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MEASURING OF ADDITIONAL NO-LOAD LOSSES IN INDUCTION MOTORS AND PROOF OF PROPOSITION Pado~I_0^2

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Abstract: *This paper presents and proveds idea that the total no-load core losses (P_{Fe}) in induction motors can be divided in two components: the basic core losses ($P_{Fe1} = P_{Fe1,n}(U_0/U_n)^2$) and the additional no-load losses ($P_{ado} = P_{ad0,n}(I_0/I_{0,n})^2$). This second quotes that the saturation of the machine, practically, don't influence on the slot permeance harmonics $(B_{xJ0} \sim I_0)$. Basic core losses P_{Fe1}, and additional no-load losses ($P_{ado,n}$) at rated voltage $U_0 = U_n$, are determined from the no-load test, performed for two different voltage values.*

Keywords: ***No-load Losses, Indirect Measuring***

1. INTRODUCTION

According to a usual classification, the total no-load losses (P_0) consist of stator I_0^2R losses (P_{Cu10}), friction and windage losses (P_{fw}) and core losses (P_{Fe}). The additional no-load losses (P_{ad0}) are included in the latter, i.e.:

$$P_{Fe} = P_0 - P_{Cu1} - P_{fw} \quad (1)$$

$$P_{ad0} = P_{Fe} - P_{Fe} \quad (2)$$

P_{Fe1} - fundamental core losses, those result from the fundamental harmonic of flux density, appeared in stator.

Approximately, (90÷95)% of additional no-load losses appear in rotor, and are caused by high frequency field fluctuations in the air gap. Therefore, high frequency rotor losses are assumed as additional no-load losses [1÷5].

The additional no-load losses are usually obtained by driven rotor test, no-load slip test and method of no-load loss segregation [1,2,3], i.e. by complicated methods.

2. SLOT HARMONICS IN (UN)SATURATED INDUCTION MACHINES

High frequency losses are caused by high order spatial field harmonics in the air gap. There are two high harmonics sources:

a) The slot permeance harmonics (B_{xJ0}), which is the result of the slot openings, and that exists even when the mmf is purely sinusoidal.
b) The field slot harmonics (B_{fn}), due to m.m.f. harmonics, produced by the steps in the stator load current distribution, i.e. no-load current (I_0) produced the high harmonic (B_{fn0}).

The space harmonics' waves rotate much slower than the fundamental wave. They introduce dips and cusps in the motor torque-speed curve, and they cause stray losses and noises as well. Slot permeance harmonics (B_{xJ0}), which occur under no-load and load conditions, are particularly significant, and they have a vital influence on the phenomenon mentioned above.

In order to present a possibility of sufficiently precise calculation of the magnitude of so-called slot harmonics flux densities, author points out two engineering methods [6,7], as well as the possibility of neglecting the saturation for the slot harmonics. This latest is proved experimentally, through indirect method for measuring the additional no-load losses [8].

It is usually considered [9,10] that the magnetic saturation has a little influence on the slot harmonic values (B_{fJ}), due to mmf slot harmonics, while it is pointed out [11] that the slot permeance harmonic fields (B_{xJ}) are directly proportionate to the fundamental harmonic field values (B_1) i.e. that the additional no load losses corresponding are directly proportionate to the squared voltage values. On the contrary, the assumption that the additional no-load losses change proportionally to the squared value of no-load current, i.e. to the far greater extent that the squared motor voltage values, is experimentally verified, in the paper [8].

On the basis of this results [8] and a theory presumption, in this paper it will be researched the influence of the magnetic saturation on the both kinds of the field slot harmonics (B_{fJ}, B_{xJ}).

