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Assessment of Electromagnetic Stress in a Permanent Magnet Synchronous Machine with Commutable Poles

The permanent magnet synchronous machine is an adequate solution in a large range of power in high performance electrical drives and energy conversion systems. In this paper has been assessed the permanent magnet synchronous machine electromagnetic stress for the case of stator winding with commutable poles. Based on simplified assumptions, an analytic relationship of the dependence of electromagnetic stress has been obtained. Numerical simulation performed for a case study confirms the validity of the theoretical approach developed.

Keywords: permanent magnet synchronous machine, electromagnetic stress, commutable poles, design

1. Introduction

The energy conversion systems play a major role in worldwide energy politics. This is a consequence by the limitation of the distribution of the classical resources on the earth and, in addition, by the negative effects on the environment impact. An important direction is about conversion of energy with high performances electrical machines in modern drive. Classical electrical drives are design with DC machine and induction one. A high technology is about synchronous machine with excitation based on permanent magnets.

Electrical machines are treated, in literature survey, after more criteria: design, control, environmental impact etc [1]-[6], [8]-[10].

The design of electrical machines with a minimal value of costs and consumption of active materials (Fe, Cu and PM-permanent magnet) is one of the nowadays problem [7], [12]-[14], but this problem must be solved by a multi-approach global optimization, where additional constraints but me tacked into consideration according to machine destination.

In the paper is approached the problem of assessment of electromagnetic stress for a case situation of speed variation by commutable poles for a permanent magnet synchronous machine.

2. Assessment of Electromagnetic Stress for a Permanent Magnet Synchronous Machine with Commutable Poles

The general designing methodology of electrical machines involves, in general, different steps in the order to find the desirable optimal solution according to various imposed criteria: economic criteria, dimensional one, performances etc. From this point of view, many scenarios - according to the specifics of applications - may be investigated. Due to the fact that the numbers of design methodology freedom degrees are bigger than unknown variables, additional constraints must be having into account [16]-[17]. From the electromagnetic point of view, it is fallows that electrical stress represented by current density J_1[A/mm^2] and linear current density A_1[A/mm^2] respectively, and magnetic stress as magnetic flux density in the air gap B_δ[T] to be placed in a admissible range according to accumulated practical experiences in the graphical monograms [8]. From this point of view, the traditional design of electrical machines is strong linked by the already constructed machines. Thus, beside those constraints, the product of electrical stress -as a thermal constraint -must be chosen according to machine degree protection (IP) [13], [14] and [18]:

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

Based on this restriction, the thermal flow of losses in the active part of stator winding may be estimated, according to the range [13], [14] and [18]:

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

where the thermal flow is described by: $Q_{1T}=\rho_1 A_1 J_1$ (ρ_1- copper resistivity).

In the paper [7] has been establishing an important and useful relationship for computing of slots number per pole and phase:

$$q_1 = \text{¥}_1 \cdot k_{z1} \frac{\text{®}D_1}{2m_1 p_1 h_{c1}}. \tag{3}$$

where p_1 - is the number of stator poles pairs, h_{c1} - height of stator, γ_1 - architecture factor of slot, k_{z1} – slot factor and m_1 –number of phases.

By applying the above relationship for the both case of different poles, is obtained:

$$q_{11} = \gamma_{11} \cdot k_{z11} \frac{\pi D_{11}}{2m_{11} p_{11} h_{c11}} \tag{4}$$

$$q_{12} = \gamma_{12} \cdot k_{z12} \frac{\pi D_{12}}{2 m_{12} p_{12} h_{c112}} . \quad (5)$$

Due to the fact that the stator has the some construction, the next equalities resulting:

$$D_{11} = D_{12} = D_1 \quad (6)$$

$$h_{c11} = h_{c12} = h_{c1} \quad (7)$$

$$m_{11} = m_{12} = m_1 \quad (8)$$

$$\gamma_{11} = \gamma_{12} = \gamma_1 . \quad (9)$$

The poles pairs and the slot factor are different for both two situations of poles commutable:

$$p_{11} \neq p_{12} \quad (10)$$

$$k_{z11} \neq k_{z12} . \quad (11)$$

Those particularities described by relationships (6)-(11) are important in the computing phase of electromagnetic stress. Based on this, electromagnetic stress will be computed the reference state represented by rated one.

