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ICEM 96
INTERNATIONAL CONFERENCE ON
ELECTRICAL MACHINES

VIGO, SPAGNA, 10-12 SETTEMBRE 1996

ICEM96 Proceedings

Volume II

International Conference on Electrical Machines

10^{th}-12^{th} September, 1996

Organised by the Vigo Electrical Machines Research Group

ETSEM - Universidade de Vigo- S P A I N

DESIGN AND EXPERIMENTAL ANALYSIS OF ON-BOARD PROBE WINDINGS FOR THE STATOR ON-LINE DIAGNOSTICS OF EMS MAGLEV SYSTEMS

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Abstract
The implementation and the use of devices for on-line diagnostics, suited to timely detect circumstances of incoming faults, is essential in order to ensure service continuity and reliability in the Maglev systems.
The description and the application of a method suited to locate anomalous operating conditions in the stator windings of a Maglev system with attractive levitation (EMS) is proposed, based on the measurement of the stator currents unbalance, performed via electromagnetic induction in on-board probe windings.

Keywords
Maglev, stator winding diagnostics, design and experimental tests of on-board probe windings.

Introduction

The availability of apparatuses for the on-line diagnostics is a fundamental feature of Maglev transportation systems, that minimises the risks of unexpected faults and the maintenance costs, ensuring transport safety and reliability; these goals have utmost importance, also for the need to make Maglev competitive compared with other high speed conventional systems.
To this aim, an automatic system for the preventive maintenance (that allows a real time monitoring during the service, the on-board processing of the collected data and their transmission to the station receivers) is needed. Certainly, for a long time a lot of resources have been oriented in this direction: nevertheless, the related literature is poor, maybe because of industrial security reasons.
The problems of the diagnostics in the Maglev systems are complicated and different, also implying important technological aspects. This paper analyses some method points of view, with limited reference to the electrical diagnostics of the stator guideway, that anyway represents an important subsystem, being distributed all along the line and particularly subjected to fault risks.
The possibility to detect anomalous operating conditions of the stator windings by detecting the phase current unbalance, by means of suited on-board probe windings, is investigated: the operating modes of these windings, together with their design and compatibility with the system features, are analysed.
In their basic version, these windings consist of single coils, made with thin wires, located in two slots towards the air gap, along the pole shoes of both the vehicle sides.
Under unbalanced stator currents conditions extra harmonic m.m.f.s are generated in the air-gap: these m.m.f.s induce in the probe coils e.m.f.s (non existent in the balanced operation) that give an index of the unbalance.
The remarks that make this method better than a simple three-phase current measurement in the feeding substations are the following:
- the substation inverters are regulated to feed the active guideway sections with balanced currents: if these inverters operate correctly, they actually deliver three balanced currents; thus, the current measurement in the substations does not allow any direct check of the currents actually flowing in the guideway;
- in case of degradation of the stator winding insulation, a local, even small, phase current unbalance can occur, without any possibility to detect this anomalous condition by the ground monitoring system: nevertheless, this unbalance is an important index of an incoming damage and, if it is not detected and eliminated, it can lead to more serious faults;
- the use of an on-board probe winding, suited to act a magnetic detection of local unbalance conditions, allows a timely identification of a beginning fault.

In the paper, some operation and design aspects concerning the probe winding are analysed:
- decomposition of the stator currents into symmetrical components and evaluation of their induced e.m.f.s;
- choice of the harmonic e.m.f. as an unbalance index and choice of the probe winding pitch;
- analysis of the influence of the stator teeth, of the on-board linear generator and of the distortion of the inverter supply currents on the diagnostic signal.

Some tests on a prototype complete the analysis.

Work supported by the Italian Research National Council (CNR)

M.m.f. harmonic fields and elementary e.m.f.s

The beginning study is made under these hypotheses:
- the linear synchronous motor (LSM) has a salient-pole structure and a 3-phase winding with q=1 slot/(pole-phase) (fig.1): the winding factor for all the harmonics and the N° of conductors/slot equal unity: thus the N° of conductors/section equals the N° of poles;

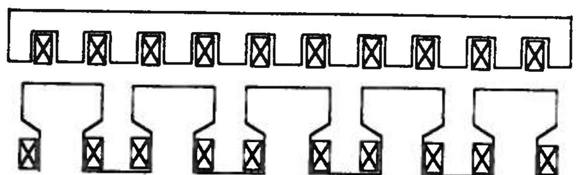

Fig.1 - Structure of the active part of an EMS Maglev system, with a stator winding with q = 1 slot/(pole-phase) and field-levitation poles disposed on-board.

- the higher order time harmonics of the stator current are neglected; i.e. just the fundamental current components delivered by the PWM inverters are considered;
- the steady state operation is supposed: the transient situations, with instantaneous current unbalance, could be wrongly interpreted as fault conditions, and thus the monitoring system must be in stand-by during the vehicle starts and stops;
- the magnetic voltage drops in the ferromagnetic branches are neglected: for levitation safety and control, the flux density in the core is low; thus, there is a linear link between fluxes and m.m.f.s acting in the air-gap;
- the longitudinal end effects can be neglected, thanks to the high number of on-board pole shoes.