2.1. High Harmonics of the Magnetmotive Force (mmf) and the Flux Density Corresponding

A balanced 3-phase winding produces no triple harmonics. Because of this the resultant mmf may only contain some of the harmonics whose order is given by

$$J_f = p(6c \pm 1) \quad c = 0,1,2,3,\ldots \tag{1}$$

The peak value of harmonic mmfs (F_J) are given by equation:

$$F_J = \frac{3}{p} \cdot \frac{K_{dJ} \cdot K_{pJ}}{J_f} \cdot \sqrt{2} I_1 w_1 \tag{3}$$

where I_1 - rms phase current, $w_1 = 2pw_s \times q_1$ number of the-turn per phase, J

The peak value of the fundamental harmonic mmf is

$$F_1 = \frac{3}{p} K_{d1} \cdot K_{p1} \cdot \sqrt{2} I_1 \cdot w_1 \tag{4}$$

then, the peak values of the harmonic mmfs F_ϑ, may be given as

$$F_J / F_1 = \frac{1}{J} \cdot \frac{K_{dJ} \cdot K_{pJ}}{K_{d1} \cdot K_{p1}} \tag{5}$$

As a rule, that the J -th harmonics are small in peak values, because the winding factor $K_{dJ} \times K_{pJ}$ is only a few hundredths of unity while for the fundamental harmonic it is close to unity. It is attained with a judicious choice of the coil pitch (y_c » $0.83\ t$) and number of slots per pole per phase (q ≥ 3). The only exception is the so-called slot harmonics whose order (number) is given by

$$J_{fs} = kS_1 / p \pm 1 \qquad k = 1,2,3 \tag{6}$$

for that the distribution factor is equal to that for the fundamental harmonic, $K_{dJs} \cdot K_{pJs} = K = \times K_{p1}$, and the relatively value of the slot harmonics are:

$$F_{Js} / F_1 = 1 / J_{fs} \tag{7}$$

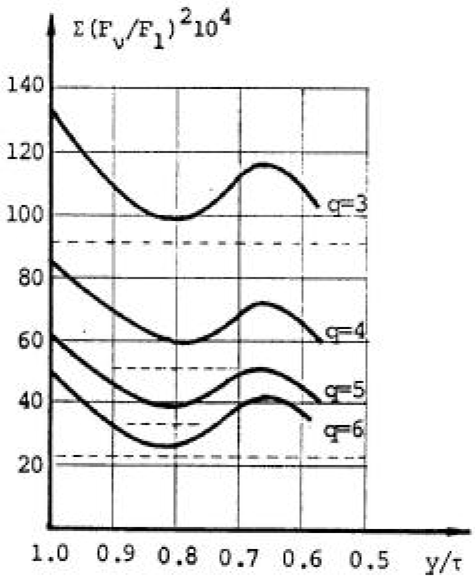

Fig. 1. *Values of the* $S(F_1/F_J)^2$*, in the dependence from the pitch-shortening* y_c/t*, for the induction motors with different number of the slots per pole per phase (q);* ― *;for all harmonics,* - - *only for the slot harmonics*

To minimize their effect, it will be good to avoid the values of $q<3$. However, already at $q=3$, the order of slot harmonics are 17 or 19, and they are only slightly present in the phase mmf.

In order to determine the differential leakage reactance and stray losses it is necessary to evaluate the values $(F_J / F_1)^2$, for particularly harmonics and their sums.

The sum $\sum (F_J / F_1)^2$ are determined:

- for $J = 6kq \pm 1,\ k = 1,2,3,4$ (slot harmonics), and
- for $J = 5,7,11,$ (unslot harmonics),

particularly and the collective, for the windings with $q=3,4,5,6,$ and for all integral combination ratios $y_c/t = 2/3$ ¸ 1. Given results are represented in fig.1.

Relatively high participation of the $\sum (F_J / F_1)^2$, for slot harmonics (i.e. $J_{fs} = 6kq \pm 1$), in the total sum $\sum (F_J / F_1)^2$ for all harmonics, it is shown in the fig.1 Considering this, it is sufficient to take into account only the slot harmonics, since the induction motor windings are must frequently with pitch-shortening y/t » 0.80.

