STUDY OF THE MAGNETIC FIELD OF THE D.C. MACHINE USING NUMERICAL METHODS

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Abstract- **The paper is a study on the effects of the saturation on the magnetic field of the D.C. machine. This fields help us to find the inductances and theirs dependence with the magnetic saturation level. In this way we can find the parameters of the machine with a good precision and also, it is possible to know the behavior of the machine in different dynamical regimes.**

Keywords: *D.C. machines, magnetic field, numerical methods.*

1. INTRODUCION

At the electrical machine, powerfully solicits magnetic, to calculate the useful and the leakage inductances and to establish their dependence on saturation it is imposing a correct calculation of the magnetic voltages on the way of the magnetic field.
To find the level of deformation of the field in the air gap for different operations regimes it is imposing to use the numerical methods to calculate, for a more elaborate study.

2. ASPECTS ON THE MACHINE WITH NOTCHED ARMATURE

It knows that because of the presence of the slots on one armature (fig.1.a) the induction created in the air gap by the inductor field is modulate in amplitude (fig.1.b).

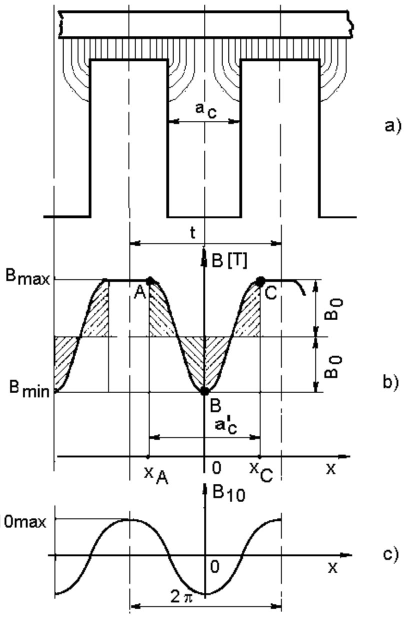


Fig. 1. a) Spectrum of the induction magnetic in the air gap in the presence of notches on one armature; b) spatial repartition of the magnetic induction; c) fundamental harmonics of the modulated wave.

The amplitude of the modulated wave (fig.1.c) is in a determinate relation with the magnetic induction in the air gap produced by the inductor field which, at its turn is inverse proportional with the width of the air gap.

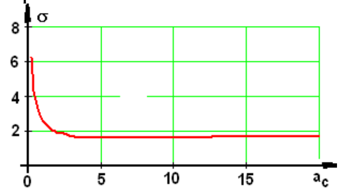


Fig. 2. Curve $\sigma = f(a_r/\delta)$.

To obtain the curve of magnetic induction (fig.1,b) are made the following steps:

$$b_d = t - a_c \qquad a_\sigma = \frac{a_c}{\delta} \tag{1}$$

From fig.2 results $\sigma = f(a_\sigma)$ and calculates:

$$a_c^/ = a_c \cdot \sigma \qquad b_d^/ = t - a_c^/ \tag{2}$$

$$\gamma = \frac{\left(\frac{a_c}{\delta}\right)^2}{5 + \frac{a_c}{\delta}} \qquad \beta = \frac{\gamma \cdot \delta}{a_c^/} \tag{3}$$

$$B_{10\max} = B_\delta \beta \tag{4}$$

$$B_{\max} = k_C B_\delta \tag{5}$$

$$B_{\min} = B_{\max} - 2B_{10\max} \tag{6}$$

The significations of the quantities can be see in fig.1 and are those known in literature. Curve of magnetic induction (fig.1.b) is obtains by interpolating with linear or squared functions on section. So, under the equivalent dental step $b_d^/$ the magnetic induction is constant with value $B_{\max}$, and between A, B and C points it has the shape of a parabola with the arms up turn. Coefficients of the interpolation function :

$$f(x) = ax^5 + bx^4 + cx^3 + dx^2 + ex + m \tag{7}$$

are finding with the condition of passing by the points A($x_A, B_{\max}$),B($x_B, B_{\min}$),C($x_C, B_{\max}$) and $f^/(x_A)$=0, $f^/(x_B) = 0$, $f^/(x_C) = 0$, where $x_A = -0{,}5a_c^/$, $x_B = 0$, $x_C = 0{,}5a_c^/$.
Calculus relation of the magnetic induction allows us to find the variable size of the air gap referred with the notches position,

$$\delta(x) = \frac{\mu_0 U_{m\delta}}{2B_\delta} \quad (8)$$

3. MAGNETIC FIELDS CALCULUS

In the first part of the paper it is proposing an evaluation and a correct graphical representation of the reaction field and then a calculus exact of the inductance. Curve of the repartition of the reaction field in the air gap is finding with the relation:

$$B_a = \frac{\mu_0 \theta_a(x)}{2\delta^{//}(x)} \quad (9)$$

where $\theta_a(x)$ is the curve of the spatial distribution of the reaction turn ampere for the armature; $\delta^{//}(x)$ equivalent air gap which taken account with the saturation and the presence of notch.