Harmonic m.m.f. fields in the air-gap

As known, the relationship between the LSM pole pitch τ_s, the vehicle speed (v_s) and the stator frequency (f_s) is:

$$v_s = 2 \cdot f_s \cdot \tau_s . \quad (1)$$

In balanced conditions with currents whose RMS value is I, there is a running field in the air-gap with only one fundamental m.m.f., synchronous with the vehicle; its harmonic fields (all tooth harmonic fields) have order:

$$h = 1 + 6 \cdot k , \quad k = 0, \pm 1, \pm 2, \dots , \quad (2)$$

and amplitudes: $$\hat{M}_h = \left(3 \cdot \sqrt{2}/\pi\right) \cdot I/|h| \quad . \quad (3)$$

The speed of the h^{th} field as regards the stator equals:

$$v_{s_h} = v_s/h = 2 \cdot f_s \cdot \tau_s/h = 2 \cdot f_s \cdot \tau_{s_h} , \quad (4)$$

with v_s fundamental field speed as regards the stator.
The fields with orders h = 7, 13, 19, ... travel in the running way of the fundamental field, while the fields with order h = −5, −11, −17, ... travel in the opposite way.
The speed v_h of the h^{th} field as regards the vehicle is:

$$v_h = v_{s_h} - v_s = v_s \cdot (1-h)/h . \quad (5)$$

Each active conductor disposed on the on-board pole shoes sees the harmonic fields running with frequency:

$$f_h = \left|v_h/(2 \cdot \tau_{s_h})\right| = \left|v_h/(2 \cdot \tau_s/h)\right| = f_s \cdot |6 \cdot k| . \quad (6)$$

This conductor sees the stator m.m.f.s two by two with the same frequency, multiple of a factor |1−h| of the stator frequency: thus, the 5^{th} and 7^{th} order m.m.f.s produce $6 \cdot f_s$ frequency e.m.f.s, the 11^{th} and 13^{th} order m.m.f.s produce $12 \cdot f_s$ frequency e.m.f.s, and so on [1].

If the stator currents are unbalanced, they can be decomposed into three terns: homopolar, direct and inverse. The presence or not of the homopolar tern depend on the system configuration pattern and on the fault type; in any case, considering that these homopolar current components produce a zero m.m.f. in the air-gap, their presence has no influence on the unbalance detection method.

The direct and inverse terns have current phasors with opposite cyclic sense, and then their fundamental m.m.f. fields run in opposite directions in the air-gap; each tern produces harmonic m.m.f.s with orders h = 1 + 6·k.
If the vehicle running direction is considered positive in accordance with the direction of the fundamental field of the direct tern, the fields with orders h = +7, +13, +19, ... of the inverse tern run in the opposite sense of the fundamental field; vice versa, the fields with h = −5, −11, −17, ... run in the same sense of the fundamental field.
The speed of the h^{th} harmonic m.m.f. produced by the inverse tern, measured referred to the vehicle, is given by:

$$v_h = -v_s/h - v_s = -v_s \cdot (1+h)/h ; \quad (7)$$

the frequency of the on-board induced e.m.f.s equals:

$$f_h = \left|v_h/(2 \cdot \tau_{s_h})\right| = \left|v_h/(2 \cdot \tau_s/h)\right| = f_s \cdot |2 + 6 \cdot k| . \quad (8)$$

Thus, when varying k, the following frequencies occur:

$$\begin{aligned} f_h/f_s &= 2,\ 8,\ 14,\ \dots \quad \text{for } k = 0,\ +1,\ +2, \dots \\ f_h/f_s &= 4,\ 10,\ 16,\ \dots \quad \text{for } k = -1,\ -2,\ -3, \dots \end{aligned} \quad (9)$$

Two important differences between (9) and (6) are:
- the fundamental field of the inverse tern induces a double frequency e.m.f.; the direct sequence field, synchronous with the vehicle, does not produce any e.m.f.;
- the pair of values ±k of the inverse tern does not produce two e.m.f.s with equal frequency.

On-board elementary harmonic e.m.f.s

The harmonic e.m.f. e_h in each active conductor long ℓ_e (transversal width of the lamination stack) is given by:

$$e_h = \ell_e \cdot v_h \cdot \hat{B}_h/\sqrt{2} \quad (10)$$

where, by neglecting the presence of the teeth, $\hat{B}_h$ equals:

$$\hat{B}_h = \mu_o \cdot \hat{M}_h/\delta = \left[\left(3 \cdot \sqrt{2} \cdot \mu_o\right)/(\pi \cdot \delta)\right] \cdot I/|h| \quad (11)$$

where δ is the LSM air-gap. Thus, eq.(10) becomes:

$$e_h = \left(6 \cdot \mu_o \cdot \tau_s \cdot \ell_e/(\pi \cdot \delta)\right) \cdot I \cdot f_h/h^2 = K_e \cdot I \cdot f_h/h^2 . \quad (12)$$

For a given system, K_e can be considered constant.
If we distinguish the harmonics due to the direct (I_d) and to the inverse (I_i) current tern, we have (h=h(k), see (2)):

$$e_{d_h} = K_e \cdot I_d \cdot f_s \cdot \alpha_d(k) \ ; \ e_{i_h} = K_e \cdot I_i \cdot f_s \cdot \alpha_i(k), \text{ with} \quad (13)$$

$$\alpha_d(k) = 6 \cdot |k|/(1+6 \cdot k)^2 , \ \alpha_i(k) = |2 + 6 \cdot k|/(1+6 \cdot k)^2 . \quad (14)$$

The analysis of the e.m.f. coefficients $\alpha_d(k)$ and $\alpha_i(k)$ allows to compare the harmonic e.m.f. amplitudes; their values are given in Table I, for the lower order e.m.f.s.