If all slot harmonics, to 6th order, to take into account, for induction motor winding with $S_1/p=18, q=3, y/t=7/9$, then is $\sum (F_J / F_1)^2$ »100×10^{-4}. In this sum the unslot harmonics participate only with $7.92 \cdot 10^{-4}$ or about 7.92%.

As q increased, slot harmonic peak values (F_J) decreased, and the sum $S(F_\vartheta/F_1)^2$ also decreased (fig.1), but participation corresponding sum for the slot harmonics remains great still (about 86%, fig.1) for winding with $q=4$ and pitch-shortening y/t » 0.8).

Peak values of the corresponding field harmonics are

$$B_{fJ} = \frac{3}{p} \cdot \frac{m_0}{g \cdot K_{gJ} K_{Fe}} \cdot \frac{K_{dJ} \cdot K_{pJ}}{J_f} \sqrt{2} \cdot I_1 w_1 \tag{8}$$

where m_0 -magnetic permeability of the air gap,
g - the air gap length,
K_{gJ} - airgap (Carter) factor ($K_{gJ} = K_{g,1}$,
for $J < S_1 - p$, and $K_{gJ} = 1$ for J ³ $S_1 - p$),
K_{Fe} - the magnetic circuit saturation factor.

For saturation factor is often taken into account that $K_{FeJ} = K_{Fe1}$ (i.e. as for the fundamental harmonic), though the influence of saturation is different for the different harmonics. While the magnetic path of the higher harmonics lies in the airgap and the tooth tops, the magnetic path of the lower harmonics also comprises the teeth and core of the stator and the rotor.

The field slot harmonics, whose order $\vartheta_{fs} = k S_1/p \pm 1$, are usually expressed in per unit:

$$B_{fJ} / B_1 = (1 / J_f) \cdot (K_{g1} / K_{gJ}) \tag{9}$$

or

$$B_{fJs} / B_1 \approx (F_J / F_1) \cdot K_{g1} \tag{10}$$

since is $K_{gJ} \approx 1$, for $J \geq S_1 / p - 1$.

Corresponding field square values are given by:

$$(B_{fJs} / B_1)^2 = (F_J / F_1)^2 K_{g1}^{\ 2} \tag{11}$$

and they are obtained, when the actual $(F_J / F_1)^2$.values are multiplied by K^2_{g1} . These magnifyings are greater, when the airgap factor values are greater, i.e. whatever the ratio s/τ_s is greater.

By equation (11) is shown that the influence of the unslot harmonic on the sum $S(B_{fJ} / B_1)^2$ is less then corresponding influence on the sum $S(F_J / F_1)^2$, i.e.<8%.

2.2. Slot Permeance Harmonic Fields

The effect of core saliency on the magnetic flux density (B) is shown in fig.2. Since the $B(a)$ wave form is symmetrical about the center of the slot pitch, it's Fourier series contains only a constant component and cosine terms [6,7]:

$$B(a) = B_{med} + \sum B_{xk} \cos(kS_1 a) \qquad (12)$$

The amplitude of the k-th slot harmonics in the Fourier series is given by [6]

$$B_{xk} = (b/2) \cdot h_k \cdot K_{g1} \cdot B_{med} \qquad (13)$$

where is the medium values of the flux density (B_{med}) is amplitude of the fundamental harmonic in the air gap.

Coefficient b, which is defined as

$$b = (B_{max} - B_{min})/(2B_{max}) \qquad (14)$$

is calculated by

$$b = 0.43\,(1-e^{-(s/g-0.7)/3.3}) \qquad (15)$$

and its dependency is shown in fig.2.

Values of coefficient η_k is given by

$$h_K = \frac{2}{pk} \cdot \frac{\sin(1.6k(s/t_s)p)}{1-(1.6k \cdot s/t_s)^2}, \qquad k = 1,2,3,... \quad (16)$$

and its values depend from the rate s/t_s.

