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Computing of the Slot Number within the Induction Machine Approached in Terms of Electromagnetic Forces

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In order to find the final solution the design of electrical machines usually involves different steps. In the starting stages of design procedure, some of the main variables are given data and all the others must be adopted by a proper approach. This paper proposes a method for determining the total slot number within the induction machine by approaching electromagnetic forces that leads to a particular relationship. The final solution is checked by some manufactured induction machine.

Keywords: *induction machine, rectangular slot, electromagnetic stress.*

1. Introduction

Electrical machines allow developing a large area of applications, which are continuously improved in order to obtain high performances.

From the electromagnetic flow direction, the electrical machines may operate in motor or generator mode. Actually, the motor mode of electrical machines is strongly developed due to major performances obtained in different associated fields, as: power electronics, PLC and microcontrollers, special network of intelligent communications etc. In generator mode, electrical machines are starting to have an important percentage, once renewable resources are developing.

In the actual applications, classical machines are the most used options. In the motor mode, for electric drives, which are present in a large number of applications in industry and residence, induction machine is the most convenient option, due to the following benefits: simple and robust construction, much less maintenance, much more versatile and practical than DC machine, less expensive, etc.

The design of the induction machine is well-known and well-developed for a long time. It is continuously improved in order to find its best performance. As a consequence of the vast knowledge about the induction machine, a classification by efficiency criteria has been developed, and up to date there are the following class: IE1-Standard Motors, IE2-Eficient Motors, IE3-Premium Motors and IE4-Super Premium Motors.

The design of induction machine is well-represented in literature [1, 2]. Generally, the design methodology is based on Esson's constant for determining the main geometric sizes of the machine.

A relatively recent approach [3, 4] based on Poynting theorem of electromagnetic energy approach proposes a new vision for designing electrical machines with symmetric geometry. The trend is set toward developing geometric relationships which are dependent on constants that can be easier estimated in practice. As a consequence of this, work is desired to improve the simple analytic relationships.

In paper [5] has been developed a simple relationship for computing the slot number per pole and phase at the rotational induction machine. The approach is based on equation of heat transfer at stator slot that allows imposing the temperature of slots' stator insulation. Thus, the slot number per pole and phase at rotational induction machine may be computed based on a limited number of quantities. Based on this approach it has been computed as Joule power losses [6].

In addition to this, other important elements of the machine, as stator turns number [7] or slot area have been determined [8].

An important attention has been paid to the evaluation of electromagnetic stress once with poles commutation [9].

In order to demonstrate the interdependence of the main phenomena within the induction machine, in paper [10] has concluded that the geometrical limitation of the induction machine can be expressed as a thermal one.

Actually, an important effort has been made for searching other approaches that may be useful for practice.

2. Computing of slot number

The design of the induction machine starts from the design theme, where the main performances are established, usually in steady-state regime, and other restrictions are adopted too according to the particularity of the design project.

The main steps for an effective design may be classified by: electromagnetic computing, thermal computing, mechanical computing etc.

In the electric field, an important attention on electric machine is paid on electromagnetic field.

In the order to find the geometrical dimensions of electrical machine, it is necessary to establish the main quantities as magnetic flux density on the air-gap B_δ[T], current density J[A/mm^2] and linear current density A[A/mm]. All the others quantities are resulting as consequence of the imposed restrictions, that may varies according to the load application of electrical machines or other supplementary conditions.

In order to reduce the number of the involved variables in the design phase, additional constraints can be added. An efficient constraint is developed by limiting the product of electric stress [1, 2]:

$$A_1 \cdot J_1 \approx 3000(I.P.44) \div 3200(I.P.23)\left[\frac{A^2}{mm^2}\right], \tag{1}$$

which, by tacking the relationship of thermal flow of losses in the active part of stator winding [2]:

$$Q_{1T} = \rho_1 \cdot J_1 \cdot A_1\left[\frac{W}{m^2}\right], \tag{2}$$

the limitation may extended on limits [2]:

$$Q_{1T} \approx 3000(I.P.44) \div 8000(I.P.23)\left[\frac{W}{m^2}\right]. \tag{3}$$

In the Figure 1 is presented a section of stator of the induction machine analysed. On the section has been depicted the geometrical dimensions of the rectangular slot.