Table I - Frequencies and induced e.m.f. coefficients due to the direct and to the inverse terns of the stator currents.

k	h_d, h_i	f_{dh}/f_s	$\alpha_d(k)$	f_{ih}/f_s	$\alpha_i(k)$
0	+1	0	0.000	2	2.000
−1	−5	6	0.240	4	0.160
+1	+7	6	0.122	8	0.163
−2	−11	12	0.099	10	0.083
+2	+13	12	0.071	14	0.083
−3	−17	18	0.062	16	0.055
+3	+19	18	0.050	20	0.055

The highest amplitude e.m.f.s of the direct tern are those with frequency $6 \cdot f_s$ (induced by the 5^{th} and 7^{th} order m.m.f.s); for the inverse tern, the prevailing induced e.m.f. is that with frequency $2 \cdot f_s$.
Assumed as a reference the rated current of the LSM,

$$I_{dpu} = I_d/I_n \qquad I_{ipu} = I_i/I_n \quad (15)$$

are the p.u. values of the direct and inverse currents.
On the other hand, for the 2^{nd} of eq.s(15), we can write:

$$I_{ipu} = (I_i/I_d) \cdot I_{dpu} = \rho_i \cdot I_{dpu} \quad ; \quad (16)$$

ρ_i is the unbalance factor; I_{dpu} indicates the load condition of the LSM, while I_{ipu}, proportional to ρ_i, is the index of the anomalous operation of the stator winding.
Thus, the harmonic e.m.f.s can be expressed as follows:

$$e_{d_h} = K_e \cdot f_s \cdot I_n \cdot \alpha_d(k) \cdot I_{dpu} \quad , \quad (17)$$

$$e_{i_h} = K_e \cdot f_s \cdot I_n \cdot \alpha_i(k) \cdot I_{ipu} \quad ; \quad (18)$$

considering that the factor $K_e \cdot f_s \cdot I_n$ is in common, the harmonic e.m.f.s due to the direct and inverse terns can be compared by means of their e.m.f. coefficients.
Only a complete knowledge of the system (relating type and severity of the anomalous operation with the current unbalance level) can allow to establish which is the minimum unbalance value for which a stator winding fault can be considered imminent: the present analysis will be limited to show the link between the unbalance level and the diagnostic signal obtainable by the probe winding.

Operation and design of the probe winding

The h^{th} e.m.f. induced in the probe winding equals:

$$E_h = 2 \cdot N_t \cdot e_h \cdot k_{w_h} \quad , \quad (19)$$

where N_t is the N° of turns of the winding and k_{w_h} the winding factor for the h^{th} harmonic, in this case given by:

$$k_{w_h} = \sin\left(h \cdot (\pi/2) \cdot (\tau/\tau_s)\right) . \quad (20)$$

where τ is the coil pitch of the only coil of the winding.
If $$\hat{\tau} = \tau/\tau_s \quad (21)$$
is the pitch of the probe winding, expressed in p.u., referred to the LSM polar pitch τ_s, the e.m.f.s induced by

the harmonic m.m.f.s have amplitudes depending on the pitch $\dot{\tau}$; from the previous expressions we obtain:

$$E_i(k, I_{ipu}, \dot{\tau}) = 2 \cdot N_t \cdot e_{i_h} \cdot \left|\sin\left(\pi \cdot \dot{\tau} \cdot |1+6 \cdot k|/2\right)\right|$$
$$E_d(k, I_{dpu}, \dot{\tau}) = 2 \cdot N_t \cdot e_{d_h} \cdot \left|\sin\left(\pi \cdot \dot{\tau} \cdot |1+6 \cdot k|/2\right)\right| \quad (22)$$

Eqs. (20) and (22) show that the harmonic e.m.f.s are zero (maximum) for τ equal to a even (odd) multiple of the polar pitch $\tau_{sh}=\tau_s/h$ of the inducing harmonic m.m.f..
Fig.2a shows the amplitudes of the harmonic e.m.f.s E_i induced in the probe winding by the inverse current tern for h = –5, +1, +7 (i.e. k = –1, 0, +1) and I_{ipu} = 0.1, as a function of $\dot{\tau}$; the e.m.f.s are in p.u., referred to the quantity $N_t \cdot K_e \cdot f_s \cdot I_n$; fig.2b shows the e.m.f.s E_d induced by the direct current tern, for h = –5,+7 (k= –1, +1), with I_{dpu} = 1.

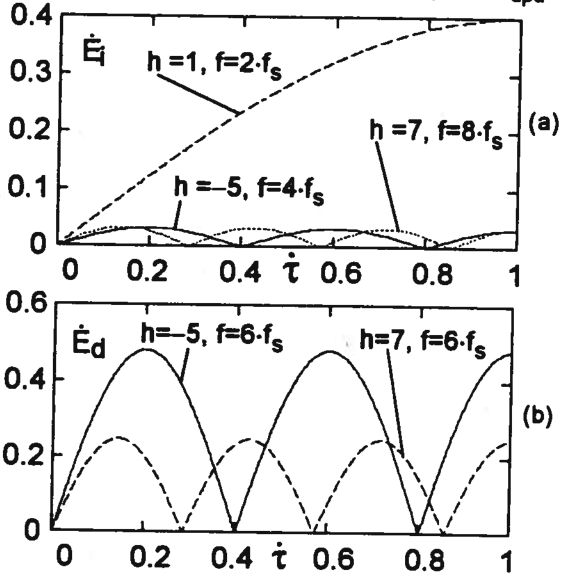

Fig.2 - Amplitude (in p.u., referred to $N_t \cdot K_e \cdot f_s \cdot I_n$) of the probe winding e.m.f.s induced by the stator m.m.f.s of the direct and inverse tern currents, as a function of $\dot{\tau}$:
(a): e.m.f.s E_i induced by fundamental (h=+1) and harmonic (h=–5,+7) m.m.f.s of the inverse tern currents, I_{ipu}=0.1; (b): e.m.f.s E_d induced by the harmonic m.m.f.s (h = –5, +7) of the direct tern currents, for I_{dpu}=1.