Airgap (Carter) coefficient is defined as

$$K_g = B_{max}/B_{med} = t_s/(t_s - 1.6b \cdot s) \qquad (17)$$

The ratio

$$B(a)/F_1 = l(a) \qquad (18)$$

is considered as the permeanse of the air gap with the toothed core *C1* and a smooth surface *C2*, fig 2.. Using equations (12) and (18), the magnetic permeance $l(a)$ can be described by the following equation

$$l(a) = l_0 - \sum_{k=1}^{\infty} l_k \cos kS_1 a \qquad (19)$$

where is the constant component of the magnetic permeance (l_0) is given by equation:

$$l_0 = 1/(k_{g1} \cdot g) \qquad (20)$$

and the amplitude of the expansion term can be readily found

$$l_k = (1/g) \cdot B \cdot h_k \qquad (21)$$

To take l_0 and as well as the first and second member of series (19), for $l(a)$ is obtained

$$l(a) = l_0 - l_1 \cos(S_1 a) - l_2 \cos(2S_1 a) \qquad (22)$$

On the base equations (18) and (22) is concluded that the fundamental harmonic mmf ($F_1 \sin wt$) is produced of the flux density $B(a,t)$

$$\begin{aligned} B(a,t) = {} & F_1 l_0 \cdot \sin(wt - pa) - \\ & -0.5 F_1 l_1 \cdot \sin[wt + (S_1 - p)a] + \\ & +0.5 F_1 l_1 \sin[wt - (S_1 + p)a] - \\ & -0.5 F_1 l_2 \sin[wt + (2S_1 - p)a] + \\ & +0.5 F_1 l_2 \sin[wt - (2S_1 + p)a] \end{aligned} \qquad (23)$$

Thus, because of the slot-opening of the stator, the fundamental harmonic of mmf, beside of the fundaments, creates a series of pair of traveling waves - slot permeance harmonic fields. The most considerable of these is:

- two slot harmonics of the first order $x_1 = S_1 \pm p$, and
- two slot harmonics of the second order $x_2 = 2S_2 \pm p$,

Generally speaking, the every (J) harmonic mmf creatures following of the flux density harmonics:

- harmonics of the ordered $J_f = Jp$ (or $J_f = J, p = 1$) and
- slot (permeance) harmonics of the ordered $k=1,2,3...$ $x_K = kS_1 \pm J_f p$, (or $x_K = kS_1 \pm J_f$, for $p = 1$),

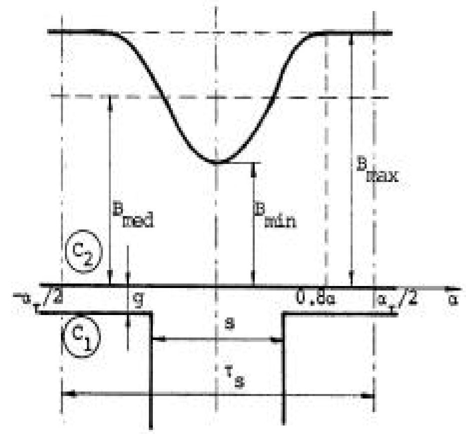

Fig. 2 - *Distribution of the magnetic flux density (B) in the airgap within the slot pitch length (t_s)*

In order to determine the differential leakage reactance and stray no-load losses it is necessary the evaluate the values $B_{xK}/B_1, (B_{xK}/B_1)^2$ and the corresponding sum $\sum (B_{xK}/B_1)^2$ for $k = 1,2,3,...$

For the induction motor with ratios $s/d = 10$ and $s/t_s = 0.2;0.3;0.5$, the values $B_{S1} \pm p/B_1$, $B_{2S1} \pm p/B_1$ and $B_{3S1} \pm p/B_1$, as well as the corresponding values $(B_{S1} \pm p/B_1)^2$, $(B_{2S1} \pm p/B_1)^2$ and $(B_{3S1} \pm p/B_1)^2$, for m_{Fe}®¥, are compared.