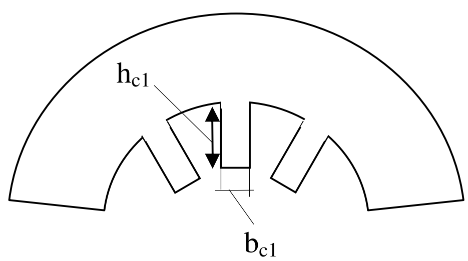

Figure 1. Stator section of induction machine.

In the paper is considerate only induction machine with rectangular slots. In this situation, the geometrical dimensions of the slot are [1-2]:

$$h_{c1} \cong \frac{A_1}{J_1 k_{U1}(1-k_{z1})}[m], \tag{4}$$

$$\gamma_1 = \frac{h_{c1}}{b_{c1}} \geq 3, \tag{5}$$

which leads to slot area described by.

$$S_{c1} = h_{c1} \cdot b_{c1} = \frac{h_{c1}^2}{\gamma_1}. \tag{6}$$

For developing our approach, we will start from the total area of stator slots may be computed by [1-2]:

$$Q_s = \frac{16 p k_E S_1}{\pi^3 \sqrt{2} \alpha_0 k_{w1} f Z_1} \cdot \frac{1}{f_u} \cdot \frac{1}{J B_\delta L D}. \tag{7}$$

Taking into account the relationship of inner electromagnetic apparent power:

$$S_e = S_p \pi D L, \tag{8}$$

results:

$$DL = \frac{1}{\pi} \cdot \frac{S_e}{S_p}. \tag{9}$$

With the help of the last relationship, the relationship (7) becomes:

$$Q_s = \frac{16 p k_E}{\pi^2 \sqrt{2} \alpha_0 k_{w1} f Z_1} \cdot \frac{1}{f_u} \cdot \frac{1}{J B_\delta} S_p. \tag{10}$$

With the relationship of electromagnetic force density in air gap of induction machine, expressed b:

$$f_\delta = \frac{1}{\sqrt{2}} J B_\delta, \tag{11}$$

the total area of stator slots relationship becomes:

$$Q_s = \frac{16 p k_E}{\pi^2 2 \alpha_0 k_{w1} f Z_1} \cdot \frac{1}{f_u} \cdot \frac{1}{\overline{f_\delta}} S_p. \tag{12}$$

The Poynting vector magnitude may be expressed as a function of peripheral speed and air gap electromagnetic stress [3]:

$$S_p = V_1 \sigma_\delta. \tag{13}$$

With the help of the last relationship, relationship (12) becomes:

$$Q_s = \frac{16 p k_E}{\pi^2 2 \alpha_0 k_{w1} Z_1} \cdot \frac{1}{f_u} \cdot \frac{V_1}{f} \frac{\sigma_\delta}{\overline{f_\delta}}. \tag{14}$$

If we take into account the relationship of total number of stator slot becomes:

$$Z_1 = \frac{\pi D}{t_1}, \tag{15}$$

and the one of peripheral speed:

$$V_1 = \Omega_1 \frac{D}{2}, \tag{16}$$

relationship (14) becomes:

$$Q_s = \frac{4 p k_E}{\pi^3 \alpha_0 k_{w1}} \cdot \frac{1}{f_u} \cdot \frac{t_1 \Omega_1}{f} \frac{\sigma_\delta}{\overline{f_\delta}}. \tag{17}$$

The electromagnetic stress in the air gap may be expressed as a function of force density [2]:

$$\sigma_\delta = f_\delta \cdot \Delta, \tag{18}$$

where Δ is the thickness of current density.