Fig.2 suggests the following considerations:
- for the e.m.f.s induced by the m.m.f.s with order h=+7:
  - the e.m.f. with $f=8 \cdot f_s$ due to the inverse tern is zero for the same τ values the make zero the e.m.f. with $f=6 \cdot f_s$ of the direct tern (multiples even of $\tau_s/7$);
  - these e.m.f.s are maxima for τ odd multiple of $\tau_s/7$.
- similar remarks can be made for zeros and maxima of the e.m.f.s generated by the m.m.f.s with order h= –5;
- the harmonic e.m.f. with $f=2 \cdot f_s$ induced by the fundamental m.m.f. (h=1) of the inverse tern of currents is always different from zero and grows with τ.

In conclusion, the 2nd harmonic e.m.f. is the key element for the detection of a stator current unbalance, sign of an anomalous operation of the stator windings.

The pitch τ must satisfy the following requirements:
- the 2nd harmonic e.m.f. signal must be clearly detected by a spectrum analyser: to this aim, it is necessary that the amplitudes of the higher harmonic e.m.f.s be reduced as much as possible;
- the value of τ must be compatible with the constructional and functional constraints of the system.

In order to help the choice of τ it is useful to analyse the dependence of the following quantities on $\dot{\tau}$:
- ratios $E_{i(4)}/E_{i(2)}$ and $E_{i(8)}/E_{i(2)}$ between the e.m.f.s with $f=4 \cdot f_s$ and $f=8 \cdot f_s$ and the e.m.f. with $f=2 \cdot f_s$, due to the inverse tern;
- ratio $E_{d(6)}/E_{i(2)}$ between 6th and 2nd harmonic e.m.f.s.

Fig.3 shows $E_{i(4)}/E_{i(2)}$ and $E_{i(8)}/E_{i(2)}$, for I_{ipu}=0.1.

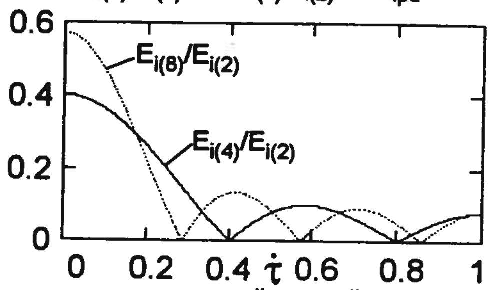

Fig.3 - Ratio between the 4th and 8th harmonic e.m.f.s and the 2nd harmonic e.m.f., as a function of the p.u. probe winding pitch $\dot{\tau}$, for I_{ipu}=0.1 .

Fig.3 suggests that, for each value of $\dot{\tau}$, the 8th and 4th harmonic e.m.f.s are lower than the 2nd harmonic e.m.f., but a pitch value that simultaneously makes zero both these higher order harmonic e.m.f.s does not exist.

As regards the direct tern, for each value of k there are harmonic e.m.f. components with the same frequency; here only the 6th order harmonic e.m.f. components are considered (prevailing), induced by the m.m.f.s with h= –5 e h= +7 generated by the direct tern currents: in order to distinguish them on the basis on the corresponding m.m.f., these e.m.f.s will be indicated by $E_{d[5]}$ and $E_{d[7]}$.
On the basis of the LSM vector diagram, called β the angle between stator and field current vectors, it can be shown that [1], when varying β, the elementary e.m.f.s in each active conductor have a phase shift given by:

$$\beta_h = \beta \cdot |h| \; ; \quad (23)$$

thus the phase shift $\Delta\beta$ between $E_{d[5]}$ and $E_{d[7]}$ equals:

$$\Delta\beta = \pi + \beta_7 - \beta_5 = \pi + 2 \cdot \beta \; . \quad (24)$$

The phasor sum of the two e.m.f.s has amplitude:

$$E_{d(6)} = \sqrt{E^2_{d[5]} + E^2_{d[7]} + 2 \cdot E_{d[5]} \cdot E_{d[7]} \cdot \cos(\Delta\beta)} \, . \quad (25)$$

The maximum value $E_{dM(6)}$ of $E_{d(6)}$ verifies for $\beta=\pi/2$, when $E_{d[5]}$ and $E_{d[7]}$ are in phase (prudent condition).
Fig.4 shows the ratio $E_{dM(6)}/E_{i(2)}$ as a function of the pitch $\dot{\tau}$, again for I_{ipu}=0.1 .

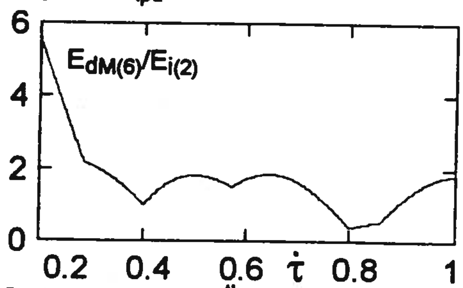

Fig.4 - Ratio between the 6th harm. e.m.f. $E_{dM(6)}$ (due to the m.m.f. with h=–5 and h=+7 of the direct tern currents) and the 2nd harm. e.m.f., as a function of $\dot{\tau}$ (I_{ipu} = 0.1) .