The slot permeance harmonic fields (B_{xJ}) produced by the fundamental harmonic mmf are at standstill with respect to the field slot harmonics (B_{fJ}), created by the corresponding slot harmonic mmf. In the no-load condition, harmonic values (B_{xK}) are considerable greater then the values of the harmonics B_{fJ} for the same orders ($J_f = xk = kS_1 \pm p$). Consequently, the corresponding values $(B_{xK}/B_1)^2$ and $S(B_{xK}/B_1)^2$ are greater for several time from values $(B_{fJ}/B_1)^2$ and $S(B_{fJ}/B_1)^2$ for the same orders harmonics.

From the two slot permeance harmonic fields of first order ($x_K = S_1/p \pm 1$), one, which rotates in the same direction as the motor, has a sign opposite to the corresponding field slot harmonic, while the other, which rotates in the opposite direction, has the same sign as the corresponding field slot harmonics. In this case, the corresponding resultants for one pair of harmonics the same order, for example $J_f = x_K = 17$ and 19, are

$$B_{fx,17} = B_{f,17} + B_{x,17}, \quad \vartheta_f = x_K = 17 \qquad (24)$$

$$B_{fx,19} = B_{f,19} - B_{x,19}, \quad \vartheta_f = x_K = 19 \qquad (25)$$

and then is

$$B_{fx,17}^2 = B_{f,17}^2 + 2B_{f17} \cdot B_{x17} + B_{x17}^2 \quad (26)$$
$$B_{fx,19}^2 = B_{f,19}^2 - 2B_{f19} \cdot B_{x19} + B_{x19}^2 \quad (27)$$

Equation (27) and (28) give it

$$B_{fx,19}^2 + B_{fx,17}^2 » B_{f17}^2 + B_{f19}^2 + + B_{x17} + B_{x19}^2 \quad (28)$$

since value $2B_{f17}B_{x17} - 2B_{f19}B_{x19}$, is a considerable less than the value given on the right hand equation (27).

By equation (28), it is concluded that the no-load losses, produced by high harmonics, will be able to divide in two part: on, which corresponds to the field slot harmonics (B_{fJ}) and other, which corresponds to the slot permeance slot harmonics (B_{xK}). It is proved that the no-load losses, produced by B_{xK} harmonics, are several (7÷10) time greater then the corresponding losses produced by B_{fJ} harmonics.

2.3. The (Un)Saturation of the Flux Paths for the Slot Harmonics (The quality analysis)

The flux density variations along the airgap machine is shown at the fig.3, for purely sinusoidaly distribution mmf. Fundamental harmonic (MMF'), which peak value is MMF'=5 unit, creates the fundamental harmonic of the field, which peak value is $B'_{1m} = 5$ unit, also, while distribution of the flux - density are considerable different from sinusoidaly.

Let, at double value MMF = 2MMF' = 10 unit (fig.3a), fundamental harmonic flux-density have value $B_{1m} = 8$ unit < $2B'_{1m}$, i.e. it's values wasn't duplicated by reason of saturation. Total flux-density along airgap, in the region from *O-p/3* and *2p/3-p*, is duplicated in regard to the originally value *B'*, but is *B/B'<2* in the region from *p/3-2p/3-p* by reason of saturation. It is transparently that, in the entire region *0<x<p*, approximately, is valid

$$B - B_1 » 2(B'-B'_1)$$

i.e., the flux-density slot variations (sl.3b) are, practically, proportionate to MMF values and no-load current values (fig.3b). For given ratio $s/t_s=0.5$, the flux - density slot variations, practically, contain only the slot-harmonics of first order, i.e. 11th (backward) and 13th (forward) harmonic (fig.3c), because values of the factors h_2 and h_3 (equation 16) may be neglected. Practically, for the case with fig.3, for the slot permeanse harmonic fields, is valid:

$$B_{11}/B'_{11}=B_{13}/B'_{13} » 2$$

It quotes that the peak values of the slot permeanse harmonic fields (B_{xk}), are, approximately, proportionally to the no-load current values, i.e.

$$B_{xk0} / B_{x0,n} = I_0/I_{0n} \quad (29)$$

3. THE ADDITIONAL NO-LOAD LOSSES

3.1 Quality Analysis and Dependences

Practically, additional no-load losses (P_{ado}) are caused by slot harmonics field fluctuations in the airgap, and those are:

- the slot permeance harmonic fields (B_{xk0}), and

the field slot harmonics (B_{fJ0}) produced by MMF harmonics.

