Brush Wear Modelling in High Speed Universal Motors

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Abstract
The brush wear in small rating, high speed, universal motors is analysed, developing a model for its estimation, as a function of the operating and constructive quantities. Particular attention is devoted to the effect of the turns distribution in the armature slots: to this aim, two universal motors are considered, with the same constructive quantities, except for the number of turns of the two coil sections per layer-slot; in the former motor this number is the same, in the latter different, maintaining nevertheless the same sum. Using a suited equivalent network to study the commutation, the significant figures of merit are found out, giving an explanation of the different wear in the two cases.

1.- INTRODUCTION

Among the small rating machines, the universal motors are very widespread, thanks to their favourable manufacture, operation and low cost features: for these reasons, they are used in a lot of household appliances.

During the last years, a great effort has been made to improve the performances of universal motors, with the aim to contrast the increasing competition of other motor solutions. Typical design goals, pursued by universal motor model refinements and design optimization, have been: increase of rotational speed, output power, power density, energy efficiency [1, 2, 3].

On the other hand, a key issue to be always considered as a priority, whichever be the re-design approach, is the preservation or the improvement of brush life. As known, brushes and commutator are the most delicate elements in a commutator motor, and several studies have been carried out to analyse brush life phenomena.

In [4] several factors influencing brush life in d.c. motors are described, suggesting best values of key quantities and giving some advice based on a long experience.

In [5] some wear measures are carried out, making the brushes run on a smooth or a wavy rotor. In the latter case a smaller wear occurs, explicable on the basis of the spatial harmonics of the commutator waviness, whose amplitude is about some hundreds micron.

Here the brush wear will be analyzed, developing a model that can show the dependence on several constructive and operating quantities. Particular care will be given to the influence of the winding characteristics: the study will consider motors with two coil sides per layer – slot, aiming at explaining why differentiating opportunely the number of coil sides between the two coil sections, being the sum equal, brush life increases.

Two motors will be analysed, in the following called “with equal coil sections” and “with unequal coil sections” (see data in Table I and cross section in fig. 1).

Table I – Data of the analyzed universal motors

V_n [V]; I_n [A]; $P_{in\ n}$ [W]	220; 5.8; 1250
f_n [Hz]; Ω_n [RPM]	50; 32,000
N° of poles p; N° of commutator segments k	2; 24
N° of slots c; coil sides/(layer-slot): u; rotor winding parallel paths: a	12; 2; 2
turns N° of the coil sections: s_1; s_2 **1st motor** (with equal coil sections): **2nd motor** (with unequal coil sections):	$s_1 + s_2 = 30$ 15; 15 20; 10
rotor wire diameter [mm]	0.40
angles: pitch shortening ε; brush “shifting” α	30°; 22.5°
brush – segments contact ratio β	1.96
air gap δ [mm]; axial length [mm]	1.47; 32
commutator diameter D_k [mm]	24.5

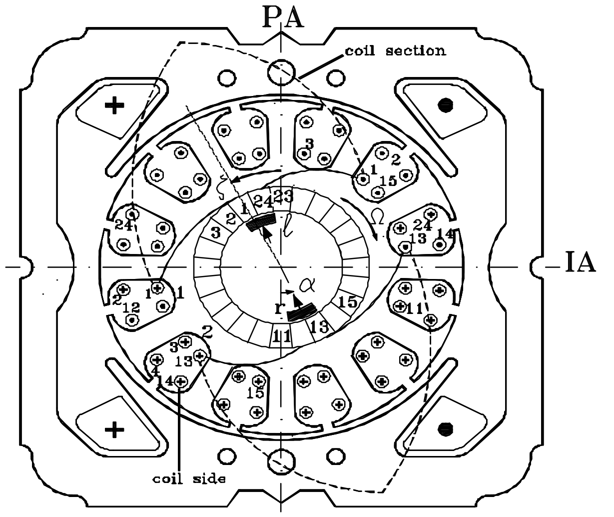

Fig. 1 - Machine cross section, indicating the "brush shifting" angle α, two coil sections of the rotor winding (with a shortened pitch) and the instantaneous directions of the currents.

