE 6 CROSSED DOUBLE WINDING 2 x (p′=2 ; q′=1 ; u′=2) TWO RECTIFIERS	

Fig.5. Synthetic description and schemes of some LSG single-phase windings (U′=8).

1st Case: single extended winding with p′=4; q′=2; u′=1.

It is a winding with slots uniformly distributed along the LSM field pole.

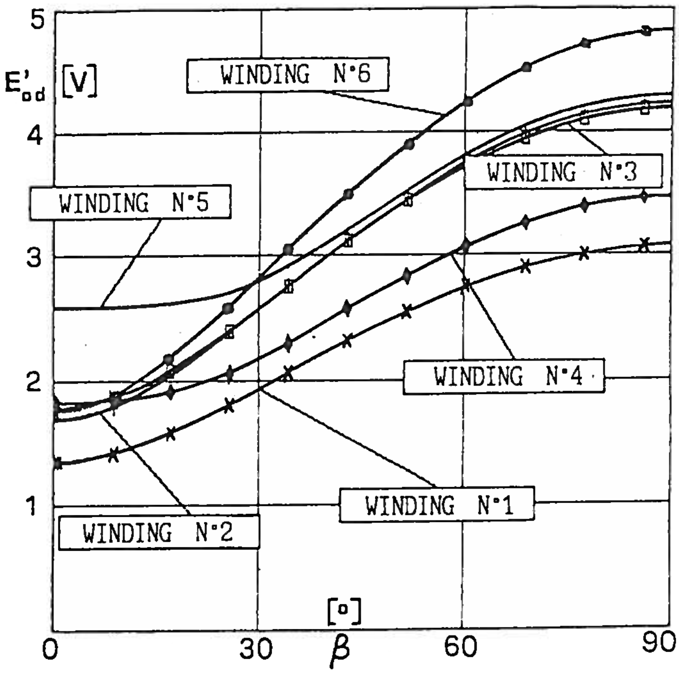


Fig.6. No-load rectified voltages E'_{od} of the 6 windings of fig.5, as a function of β.

An interesting remark concerns the value of the coil pitch τ' for which the maximum of E'_{od} occurs: it is exactly the intermediate value between the polar pitch of the 5-th and the 7-th harmonic m.m.f.s.
The low value of the rectified voltage (the lowest among the 6 shown cases), together with the constructional complications of two end winding crossings, suggest that the adoption of the structure N° 1 is not convenient.

2nd Case: single extended winding with $p'=4;\ q'=1;\ u'=2$.

It is a winding having a number of slots halved compared with those of case 1, again uniformly distributed: in confirmation of what already observed as regards the distribution factor (k'_{dn}), concentrating the active sides of one pole in the same slot leads to increase the value of the rectified voltage.
Another element in favour of this winding is the absence of end winding crossings.

3rd Case: double extended winding with $2\cdot(p'=4;q'=1;\ u'=1)$.

The conductors are arranged in the same slot structure of case 1, but they are connected in such a way to form 2 distinct windings, whose voltages are separately rectified and added at the D.C. side of the rectifiers.
This subdivision partially reduces the negative effect of the phase displacement between the elementary e.m.f.s: then an improvement occurs, compared with case 1, with an increase of the voltage $E'_{od(max)}$; nevertheless, this voltage remains lower than that of case 2; moreover, it requires the doubling of the N° of the rectifiers and, above all, implies a high N° of end winding crossings, with the corresponding constructional complications.

4th Case: double coil winding with $2\cdot(p'=2;q'=2;u'=1)$.

It shows a different connection among the conductors, arranged in the same structure of case 1, from which it is evident the origin, based on a simple central separation.
In this case the increase of the rectified voltage, pursued by the subdivision of the winding into two portions, implies the halving of the number of end winding crossings of case 3, but the amplitude of $E'_{od(max)}$, compared with that of case 2, makes this solution not particularly interesting.

5th Case: double coil winding with $2\cdot(p'=2;q'=1;u'=2)$.

This structure represents the natural evolution of case 2, from which it is obtained by subdividing the winding in the central zone: similarly to case 2, it has the advantage of the absence of crossings.
In case of coil active sides arranged in uniformly distributed slots, the rectified voltage value is slightly higher compared with that of case 2, but with respect to this case, the number of necessary rectifiers is double.

6th Case: crossed double winding with $2\cdot(p'=2;q'=1;u'=2)$.

This disposition can be considered derived from the previous one, by approaching and intersecting the two coils, up to obtaining a sequence of uniformly distributed active sides: this transformation leads to an important increase of the rectified voltage amplitude (it is the highest among the 6 cases).

On the other hand, this kind of winding implies serious constructional difficulties: here, the problem of the end winding crossings, considered important for some of the previous cases, is much more worsened by the simultaneous crossing of four end windings for each field pole front.

The previous analysis leads to recognize that the configurations of cases 2 and 5 are globally more valid, both in operational and in constructional terms: however the disposition of case 5 allows further improvement opportunities.
As a matter of fact, applying to the configuration of case 5 the idea of approaching the two coils, without reaching their crossing, it is possible to obtain the disposition represented in fig.7: the winding has the same winding data of case 5, but the two coils have the adjacent sides arranged in the same central slot. This slot has a double width compared with that of the slots at the opposite extremes of the LSM field pole.
The winding represented in fig.7 can be called "double winding with adjacent coils".