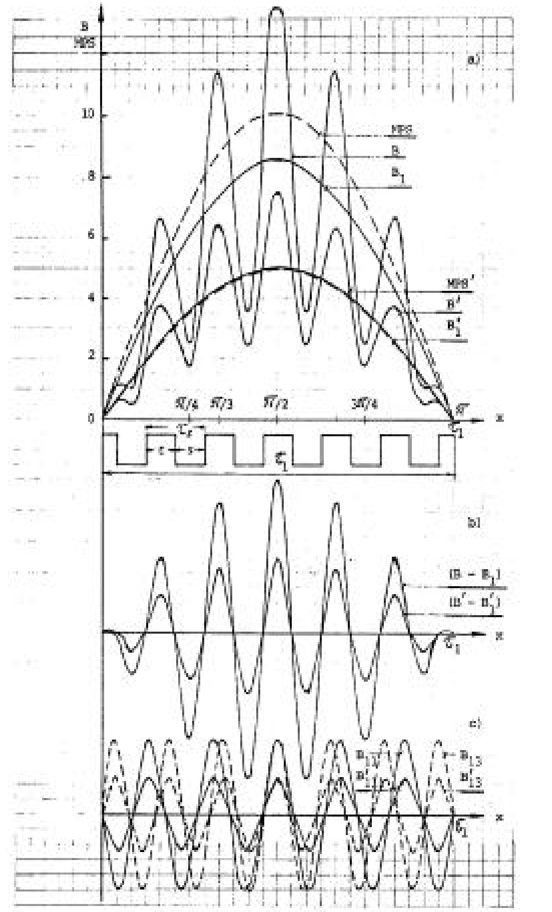

Fig. 3. - *a) Field distribution (B) along the saliency of the stator core, set up only by the fundamental harmonic mmf: 1) values MPS' and 2) values MPS = 2MPS',*
b) Variation fields = total field - fundamental harmonic
Variation fields (with fig.b) decomposed on the forward and backward revolving field wave.

In the no-load condition, resultant peak value of the slot harmonics (B_{J0}) determine as the sums of the corresponding components, i.e.:

$$B_{J0} = B_{xkO} + B_{fJ0} \quad (30)$$

As, the additional no-load losses are proportionate to the squared flux density, it is convinient that they are calculated separetly, for the particular harmonics, i.e.:

$$P_{ado,J} = K_{\vartheta} \cdot B^2_{J0} \quad (31)$$

The total additional no-load losses, if limited to losses caused by high-order harmonics, may be defined as the sum of the individual losses created by particular harmonics, i.e.:

$$P_{ado} = \sum_J P_{ado,J} \quad (32)$$

and then is

$$P_{ado} = \sum_J K_J \cdot B^2_{J0} \quad (33)$$

If P_{ado} expressed by additional no-load rated losses ($P_{ado,n}$) then is:

$$P_{ado} = P_{ado,n} \, S(B_{\vartheta 0} / B_{\vartheta 0,n})^2 \quad (34)$$

On the base equations (34) and (29), it is obtained:

$$P_{ado} = (I_0 / I_{0n})^2 \cdot P_{ado,n} \quad (35)$$

i.e. the additional no-load losses, are practically proportional to the squared no-load current values. It occurs even at high flux density values, corresponding voltage values U £ $1.1\ U_n$. i.e. to the far, greater then the squared voltage value.