2.- BRUSH CHARACTERISTICS AND WEAR EXPERIMENTAL DATA

In the universal motor commutation phenomena, whose analysis is required in order to estimate some quantities affecting the brush wear, an important role is taken by the electrical and mechanical characteristics of the brush – commutator system. Thus, some theoretical and experimental results will be considered in the following.

The static and dynamic characteristics [10] of the anodic and cathodic brushes follow these laws:

$$v_{bs} = V_{bn} \cdot (G_s/G_n)^{(1/n)} \quad (1)$$

$$v_{bd} = V_{bn} \cdot (G_s/G_n)^{(1/n-1/m)} \cdot (g_b/G_n)^{(1/m)} \quad (2)$$

with: v_{bs}, v_{bd}: static (s) and dynamic (d) voltage drops at the brush – commutator contact; V_{bn}: voltage drop at rated current density G_n; G_s: rms current density; g_b: instantaneous value; m, n: experimental parameters (see Table II, for the employed brushes - resin bonded type-).

Table II. Equations (1), (2) parameters of the employed brushes (resin bonded); A: anodic; C: cathodic

resistivity [μΩ·m]	1250
brush sizes: b · w · h [mm]	6.3 · 10.95 · 37
$V_{bn\,A}$; $V_{bn\,C}$ [V]	2.02; 1.43
m_A; m_C;	1.27; 1.15
n_A; n_C;	1.98; 1.87
spring force P [N]	3.20

A first brush life test has been carried out on 6 "unequal coil sections" motors, applying the voltage $V = 1.1 \cdot V_n$ for 48 h and $V = V_n$ for the remaining motor life. Fig. 2 shows the mean value of the brush wear Δh_b measured lengthwise and, for each point, the standard deviation.

As for the effect of vibrations, [5] refers non univocal results, depending on the employed material. We have experimented that in the two kinds of analysed motors the vibration magnitude does not differ; thus, the vibration influence has been neglected in the wear analysis.

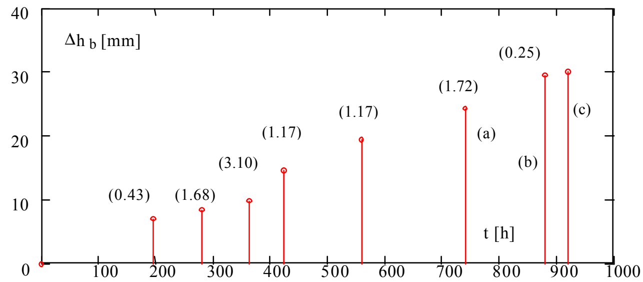

Fig. 2 – Brush wear (6 motors population). In parentheses the standard deviation. (a) a motor has ceased to run after 709 h, for a commutator defect; (b) two other motors have ceased to operate after 873 h and 851 h; (c): only one motor operating.

Besides, the tolerance in the several commutator segments height is equal to 2 μm; this value is low (see [8]) and it does not imply to be in the same wavy commutator conditions explained in the introduction of [5], where the surface waviness is about 10 ÷ 100 μm.

3.- FACTORS AFFECTING THE BRUSH WEAR

Some authors [6, 7] examined quantitatively the brush wear in d.c. motors, with a unitary brush – segments contact ratio, analyzing the numerous contributions.