The fig.s 3 and 4 suggest different values of τ that reduce the higher order harmonic e.m.f.s, thus allowing a good resolution in detecting the e.m.f. $E_{i(2)}$ with the FFT:
- the choice $\dot{\tau}$ = 0.8, in principle good, is not compatible with the constructional constraints: the pole shoe (hosting the probe winding) extends to roughly $(2/3) \cdot \tau_s$;
- the choice $\dot{\tau}$ = 0.4 appears interesting; in fact:
  - it is fully compatible with the constructional limits;
  - with $\dot{\tau}$ =0.4 the e.m.f. $E_{i(4)}$ is zero, while $E_{i(8)}$ has an amplitude reduced to roughly $0.1 \cdot E_{i(2)}$;
  - for I_{ipu} = 0.1, $E_{dM(6)}$ equals $E_{i(2)}$; on the other hand, considering that actually $\beta \neq \pi/2$, it follows $E_{d(6)} < E_{dM(6)}$, with further advantages in detecting $E_{i(2)}$.

Thus, one can conclude that it is possible and convenient to choose $\tau = 0.4 \cdot \tau_s$ as the coil-pitch of the probe winding.

Effects of the tooth-slot variations, of the linear on board generator and of the LSM supply inverter

In this section the simplifying hypotheses adopted at the beginning of the analysis will be progressively removed: also in the real situation of a complete Maglev system, a probe winding with the described features can perform its diagnostic function of detection of the stator current unbalance.

As known, the tooth-slot variation (that occurs during the motion, between the pole shoes and the toothed stator structure faced to them) causes a field flux modulation; thus, the field flux is composed by a constant and a variable component superposed.

The fundamental frequency of this flux modulation is linked to the number of tooth-slot variations within a displacement equal to a double pole pitch, that is $6 \cdot q \cdot f_s$. This modulation affects also the probe winding and, by transformer effect, it induces in this winding a "toothing" e.m.f. $e_t(t)$, also with frequency $6 \cdot q \cdot f_s$.

For q=1 slot/(pole-phase), the e.m.f. $e_t(t)$ induced by this effect has frequency $6 \cdot f_s$: thus, its fundamental RMS value E_t (that does not depend on the stator current unbalance) must be added in phasor terms to the e.m.f. $E_{d(6)}$ (with $f=6 \cdot f_s$, induced by the harmonic m.m.f.s with order 5 and 7, produced by the direct tern of the stator currents).

Thus, the e.m.f. E_t does not interfere with $E_{i(2)}$, and it remains well distinguished in terms of spectral frequencies; thus the effect of the presence of the teeth does alter the diagnostic function of the e.m.f. $E_{i(2)}$, that remains the index of the current unbalance and thus indicates a potential or an actual fault in the stator windings.

The amplitude of this transformer e.m.f. E_t depends, among other things, on the ratio between the probe winding pitch τ and the LSM slot pitch (for q=1 equal to $\tau_s/3$).

Let us assume, as a first approximation, that the stator slot and tooth widths be roughly equal: in this case, for q=1, two limit situations occur, that maximise and minimise E_t. Indicated with n a positive integer number, the e.m.f. E_t is maximum for a value of $\tau = \tau_{max}$ equal to a odd multiple of half slot pitch, while E_t is minimum for $\tau = \tau_{min}$, even multiple of half slot pitch:

$$E_{tmax} = E_t(\tau_{max}) \; , \quad E_{tmin} = E_t(\tau_{min}) \qquad (26)$$

$$\text{with} \quad \tau_{max} = (2 \cdot n + 1) \cdot \tau_s / 6 \; ; \; \tau_{min} = (2 \cdot n) \cdot \tau_s / 6 \; . \qquad (27)$$

Of course, the interesting value of "n" in (27) is n=1: it follows that the choice $\tau = 0.4 \cdot \tau_s$ (illustrated in fig.5) leads to an e.m.f. E_t (due to the tooth-slot variation effect) of intermediate amplitude among the limits E_{tmax} and E_{tmin}.

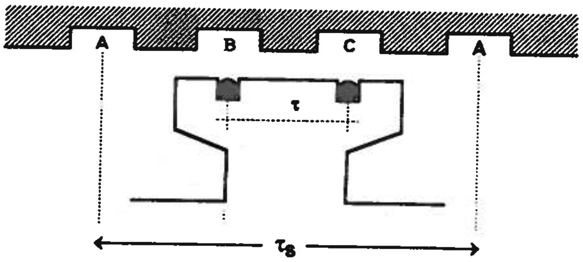

Fig. 5 - Schematic structure of the probe winding with coil pitch $\tau = 0.4 \cdot \tau_s$, disposed in slots obtained along the LSM pole shoe.

As regards the dependence of the probe winding signal on the presence of the windings belonging to a possible linear synchronous generator (LSG), also disposed in slots obtained along the pole shoes, the following remarks can be made:

- the presence of the slots of the LSG generates a further contribution to the modulation of the field flux: moreover, it can be shown that also this effect generates harmonic e.m.f.s with $f=6 \cdot f_s$, thus distinguished from the 2nd harmonic e.m.f.;
- in the loaded operation of the LSG (whose only load is usually an a.c.-d.c.converter) the current circulation in the LSG active sides generate further m.m.f. contributions in the air-gap; nevertheless, their presence does not substantially modify the described operation of the probe winding; in fact:
  - the amplitude of the m.m.f.s produced by the loaded operation of the LSG is greatly lower than that of the m.m.f.s generated by the LSM (between the corresponding powers there is a ratio of roughly $1/10^3$);
  - it can be demonstrated that the prevalent effect of these m.m.f.s is the generation of a further e.m.f. with $f=6 \cdot f_s$, whose amplitude depends on the mutual coupling between the LSG and the probe winding.