For a correct evaluation of this winding it is opportune to take into account the effective room requested by the active sides, as shown in fig.7: then, told b'_c the width of the slots in the extreme positions of the pole (for the central slot, b'_c is the distance between the axes of two adjacent active sides), the middle of the coils is at a distance

$$y = 0.5\cdot(\tau'+b'_c)$$

from the polar axis of the field pole.
Modifying the b'_c value (to be defined during the LSG design) changes the position of the coils and varies the rectified voltage; the values of $E'_{od(max)}$ are shown in Table IV for 3 possible values of b'_c (and for $\beta=\pi/2$): in all the cases, the coil pitch τ' corresponding to the maximum value of E'_{od} is equal to 1/6 of the polar pitch τ.

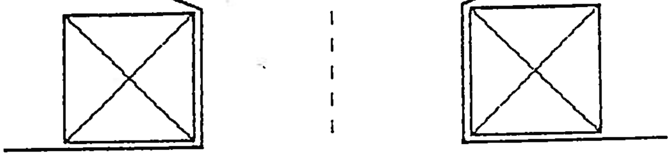


Fig.7. Double single-phase winding with adjacent coils arranged in three slots.

Table IV
Maximum values of the rectified voltage $E'_{od(max)}$ of a double winding with adjacent coils, as a function of the slot width b'_c; coil pitch: $\tau' = 42.5$ mm $= \tau/6$.

b'_c	[mm]	10	20	30
$E'_{od(max)}$	[V]	4.63	4.53	4.43

From the previous analysis one can conclude that:
- the double winding with adjacent coils can generate values of rectified voltage having interesting levels, of the order of those obtainable with the double winding with crossed coils (case 6);
- quite wide variations of slot width b'_c implies low variations of E'_{od};
- the winding is easy to be manufactured.

In conclusion, this winding seems to be the best one among the different examined single-phase windings.
As regard the dependence on the LSM operation quantities (β, f, I), the following expression is valid:

$$E'_{od} = K_e(\beta)\cdot f\cdot I \quad . \qquad (16)$$

Chosen the traction diagram, consisting of a first part with constant thrust and a second part with constant power, it follows that E'_{od} linearly grows in the first part (up to 50 m/s roughly), and then it remains practically constant in the other part; moreover, the study shows that β affects quite weakly the voltage E'_{od}.
This behaviour is favourable to the dimensioning of the battery and of the on board generator system.

V. THE GENERATION-CONVERSION MODULES OF THE LSG SYSTEMS

A suitable configuration of the LSG system implies the use of several modules in parallel, each of the kind represented in fig.8; the characteristics of the module are the following:
- every electrical unit G contains all the fore (or hinder) series connected coils of each magnetic unit;
- among all the units G of one module, those equipped with fore coils are paralleled to the input of one rectifier, while the units with hinder coils are paralleled to the input of the other rectifier;
- the outputs of the two rectifiers of each module are series connected and sent to a step-up chopper.

This modular structure allows:
- operation in case of failure of one module;
- reduction of the D.C. side harmonic pollution, thanks to the series connection of the rectifiers;
- decoupling of the voltage level of the high voltage D.C. bar from the level of the units.

VI. CONCLUSIONS

In this paper some design problems regarding the linear on board generators of the EMS MAGLEV systems have been discussed. The analysis concerned:

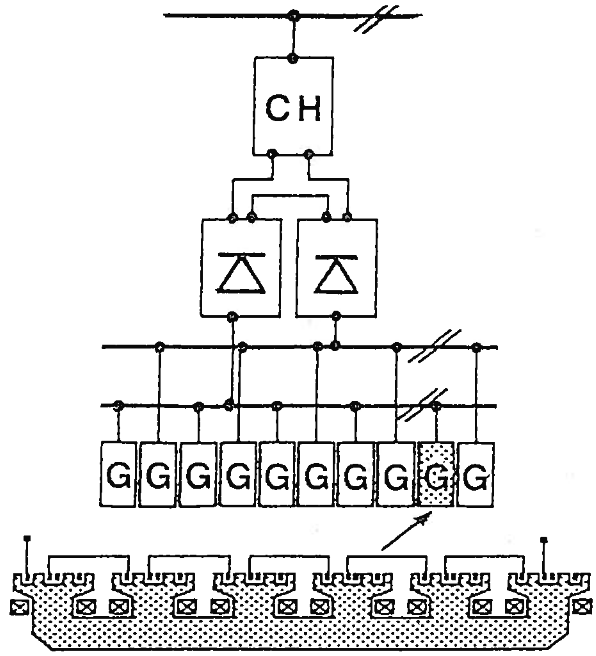


Fig. 8. Scheme of one LSG generation-conversion module (G) and detail of one magnetic unit equipped with fore series connected coils.

- the characteristics of the LSM harmonic m.m.f.s;
- the LSG elementary and winding e.m.f. amplitudes and phases;
- the choice between three-phase or single-phase windings;
- the distribution and connection of the LSG active sides;
- the structure of the generation-conversion modules.

The studies will go on, according to different research lines:
- winding configurations of the LSG;
- improvement of the model for studying the operation;
- choices regarding the conversion devices.

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