Referring all the quantities to the SI unit system, the general formula is [7]:

$$W = s \cdot \left[P \cdot \left(W_0 + W_1 \cdot I + g \cdot \sqrt{Q/s}\right) + \omega \cdot (Q/s)\right] \;\; [m^3] \quad (3)$$

where:

- s: distance covered by the brush on the commutator;
- P: spring force;
- W_0: wear, per unit spring force and covered distance, due only to friction, without electric current.
- W_1: wear due to contact surface roughness caused by flashes (small overvoltages unable to start an arc);
- I: current intensity; Q: charge carried by the arc during the brush – segment detaching;
- $g \cdot \sqrt{Q/s}$: wear contribution, equivalent to W_1, but given by the charge Q/s carried by the arc, per unit covered distance; in fact, after a certain charge is passed

through, the surface roughness reaches a limit without increasing further on;
- $\omega \cdot Q/s$: brush wear due to evaporation given by the arc.

Defined:
- $w_h = \Delta h_b/\Delta t$ the brush wear rate lengthwise;
- $q = \Delta Q/\Delta t$ the charge conveyed per unit time by the arc;
- $A_b = b \cdot w$ the total brush contact area;
- $v_k = \Omega \cdot D_k/2$ the commutator tip speed.

By rearranging (3), the following expression of the wear rate w_h, in [m/s], can be obtained:

$$w_h = \frac{P \cdot v_k}{A_b} \cdot (W_0 + W_1 \cdot I) + \frac{P \cdot g}{A_b} \cdot \sqrt{v_k \cdot q} + \frac{\omega \cdot q}{A_b} \quad (4)$$

The validity of (3) and (4), has been experimentally proved from d.c. motors, with constant armature current I: nevertheless, in the following (4) will be extended to the line current instantaneous values i_ℓ.

According to (4), the predominant term is not that due to the electric arc, but that named W_1. It is related to the duration and number of the commutator overvoltages:

$$W_1 = C_1 \cdot [n_2 \cdot \bar{t}_2 + 2 \cdot n_5 \cdot \bar{t}_5] \quad (5)$$

with n_2, n_5: N° of flashes per second with amplitude of about 2V (5V); $\bar{t}_2$, $\bar{t}_5$: duration of a flash with amplitude of about 2V (5V).

As for the values of the several coefficients, it gets [6,7]:

$W_0 = 3.5 \cdot 10^{-16}$ m^3/(N·m); $C_1 = 8 \cdot 10^{-16}$ m^3/(N·m·A);

for the cathodic brush:

$g = 6.6 \cdot 10^{-14}$ m^3/(N·$\sqrt{m \cdot C}$); $\omega = 3 \cdot 10^{-12}$ m^3/C;

for the anodic brush:

$g = 4.6 \cdot 10^{-14}$ m^3/(N·$\sqrt{m \cdot C}$); $\omega = 0.8 \cdot 10^{-12}$ m^3/C.

4.- WEAR IN MOTORS WITH COIL SECTIONS WITH EQUAL OR UNEQUAL TURNS NUMBER

In order to study the waveform of the several important quantities during the commutation, a model has been developed [11] (fig. 3). It is based on an electric network, where the coil sections simultaneously commutating, among which a magnetic coupling occurs, are taken into account. Each coil section involved in the commutation is characterised by the following quantities:
- self resistance R;
- self inductance L and mutual inductance M, with other coil sections commutating at the same time;
- instantaneous EMF e induced by the variation of the flux linkage sustained by the line current in field and armature windings: this EMF includes the transformer and speed contributions, but not the effects of the quick current variations in the commutating coil sections, taken into account by L and M parameters.

In [11] the self and mutual inductances L and M have been evaluated both analytically and experimentally. It has been found that:
- they depend on the saturation of the motor main magnetic circuit, according to minor hysteresis loops;
- called L_o the unsaturated coil section self inductance (e.g. 1, fig.1), the mutual inductance with a coil section set in the same pair of slots (e.g. 2) equals: $M_{1\text{-}2} \approx 0.92 \cdot L_o$, being the turns number equal. The mutual inductance with a coil section set in an adjacent pair of slots (e.g. 3) equals: $M_{1\text{-}3} \approx 0.60 \cdot L_o$. As for the 1st motor, "with equal coil section", $L_o \approx 150$ μH.