Finally, concerning the presence of time harmonics in the LSM stator currents, due to the inverter supply, and previously neglected with the hypothesis of perfectly sinusoidal currents, the following remarks are valid:

- the inverters are of the current control type, but they feed the circuit by imposing the voltages: thus, the current time harmonics are significantly reduced by the high values of the phase reactances;
- the first harmonics that are present in the current spectrum of the LSM are around the PWM carrier frequency: thus, they are frequencies greatly higher than those of interest for the present application and, therefore, within a spectral band well separated by that used for the diagnostics purposes in the probe winding.

In conclusion, while the amplitudes of some harmonic e.m.f.s, evaluated by means of the previous theory, can be affected by the presence of the teeth, of the LSG and of the LSM supply inverter, their frequencies are not: in particular, the 2nd harmonic e.m.f., induced in the probe winding, exists only in case of stator current unbalance; thus the probe winding performs adequately its diagnostic task.

Experimental Investigation on a prototype

Some tests have been made, to check the described method for validity and robustness, using an experimental apparatus composed as follows:

- the magnetic structure is that of a salient-pole rotating synchronous machine, with constant air-gap (Table II);

Table II - Main data of the three-phase rotating synchronous machine used for the experimental tests.

rated power [kVA] ; voltage [V]	200 ; 480
rated frequency [Hz] ; N° of poles	42 ; 6
intern. diameter, air-gap [mm]; N° slots	720, 5; 108

- the probe windings pitch is $\tau = 0.4 \cdot \tau_s$ and their active side length is the same of the stator of the synchronous machine (350 mm); these windings are as follows:
  - a probe winding (N°1), with 25 turns, has the active sides parallel to the sides of the pole shoe; the last one is skewed by an angle equal to one stator tooth pitch as regards the stator teeth;
  - another probe winding (N°2) has only 1 turn and it is disposed as like as the previous one;
  - a further probe winding (N°3), with only 1 turn too, has the active sides parallel to the stator teeth;
- the terminals of these windings, disposed on the surface of a same rotor pole, are connected to a FM infrared LED transmitter, placed on the shaft and battery supplied;
- the transmitted signal is detected by a ground receiver, for the re-conversion in electrical form;
- this signal crosses an anti-aliasing active filter (7th order low-pass: cut off frequency: 1.8 kHz);

- the output of the filter is processed by a 10 bit A/D converter, transferred to a PC and elaborated by FFT.

Of course, the transmitter and the receiver (here used for the signal transfer from a rotating to a fixed part) are not present in an actual Maglev system, whose vehicle is equipped with on-board processing devices.

In order to simplify the tests, the machine has been operated as a generator; the phase windings have been loaded with three star-connected resistors, with separate regulations, in order to obtain the desired stator current unbalance.

A lot of tests have been made, varying the operation frequency f_s, the field current, the amplitude and the unbalance of the stator currents.

As an example, fig.s 6 and 7 show the waveforms and the amplitude harmonic spectra measured at the terminals of the probe winding N° 1 (of 25 turns, with the active sides skewed as regards the stator teeth), in case of balanced and unbalanced currents respectively.

The voltages V_{mh} are measured at the low-pass filter output (the corresponding harmonic voltages of each turn of the probe windings can be obtained dividing the V_{mh} by the coefficient 6.25).

The following should be remarked:

- between the various test operating conditions, those of fig.s 6 and 7 (f_s=18 Hz < f_n=42 Hz; I≈20 A ≪ I_n=240 A) have been chosen in order to show the good behaviour of the probe winding N°1, suited to detect the harmonics of the balanced and unbalanced operations even with values of frequency and stator currents that are low compared with the rated values of the machine;

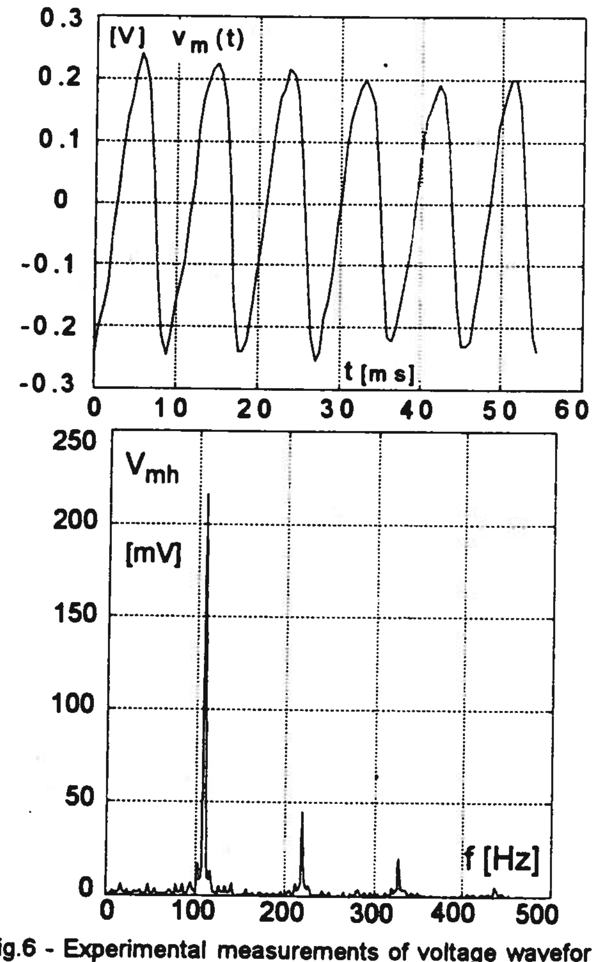

Fig.6 - Experimental measurements of voltage waveform and amplitude harmonic spectrum of the probe winding N°1 (25 turns, with the active sides skewed as regards the stator teeth), placed on the synchronous machine with the data of Table II: operation with balanced stator currents (I_a=I_b=I_c=20 A); stator frequency: f_s = 18 Hz.