We consider for the reaction turn ampere a linear triangular variation, or a triangular curve in steps, when in the axis of the notch ampere-turns jump and the case most closed of reality when the notch turn ampere rise linear and in the area of tooth is constant.

In this mode is calculating with numerical methods the average value of the induction and than is finding the inductance of the armature's winding with the relation:

$$L_{aq} = \frac{1}{2a} N_{sp/\tau} \frac{B_{aqmed} l_i \tau}{i_a} \quad (10)$$

$N_{sp/\tau}$ - number of turns on a polar step; $B_{aq\,med}$ - average value of the armature's magnetic inductance of reaction; l_i - ideal length of the machine; i_a - current on a path of current; a -number of paths of current in parallel; τ -polar step.

For different value of the load factor ($k_a = I_a / I_{aN}$), we can find the inductances L_a, and plot $L_a = f(k_a)$, to establish its dependence on level of magnetic saturation. Calculus of the excitation winding and its dependence with the level of magnetic saturation supposes a similar track.

4. SIMULATIONS AND CONCUSIONS

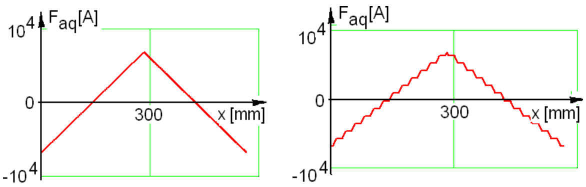
Using the numerical calculation, on the presented concepts and those known from the literature was made a MathCAD calculation and plotting program for the magnetic fields in the machines of D.C. The advantage of this sort of approach is that the obtained results can be orientated with minimum efforts towards the important studied aspects demanded by the designer or the beneficiary.

The research has been done on a DC motor with separate excitation in two construction variants, compensate and non-compensate. Rated value for the motor are: $P_N = 340$ kW; $U_N = 450$ V; $n_N = 845$ rot/min.; $I_N = 820$ A, $U_{ex} = 220$ V; $I_{ex} = 16{,}2$ A.

4.1. Non-compensated machine

Characteristic of magnetization of the machine is finding by experiments or by calculus starting with the rate dates.

Figure 3.a shows us the simplified shape (linear) for the turn ampere curve of the armature In reality, the conductors afferent to a notch for the rotor are uniform distributing on the whole surface. So the ampere-turns is constant in teeth and linear in the areas of notch (fig.3.b). For the following determinations it will be used the step curve of the ampere-turns (fig.3.b).



a) b)

Fig.3. Curves of the spatial repartition of the ampere-turns of reaction: a) linear variation; b) step variation.

This machine hasn't compensation winding on the armature, the notch of the rotor is rectangular and open with $a_{cr} = 8{,}82$ mm, and the dental step is $t_r = 22{,}7$ mm. In those conditions, the width of the air gap is variable and value calculated for the magnetic induction is very closed to the real one ($B_{\delta med} = 0{,}788$ T, and $B_\delta = 0{,}79$ T), known from technique card.

With the curve of ampere-turns (fig.3.b) and the numerical simulation of the air gap it is found the curve of magnetic induction for the real machine (fig.4 - with notch on the rotor and magnetic saturation).

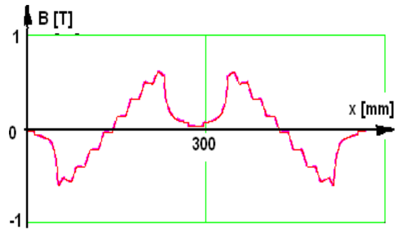


Fig.4. Curve of magnetic induction of reaction at the non compensated machine when the saturation and rotor's notches are considering.

Corresponding with fig.4 the average value of the magnetic induction is $B_{aqmed} = 0{,}236$ T. It was calculated the reaction flux of the armature and the inductance of this winding using the relation (10). At high values of the load current the saturation interfered also on the way of lines of transversal reaction field. Those determinations were made for much values of load factor ($k_a = I_a / I_{aN}$), allowed to find the dependence between inductance and saturation level of the machine and to plot the characteristic $L_{aq} = f(k_a)$ (fig.5). The values of the used quantities are:

$L_{aqN} = 0{,}839\, mH$, $I_{aN} = 820\, A$.