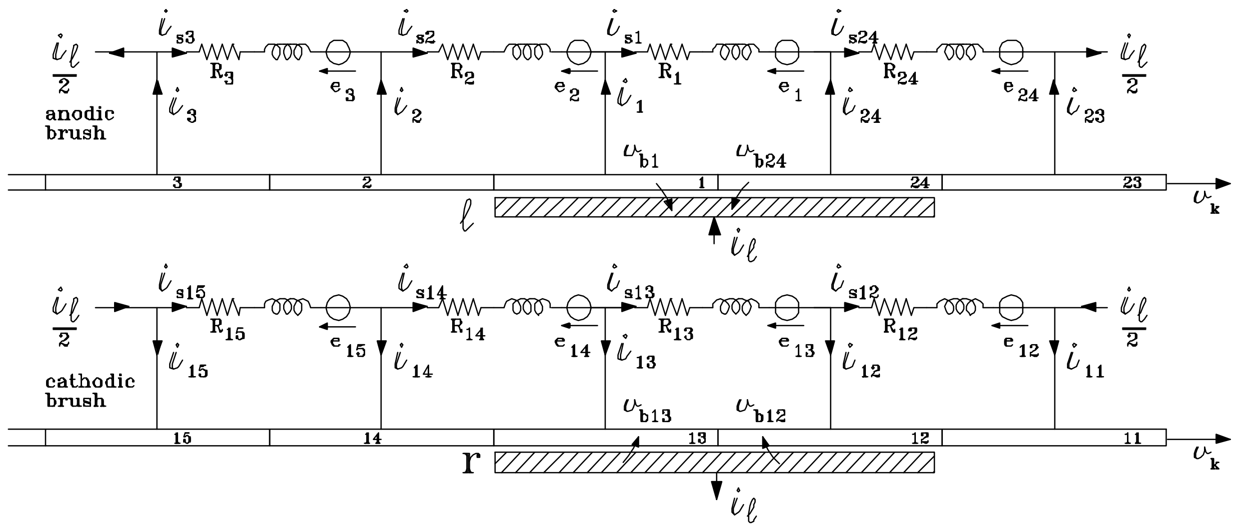

Fig. 3 - Representation of the coil sections simultaneously involved in the commutation during a slot pitch displacement.

The time interval under consideration equals the time necessary to the displacement of a slot pitch or of a multiple; during this small interval, because of high speed, the line current, with f_n frequency, is assumed constant.
The time variable τ is dimensionless: $\tau = 1$ corresponds to one segment pitch displacement, leaving from the position shown in fig. 1 and 3; in this case, the minimum interval to study the commutation corresponds to $\tau = 2$.
With $\Omega = \Omega_n$, $\tau = 1$ corresponds to 83 µs.
The model accuracy has been validated [11], by comparing the measured and calculated values of the self and mutual inductances L and M and the waveforms of the brush – commutator voltage drops.
This model is here employed to find out the possible causes of the different wear, experimentally verified, in case of motors with equal or unequal coil sections number, being the sum equal. In the latter case, the lower wear occurs when the last commutating coil section has the lower number of turns in the slot.
At first, the simulated waveforms are shown, during the rising ramp of line current i_ℓ with an instantaneous value equal to the mean value in a half cycle, $i_\ell = I_{ave}$. For a complete evaluation of the brush wear, it could seem necessary to repeat the simulations regarding the commutation transients for several instantaneous line current values, during a half cycle.
Nevertheless, the $i_\ell = I_{ave}$ choice allows to obtain an information sufficiently representing the wear rate, considering that in (4) one of the most prominent contributions is the term proportional to the current [7].
The aforesaid curves regard, as for the cathodic brush, the voltage drop and the current in some sections.
In [6], it is stated out that the electric arc sparks when the contact between the brush and the segment finishes and the voltage exceeds the spark starting value V_m, where: $V_m = 13$ V (depending on the commutator) for the anodic brush; $V_m = 20$ V (depending on the brush) for the cathodic brush.
From the following waveforms, it can be observed that, in the last contact instants ($\tau = 1.96$ for segment 13, $\tau = 2.96$ for 14), the start sparking contact voltage is never achieved; so, instead of the electric arc, only a short flash occurs (glow or Townsend's discharge).
From fig.s 4 and 6, it can be observed how the contact voltage drop is lower as for the 2nd motor, referring to the last commutation interval (e.g. v_{b13} for $1 < \tau < 2$ and v_{b14} for $1 < \tau < 3$). The reason can be explained referring to the simplified equations of two coil sections (e.g. 13