- the quality of the signals of the probe winding N°1 in the time domain is good: in the balanced case the waveform is nearly a sinusoid with frequency $6 \cdot f_s$, while in the unbalanced situation the waveform presents a $6 \cdot f_s$ frequency component, and it is modulated with a $2 \cdot f_s$ frequency component, due to the fundamental m.m.f. produced by the inverse tern of the stator currents;
- in the frequency domain, if we neglect the existence of a few noise (anyway quite low), fig.6 shows clearly the spectral lines of the voltage harmonics generated from the m.m.f.s produced by the direct tern currents: in fact these voltages are induced at the following frequencies: $6 \cdot f_s$ = 108 Hz; $12 \cdot f_s$ = 216 Hz; $18 \cdot f_s$ = 324 Hz; $24 \cdot f_s$ = 432 Hz;
- fig.7 shows the additional harmonics of unbalanced case, generated by the harmonic m.m.f.s of the inverse tern currents, with the following frequencies: $2 \cdot f_s$=36 Hz; $4 \cdot f_s$=72 Hz; $8 \cdot f_s$=144 Hz; $10 \cdot f_s$= 180 Hz; $14 \cdot f_s$=252 Hz; $16 \cdot f_s$=288 Hz; $20 \cdot f_s$=360 Hz;
- the measured values of the amplitudes cannot be directly compared with those obtainable by eq.(19), because the tested machine has a stator with q = 6 slots/(pole· phase); on the contrary, the windings considered for the Maglev applications are characterised by q = 1 (in accordance to all the present implementations of these systems);
- the presence of the harmonic voltage with $f=4 \cdot f_s$, that in theory should be zero thanks to the choice $\tau= 0.4 \cdot \tau_s$, is due to the non-perfect construction and/or assembly of the probe winding;

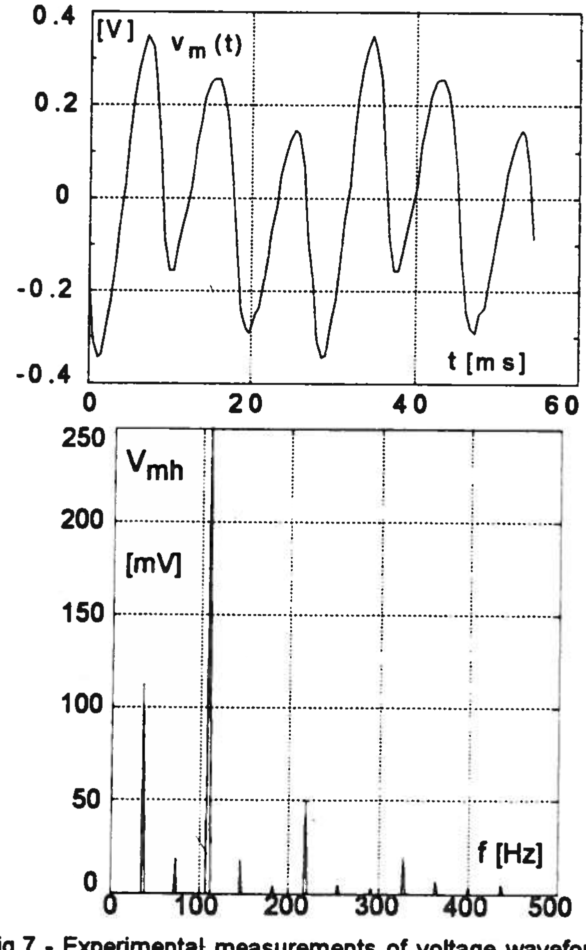

Fig.7 - Experimental measurements of voltage waveform and amplitude harmonic spectrum of the probe winding N°1 (25 turns, with the active sides skewed as regards the stator teeth), placed on the synchronous machine with the data of Table II: operation with unbalanced stator currents (I_a=I_b=20.5 A; I_c=23.5 A; current unbalance factor: ρ_i = 0.096); stator frequency: f_s = 18 Hz.

- in fig.7 the harmonics with frequency $6 \cdot f_s$, $12 \cdot f_s$, $18 \cdot f_s$, $24 \cdot f_s$ are slightly greater than the harmonics in fig.6, because in the second test the stator currents are higher than in the first one;
- the amplitude of the 2nd harmonic voltage prevails, in accordance to the choice $\tau = 0.4 \cdot \tau_s$, and it is suited to be detected by the FFT.

In the following some waveforms are shown, obtained from a digital oscilloscope, about the signals of the probe windings N°2 and N°3 (of one turn, with active sides skewed or parallel to the teeth respectively) and regarding various test conditions (balanced currents or not).

The choice of making the windings N°2 and N°3 with only one turn is due to constructional reasons (difficulties in superposing three probe windings in the small mechanical clearance of the air-gap).

Fig.8 shows the signal of the probe winding N°2 (with active sides skewed as regards the teeth), in case of stator balanced currents: neglecting the noise due to the presence of only one turn, the signal has a fundamental frequency $f = 6 \cdot f_s$, as already seen for the probe winding N°1 in similar operating conditions. .