3.2. Indirect Method for measuring the Additional No-load Losses

On the base the known depend for P_{Fe1} [25] and the proposed dependence for P_{ado} (35) it is proved that the conventional core losses can be separated in two components:

- the fundamental core losses (P_{Fe1}), which are proportionate to the squared voltage value, i.e.:

$$P_{Fe1} = P_{Fe1,n}(U_0/U_n)^2 \quad (36)$$

- the additional no-load losses (P_{ado}), which are proportionate to the squared no-load current value:

$$P_{ado} = P_{ado,n}(I_0/I_{0n})^2 \quad (37)$$

Nominal values, fundamental ($P_{Fe1,n}$) and additional no-load losses ($P_{ado,n}$), are determined from no-load test, performed for two different voltage values, i.e. from two equation (two tests) form:

$$P_{Fe} = P_{Fe1,n}\,(U_0/U_n)^2 + P_{ado,n}(I_0/I_{0,n})^2 \quad (38)$$

and, practically, dependence the total core losses (P_{Fe}) against voltage value (U_0) and no-load current (I_0) are given by equation (38).

It is interesting to notice that the difference between measured value of no-load core losses ($P_{Fe,m}$) and value (P_{Fe}) obtained by equation (38), on the base of the value ($P_{Fe1,n}$) and ($P_{ado,n}$) determined by the proposed no-load test [8], is neglected for the induction motors rated powers from 3 ¸ 75 *kW* in the voltage ranging from 0.6 ¸ $1.1\ U_n$.

3.3 Calculation of the Slot Harmonics in (Un)Saturation Machines

On the base equations (34)-(38) and the experimental verification [8], it is proved that saturation of the machine magnetic circuit, practically, don't influence on the slot harmonic peak values B_{xk} and B_{fJ}, i.e. the saturation factor values, for the field slot harmonic ($K_{Fe,\vartheta f}$) and the slot permeance harmonics field ($K_{Fe,xk}$), are

$$K_{Fe,f\vartheta} = K_{Fe,xk} = 1 \ \text{ for } \ \vartheta_f = x_K = k\,S_1/p \pm 1, \quad k=1,2,3,\ \ldots \quad (39)$$

and, values of the slot permeance harmonic filed are greater for K_{Fe1} time (K_{Fe1} - saturation factor for fundamental harmonics) from the relative values given by equation (13), i.e.:

$$B_{xK}/B_1 = (b/2)h_K \times K_{g1} \times K_{Fe1} \quad (40)$$

Equation (40) to take into account the saturation influence for the 1-st harmonic, and by this is more complete and more exactly then equation (13) which is given in literature [6].

Sum of square values of the all field slots harmonics, consequently equation (28) is:

$$S(B_{J0}(B_1)^2 = S(B_{xkO} / B_1)^2 + S(B_{Jf0} / B_1)^2, \quad J = kS_1 / p \pm 1 \quad (41)$$

4. CONCLUSIONS

The most important results, which are obtained in this paper, are briefly described in following paragraphs.

1. On the base of the presumption, for quality dependence of the slot permeance harmonic fields ($B_{xK} \sim I_0$) and field slot harmonics ($B_{xk} \sim I_0$), the dependence $P_{ado} \sim I_0^2$ is establishment. This last is proved experimentally [8].
2. The conclusion $B_{xK} \sim I_0$ gives a new theoretical approach opposite to the well known [11] that the slot permeanse harmonic fields are proportionate the main field values, i.e. the voltage values ($B_{xk} \sim U_0$). This conclusions give opportunity that the calculation of the slot permeance harmonic fields (B_{xk}) perform on the simple and sufficient exactly manner, and for the saturation induction machines.
3. Established analitical dependence of total core losses (P_{Fe}) against voltage and no-load current values (Eq. 38), enables more precise estimation of voltage value influence to power losses and motor efficiency, as well as to commend more precise choice of optimal flux density, while designing induction machines.

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