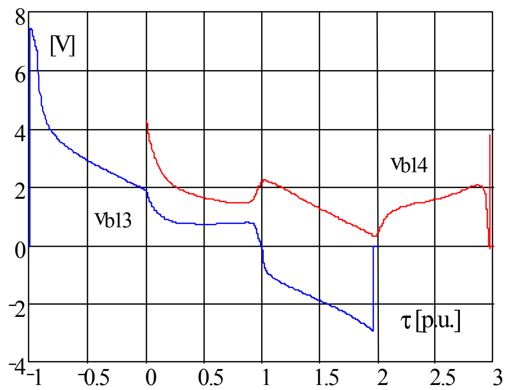

Fig. 4 – Contact voltage drop for segments 13, 14 in contact with the brush actually cathodic (1st motor: s1=s2=15); $\tau = 1$ corresponds to 83 µs.

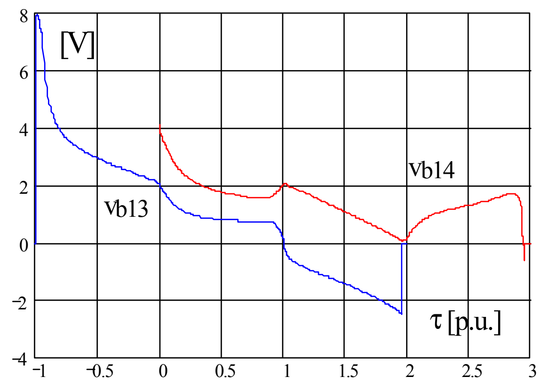

Fig. 6 – Contact voltage drop for segments 13, 14 in contact with the brush actually cathodic (2nd motor: s1=20, s2=10).

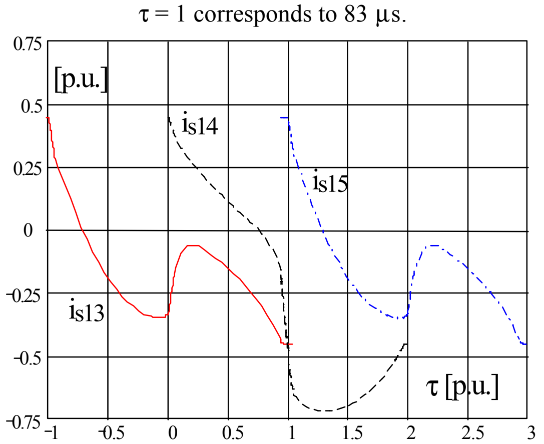

Fig. 5 – Waveform of the section currents i_{s13}, i_{s14}, i_{s15} (1st motor: s1=s2=15).