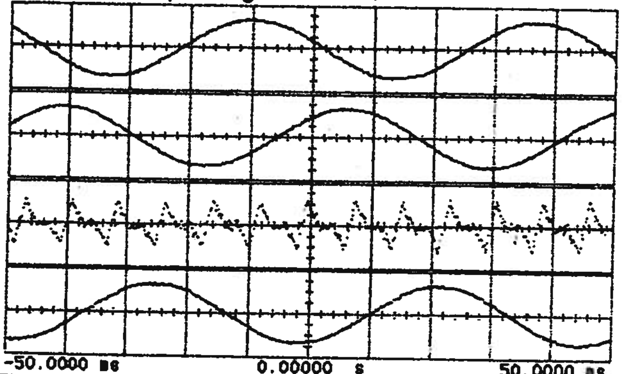

Fig.8 - Measurements of the stator currents (phases a,b,c,) and of the voltage $v_m(t)$ of the probe winding N°2 (of one turn, with skewed active sides); balanced operation; waveforms (from the top to the bottom): $i_a(t)$; $i_b(t)$; $v_m(t)$; $i_c(t)$; f_s=21 Hz; time scale: σ_t = 10 ms/div.

Fig.9 shows the signal of the probe winding N°3 (of one turn, with active sides parallel to the teeth), again in presence of the m.m.f.s due to the balanced currents only.

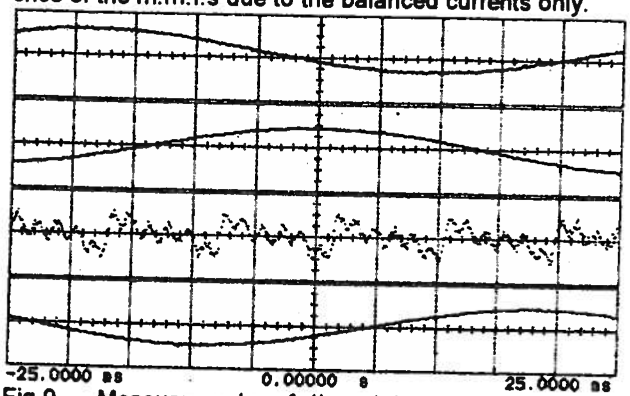

Fig.9 - Measurements of the stator currents (phases a,b,c,) and of the voltage $v_m(t)$ of the probe winding N°3 (of one turn, with active sides parallel to the teeth); balanced operation; waveforms (from the top to the bottom): $i_a(t)$; $i_b(t)$; $v_m(t)$; $i_c(t)$; f_s=18 Hz; time scale: σ_t = 5 ms/div

In this case the signal has the fundamental frequency $f_1 = 6 \cdot f_s$ and also contains one harmonic with frequency $6 \cdot f_1$: the presence of this harmonic is due to the tooth-slot variation that, as described, produces a signal with frequency $f_t = 6 \cdot q \cdot f_s$, (q=6 in the present case).

Finally, fig.10 shows the effect of the presence of a slight stator current unbalance on the signal of the probe winding N°3: it can be observed the presence of a 2nd harmonic e.m.f., that can be recognised and distinguished both from the 6th frequency component and from the component with $f = 6 \cdot q \cdot f_s$, due to the tooth-slot variation.

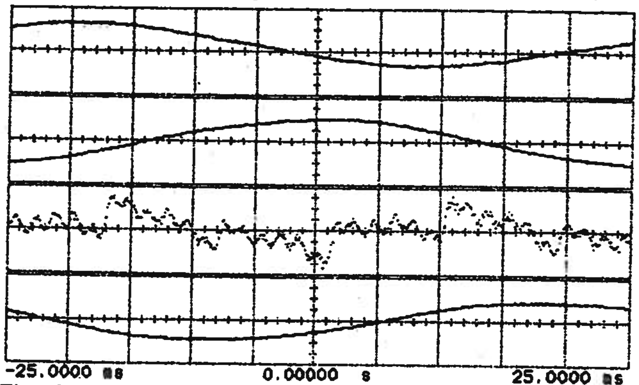

Fig.10 - Measurements of the stator currents (phases a,b,c,) and of the voltage $v_m(t)$ of the probe winding N°3 (of one turn, with active sides parallel to the teeth); unbalanced operation; waveforms (from the top to the bottom): $i_a(t)$; $i_b(t)$; $v_m(t)$; $i_c(t)$; f_s=18 Hz; time scale: σ_t = 5 ms/div.

In conclusion, the performed tests confirm that the theoretical analysis of operation and design is valid.

Conclusions

In the present paper the feasibility of a real-time monitoring method for the diagnostics of the operating conditions of the stator windings of an EMS Maglev system has been studied, by means of a probe winding disposed in the levitation-field pole shoes of the vehicle and suited to detect the stator current unbalance.

The harmonic m.m.f. fields produced by the LSM stator currents and the corresponding induced e.m.f.s have been analysed, in balanced and unbalanced conditions.

The theoretical analysis and the experimental tests have shown that the e.m.f. suited to be used as a diagnostic signal is the 2nd harmonic e.m.f., referred to the stator LSM frequency; the best pitch of the probe winding equals 0.4 times the LSM pitch, because it best reduces the higher order harmonics.

The research will be carried on, especially as regards:
- improvement of the model;
- analysis of new types of probe windings;
- further experimental tests.

Acknowledgement

The authors warmly thank Prof. Ivo Vistoli for the precious advice given during the research development.

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