Based on relationship (17), the total area of stator slots relationship (18) becomes:

$$Q_s = \frac{4pk_E}{\pi^3 \alpha_0 k_{w1}} \cdot \frac{1}{f_u} \cdot \frac{t_1 \Omega_1}{f} \Delta . \tag{19}$$

The last relationship can be expressed as a function of slip:

$$Q_s = \frac{8k_E}{\pi^2 \alpha_0 k_{w1}} \cdot \frac{1}{f_u} \cdot t_1 \Delta \frac{1}{s_1 + 1} . \tag{20}$$

If we consider the definition of tooth pitch:

$$t_1 = \frac{b_{c1}}{k_{z1}} , \tag{21}$$

the relationship (20) becomes:

$$Q_s = \frac{8k_E}{\pi^2 \alpha_0 k_{w1}} \cdot \frac{1}{f_u} \cdot \frac{b_{c1}}{k_{z1}} \Delta \frac{1}{s_1 + 1} . \tag{22}$$

The total area of stator slots may be expressed by:

$$Q_s = Z_1 \cdot S_{c1} = Z_1 \cdot b_{c1} \cdot h_{c1} . \tag{23}$$

From relationships (6), (22) and (23), the total number of stator slots becomes:

$$Z_1 = \frac{Q_s}{b_{c1} \cdot h_{c1}} = \frac{8k_E}{\pi^2 \alpha_0 k_{w1}} \cdot \frac{1}{f_u} \cdot \frac{1}{k_{z1}} \Delta \frac{1}{s_1 + 1} \cdot \frac{1}{h_{c1}} . \tag{24}$$

If we group all the constants in a global one:

$$K = \frac{8k_E}{\pi^2 \alpha_0 k_{w1}} \cdot \frac{1}{f_u} \cdot \frac{1}{k_{z1}} \Delta \frac{1}{s_1 + 1} , \tag{25}$$

we can find the final relationship of total number of stator slots described by:

$$Z_1 = \frac{K}{h_{c1}} . \tag{26}$$

According to the last relationships (24)-(26), some important remarks may make:

- Due to the fact that the relationship (26) contains quantities, which are in a steady-state regime, the selection of total number of stator slots is powerful depended on the height of stator slots as a restriction;
- In the relationship of global constant (25) may be funded, through other quantities, the synchronous speed, which has imposed values, depending on the frequency and number of stator poles pairs;
- The relationship (26) may use in various modes, considering some variables contained in (25) as a primary one, and all the other being depended on the first one.

In Figure 2 is represented the nonlinear dependence of total slots number by height of slot.

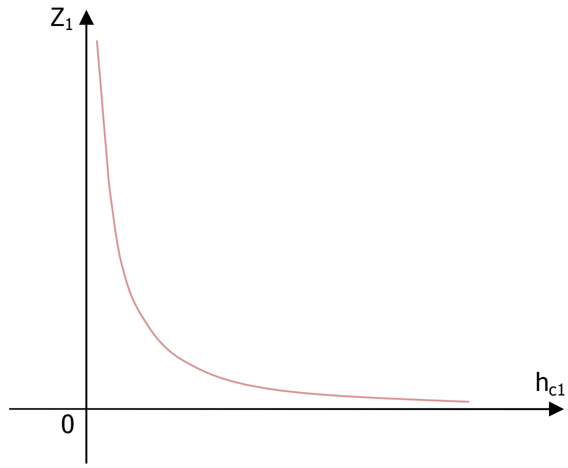

Figure 2. Graphical dependence Z_1=f(h_{c1}).

From relationship (5), the with of the stator slot can be represented by:

$$b_{c1} = \frac{h_{c1}}{\gamma_1}, \tag{27}$$

that lead to expressed the slot area:

$$S_{c1} = \frac{h_{c1}^2}{\gamma_1}. \tag{28}$$

From relationships (26)-(28), the total number of the slots results:

$$Z_1 = \frac{K}{\sqrt{S_{c1}\gamma_1}}, \tag{29}$$

which, based on

From literature [2], in practice the tooth pitch is limitated by:

$$0.05\tau < t_1 < 0.2\tau, \tag{30}$$

and if is used the aspect ratio relationship:

$$\lambda = \frac{l_i}{\tau}, \tag{31}$$

results:

$$0.05\frac{l_i}{\lambda} < t_1 < 0.2\frac{l_i}{\lambda}, \tag{32}$$

that leads to:

$$Z_{1\min} < Z_1 < Z_{1\max}. \tag{33}$$

3. Experimental checking

In this section is checked the above theoretical background on some manufactured induction machines. Based on data from [2, 3], it is represented graphically in Figure 3 the aspect ratio of the manufactured induction machines and the limits.