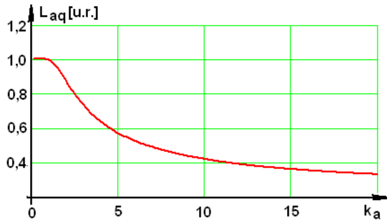
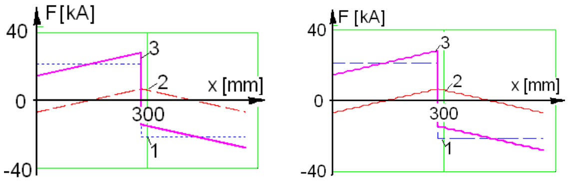


Fig.5. Dependence of the inductance of rotor's winding with the saturation level of the machine.

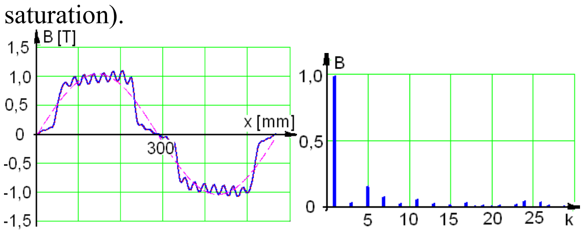
For the rate point the value is much closed with this obtain by experiment, $L_{aq\ \exp} = 0{,}832$ mH. Figure 6 shows all the curve of turn's ampere for the windings of the machine: 1- excitation; 2- armature's reaction; 3 – resulted.



a) b)

Fig. 6. Curves of ampere – turns for the non compensate machine: 1 – excitation; 2 – reaction; 3- resulted. (Linear variation; b-step variation);

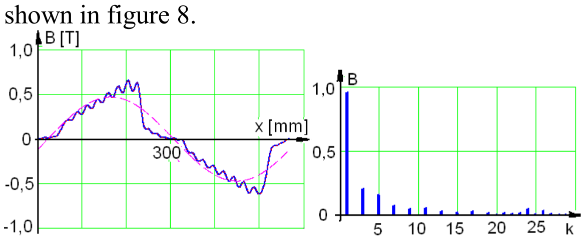
Starting with curve 1, those corresponding with the ampere- turn of excitation (fig. 6.b) and with the numeric simulation of the air gap, it was established the curve of the excitation field of the real machine (fig. 7 – with the notches on rotor and magnetic saturation).



a) b)

Fig. 7. a) Real curve and the fundamental harmonic of the inductor field for the non - compensate machine. b) spectrum of harmonics.

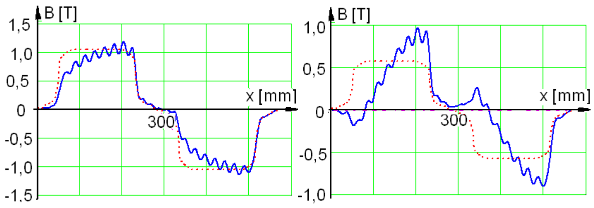
The operating at slack field $I_e = 0{,}4 I_{eN}$ of the motor, where the level of the field deformation is important is shown in figure 8.



a) b)

Fig. 8. a) Real curve of magnetic induction at slack field for the non-compensate machine; b) spectrum of harmonics.

Short lived overcharge are meet frequently in D.C. motors operation. In these regimes the reaction field is very important and deformed strongly the resulted field. There are presented qualitative and quantitative the effects of a overcharge $I_s = 3 I_N$ for the operation at full field (fig. 9.a), or slack field (fig. 9.b). At slack field the deformation is so big that can established an instable operation.

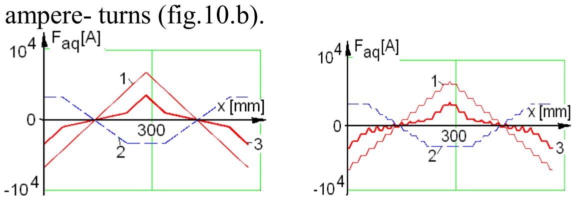


a) b)

Fig. 9. Magnetic induction curve for the non-compensated machine and overcharge: a) full field; b) slack field.

4.2. Compensated motor

For the study it is considering the same D.C. motor but compensated machine ($\gamma = 0{,}71$- level of compensation). The following analysis considers the same aspects as the non compensated machine. Curves of ampere- turns (1-reaction one, 2-compensation one, 3-resulted one) are shown in fig. fig.10.a for the uniform distributed winding on the armatures periphery, and in fig.10.b for discrete winding placed in notches. It is considering a step curve for the ampere- turns (fig.10.b).



a) b)

Fig.10. Curves of ampere- turns: 1-reaction one, 2-compensation one, 3-resulted one, established for: a) linear variation; b) step variation.

At the compensated machine the presence of the notches in rotor and armature, supposes that the width of the air gap must be much variable. The rotor's notch is rectangular and open with $a_{cr} = 8{,}82$ mm and $t_r = 22{,}7$ mm, it was used a semi – open notch for the compensation winding with $b_{cs} = 9{,}6$ mm $a_{cs} = 3$ mm, $t_s = 21{,}2$ mm.