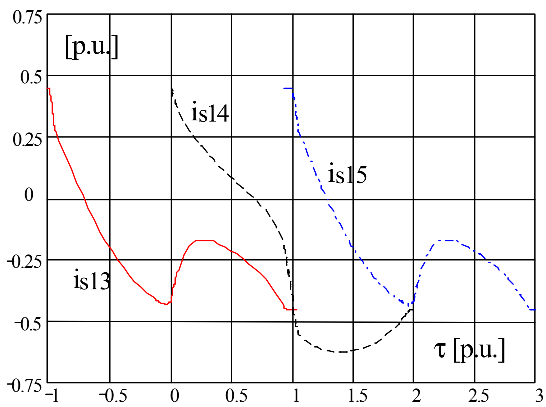

Fig. 7 – Waveform of the section currents i_{s13}, i_{s14}, i_{s15} (2nd motor: s1=20, s2=10).

and 14), set in the same pair of slots; these equations (see (6) and (7)) are said simplified, since they consider the mutual coupling only between some sections, neglecting other weaker couplings:

$$L_{13} \cdot di_{s13}/dt + M_{13-14} \cdot di_{s14}/dt + R_{13} \cdot i_{s13} + e_{13} + (v_{b12} - v_{b13}) \approx 0 \quad (6)$$

$$L_{14} \cdot di_{s\,14}/dt + M_{13-14} \cdot di_{s\,13}/dt + M_{13-15} \cdot di_{s15}/dt + R_{14} \cdot i_{s14} + e_{14} + (v_{b13} - v_{b14}) \approx 0 \quad (7)$$

As for the first commutating coil section in the slot (in the example the 13), passing from the 1st to the 2nd motor, the EMF e_{13}, the self resistance R_{13} ($\propto s_1$) and the self inductance L_{13} ($\propto s_1^2$) increase, while the mutual inductance $M_{13\text{-}14}$ ($\propto s_1 \cdot s_2$) remains roughly constant (or reduces a bit). In other words, the opposing effect of current i_{s14} on i_{s13} reduces, since the mutual inductance $M_{13\text{-}14}$ changes from a value equal to the self inductance L_{13} to a halved one. So the current in coil section 13 reaches its final value with a more regular waveform.

When current i_{s14} finishes commutating ($1 < \tau < 2$; see fig.s 5 and 7), an EMF is induced in the same coil not by current i_{s13}, since this section has already ended commutating, but by current i_{s15}. The mutual coupling between sections 14 and 15, $M_{14\text{-}15}$ ($\propto s_1 \cdot s_2$), remains roughly constant, passing from the 1st to the 2nd motor, while the self inductance L_{14} ($\propto s_2^2$) reduces. However, being the mutual permeance value between sections 14 and 15 about 60% of the self permeance of section 14, the mutual coupling change is not significant as for the current waveforms.

The section current waveforms influence the segment currents, linked to the previous by linear relations: it implies that, in the 2nd case, the segment currents show a more regular and gradual waveform, that gives rise to an analogous contact voltage drop.

This fact introduces a new possible reason of the lower wear in the second case. The segment currents, a moment before the brush – segment separation, take on the Table III values. These values are not conclusive in strictly quantitative sense, since they depend on the model used for the glow or Townsend's discharge; they are important, instead, for a comparison between the two cases.

According to these values, there is not an electric arc, but a Townsend's discharge, which nevertheless is bright, as can be also observed experimentally.

Examine for example the current i_{12}, equal to:

$$i_{12} = i_{s13} - i_{s12} \quad (8)$$

Tab. III. Computed values of the segment currents, when the segment – brush separation occurs.

τ	1st motor	2nd motor
$\beta - 1$	$i_{24} = -4.6\ \mu A$ $i_{12} = 0.11\ \mu A$	$i_{24} = -12\ \mu A$ $i_{12} = -5.1\ \mu A$
β	$i_1 = -110\ \mu A$ $i_{13} = -83\ \mu A$	$i_1 = -86\ \mu A$ $i_{13} = -66\ \mu A$