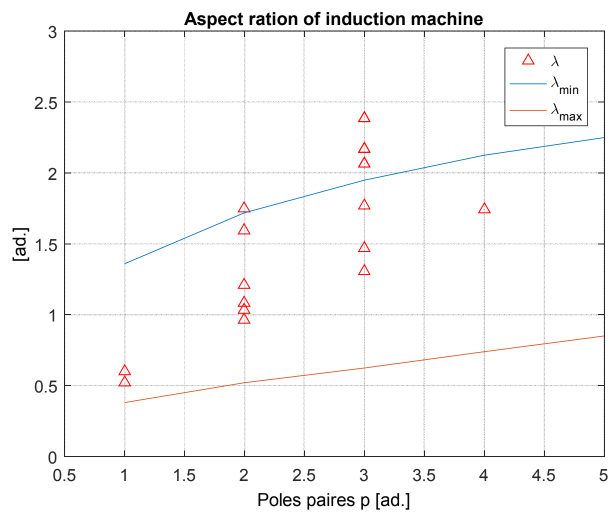

Figure 3. Aspect ratio: current designed machines and limits.

Based on conditions (32), in Figure 4 are represented the extremal values of the tooth pitch.

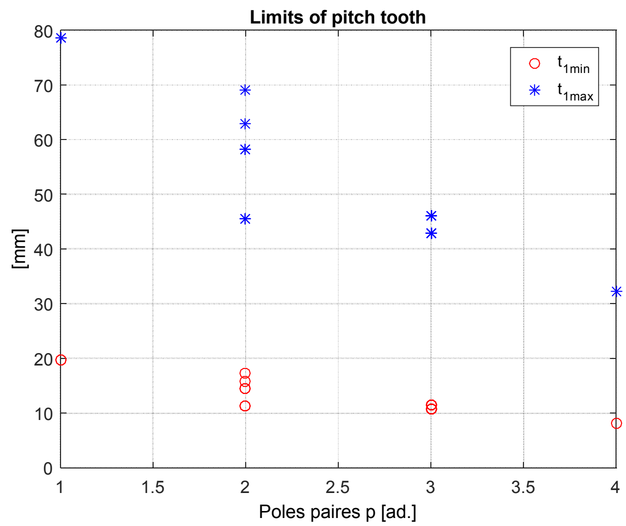

Figure 4. Tooth pitch limits.

Now, taking into account the relationships (26), (29) and (33), in Figure 5 are depicted the total number of stator slots limits and the corresponding limits.

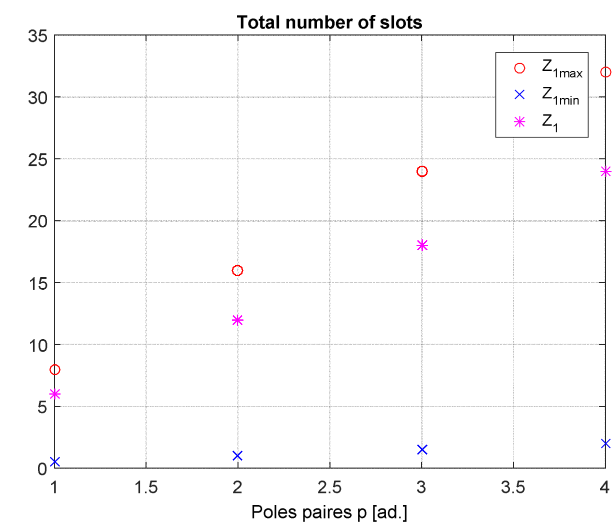

Figure 5. Total number of stator slots limits: limits and current value.

4. Conclusion

The selection of slot number of induction machine is an important task and need an adequate approach.

The work developed on the paper proposed the computing of slot number of induction machine based on electromagnetic force developed by machine. Thus, the potentiality of the induction machine is conserved.

The checking on manufactured induction machine confirms the validity of the proposed work developed on the paper.

In design process it may be analyzed different scenarios according to the final destination of induction machine. Thus, the final solution is evaluated in concrete conditions.

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