Was traced the curve of induction of reaction (fig.11, $B_{aqmed} = 0{,}013$ T), was calculated the flux and the inductance for the rotor's winding (fig.12), using the same relation (10). Rated value is $L_{aqN} = 0{,}047\, mH$, more little other of the non compensated machine.

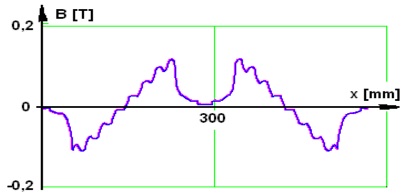


Fig.11. Curve of the induction of reaction for the compensated machine when is considered the saturation, notches of rotor and stator.

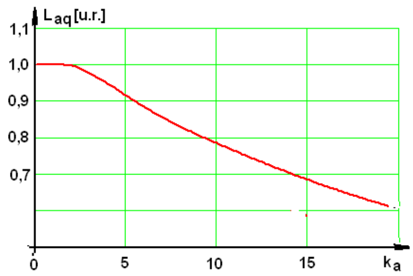
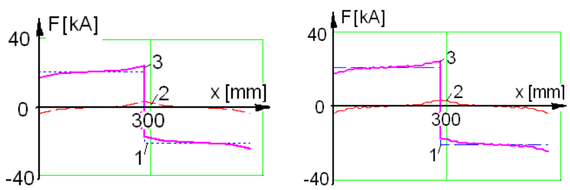


Fig. 12. Dependence between inductance of the rotor's winding and the saturation level of the machine.

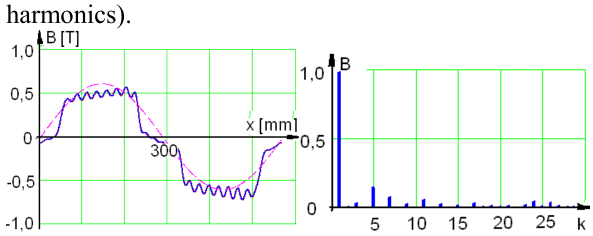


a) b)

Fig. 13. Curves of ampere- turns for the compensated machine: 1-excitation; 2-reaction, 3-resulted (a- linear variation; b- step variation).

The aspects analyzed for the inductor field are repeated, much abstract and for the compensated machine is resulted the following figures.

For the operation in slack field $I_e = 0{,}4 I_{eN}$, simulation result is in fig.14 (curve and spectrum of harmonics).



a) b)

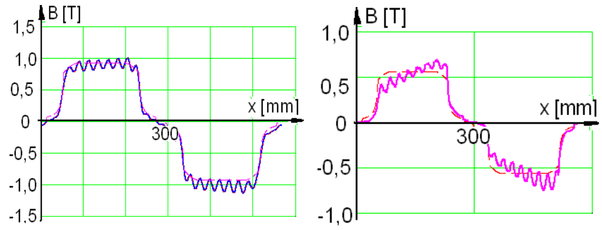
Fig. 14. a) Magnetic induction curve at slack field for the compensated machine; b) spectrum of harmonics.

It was analyzed the behavior of the compensated machine at an overcharge $k_a = I_a / I_{aN} = 3$. The significant curves for the operation in full field are shown in fig. 15.a and for slack field in fig. 15.b.

On this study we can find the repartition of the potential on the collector, and establish the critical areas (with maximal magnetic induction), where the voltage between bars:

$$U_{ek} = 2 \cdot v_a \cdot l_i \cdot B_m \qquad (11)$$

is above the admitted limits $U_{k\,adm}$ (table no.1). Those are the areas where can appear brush between bars and also 'the hoop' which is deteriorating the machine.



a) b)

Fig. 15. Magnetic induction curve for the compensated machine and overcharge: a) full field; b) slack field.

Table no.1

		Non compensated machine $U_{k\,adm}$ <16 V		Compensated machine $U_{k\,adm}$ <20 V	
		B_m [T]	U_{ek} [V]	B_m [T]	U_{ek} [V]
Full field n=845 rot/min	I_N	0,86	11,12	1,03	12,7
	$3\,I_N$	1,06	13,2	1,047	12,95
Slack field n=2350 rot/min	I_N	0,618	23,3	0,63	21,6
	$3\,I_N$	0,836	28,7	0,696	23,9

On this study we can say that the analyzed motor was good designed, with a great air gap and a compensation winding. In all operating regimes (full field, slack field, overcharge) the deformation level of the field is acceptable. This conclusion is confirmed by the good behavior of this motor in the conditions of practice in the bore-hole about 12 years.

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