At time $\tau = \beta - 1 = 0.96$, section current i_{s12} has already finished commutating (it equals $i_\ell/2$); so the Δi_{12} change of segment current i_{12}, getting to zero when the segment 12 – brush separation occurs, influences the current i_{s13}. It follows that the magnetic energy, stored in section 13, and equal to:

$$W_{12} = (1/2) \cdot L_{13} \cdot \Delta i_{12}^2 , \quad (9)$$

must get to zero. Since there is a good mutual coupling with section 14, which is under commutation, a part of this energy is delivered to it. In other words, the opposing effect of current i_{s14} on i_{s13} implies a gradual decay of i_{s12} to zero. The same is true only partially for segment current i_{13} and section current i_{s14}, since the mutual coupling between sections 14 and 15 is low; only a small quantity of the energy stored in section 14:

$$W_{13} = (1/2) \cdot L_{14} \cdot \Delta i_{13}^2 , \quad (10)$$

when current i_{13} gets to zero, is delivered to section 15. The remaining dissipates as a commutator flash.

As for the 2nd motor, with a lower number of turns for the second coil section in the slot, the last negative effect reduces.

5.- CONCLUSION

A model has been described for the estimation of the brush wear of universal motors, as a function of the main constructive and operating quantities, starting from the commutation transients calculation.

The different brush wear in two machines has been analysed, that differ only as for the turn distribution in the two coil sections per layer-slot. Being the sum equal, the number of turns is the same in the first case and different in the second case, with the last section of the slot, leaving the brush, characterised by the lower number.

Two possible reasons may be enucleated to explain the lower wear in the second case, leaving from the fact that the mutual coupling between the second coil section in the slot and the following, set in the adjacent slot, is smaller than that between coil sections in the same slot.

First of all, in the second case the section and segment currents show a more regular waveform.
Secondly, when the brush – segment separation occurs, the conveyance of the magnetic energy stored in the section to the following section is more difficult for the second than for the first. Since the undelivered amount of this energy turns into contact discharge, the lower number of turns in the second section in the slot reduces the discharge energy and then the wear.

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REFERENCES

[1] Di Gerlando, A; Perini, R.: *A Model for the Operation Analysis of High Speed Universal Motors with Triac Regulated Mains Voltage Supply*, Proc. of SPEEDAM02, Ravello, Italy, June 11-14, 2002.

[2] Di Gerlando, A; Perini, R: *Modelling and Experimental Analysis of Core Saturation and Losses of Universal Motors*, ICEM 02; Brugge, Belgium, 25-28 August 2002; Conference Record on CD; paper N° 090.

[3] Di Gerlando, A; Perini, R: *Low-Cost Redesign Criteria for the Efficiency Improvement of Universal Motors used in Domestic Appliances*, Conference EEDAL'03, Torino, Italy, 1-4 Oct. 2003.

[4] Hamilton, R. J.: *DC motor brush life*, Industrial Application Conf. 1998. 31st IAS Annual Meeting Vol. 3, pg.2217 – 2224.

[5] Bryant M., Tewari A., Lin J.: *Wear rate reduction in carbon brushes, conducting current, and sliding against wavy copper surfaces*, IEEE Trans. on Comp. Pack. and Manuf. Tech. Part A, vol. 18, n°2, June 1995.

[6] Holm R.: *Electric contacts handbook*, Springer-Verlag, Berlin,1958.

[7] Holm R., et al. "*Brush wear during commutation*" IEEE Trans. on PAS, 1966, vol. 85 pg. 84 – 87.

[8] Shobert, II E. I. *Sliding Electrical contact*" 39th Holm Conf. on Electric Contacts, 1993 pg.123-134

[9] Flinders F., Zhsng J., Oghanna W.: *Investigation on excessive commutator and brush wears in DC traction machines*, IEEE Intern. Conf. on Power Electronics and Drive Systems, PEDS'99, July 1999, Hong Kong.

[10] Matsuda T., et al. *Method for analysing the commutation in small universal motors*, IEE Proc. Electr. Power Appl. Vol. 142, n° 2, March 1995.

[11] Di Gerlando A., Perini R.: *Model of the Commutation Phenomena in a Universal Motor*, Intern. Electric Machines and Drives Conf., IEMDC 2003, Conference Record on CD, Paper N°10076, Madison, Wisconsin USA June 1-4, 2003.