Starting from the condition that total number of slots will be de same (despite of the situation when the number of slots per pole and phase may be different):

$$Z_{11} = Z_{12} = Z_1 \quad (12)$$

It is resulting that:

$$p_{11} q_{11} = p_{12} q_{12} \quad (13)$$

Taking into account the above relationship, relationships (4)-(5) and conditions expressed by relationships (6)-(11), it is resulting:

$$p_{11} q_{11} k_{z12} = p_{12} q_{12} k_{z11} \quad (14)$$

From de above relationship, the magnetic flux density result as:

$$B_{\delta 12} = \frac{B_{\delta 11} \cdot B_{d12}}{B_{d11}} \quad (15)$$

Now, from relationships (4) and (5) we obtain the architecture factor of right slot:

$$\gamma_{11} = \frac{Q_{11T}}{2(1 - k_{z11}) Q_{11c}} - 1 \quad (16)$$

$$\gamma_{12} = \frac{Q_{12T}}{2(1 - k_{z12}) Q_{12c}} - 1 \quad (17)$$

Due to the fact that both factor represented by relationships (16) and (17) must be equal (because the slot remains the same), we obtain for thermal flow of losses in the active part of stator winding, for the second case, the next relationship:

$$Q_{12T} = Q_{11T} \frac{1-k_{z12}}{1-k_{z11}} \cdot \frac{Q_{12s}}{Q_{11s}}. \tag{18}$$

If we take into consideration the relationship (14), we get the next relationship for thermal flow:

$$Q_{12T} = Q_{11T} \cdot \frac{Q_{12s}}{Q_{11s}}. \tag{19}$$

A useful relationship may be expressed between thermal flow and temperature rise on the stator slot insulation:

$$\theta_{ins} \cong \frac{\Delta_{in1}}{\lambda_{in1}} \cdot Q_s \le \theta_{inad} [30^0 \div 40^0], \tag{20}$$

where: Δ_{in1} thickness of insulation and λ_{in1} is thermal conductivity, while in the parentheses was noticed, by practical experiences, from design machine, the maximal values of temperature.

Based on relationship (20) the thermal flow of losses in the stator slot insulation may express as:

$$Q_{11s} = \frac{\lambda_{in11}}{\Delta_{in11}} \cdot \theta_{in11}, \tag{21}$$

$$Q_{11s} = \frac{\lambda_{in11}}{\Delta_{in11}} \cdot \theta_{in12}. \tag{22}$$

Taking into account the relationships (19), (21) and (22), the thermal flow of losses in the active part of stator winding becomes:

$$Q_{12T} = Q_{11T} \cdot \frac{\theta_{in12}}{\theta_{in11}}. \tag{23}$$

All the relationships developed until now are used for a global approach, in the particularly case, a thermal one. More useful approach is the one that may express the electromagnetic stress, which are very important in the design procedure of electric machine. A fundamental relationship makes the link between thermal flow and electromagnetic stress:

$$Q_{11T} = \rho_{11} A_{11} J_{11} \tag{24}$$

$$Q_{12T} = \rho_{12} A_{12} J_{12} \tag{25}$$

If we considerate that the resistivity does not vary with temperature ($\rho_{11}=\rho_{12}$) and based on relationship (23)-(25), we obtain the next dependence:

$$A_{12} J_{12} = A_{11} J_{11} \frac{\rho_{11}}{\rho_{12}} \cdot \frac{\theta_{in12}}{\theta_{in11}} \tag{26}$$

Based on the least relationship, the electromagnetic stress as current density and linear current density are expressed by the next two relationships:

$$J_{12} = J_{11} \frac{A_{11}}{A_{12}} \cdot \frac{\rho_{11}}{\rho_{12}} \cdot \frac{\theta_{in12}}{\theta_{in11}} \tag{27}$$

$$A_{12} = A_{11}\frac{J_{11}}{J_{12}}\cdot\frac{\rho_{11}}{\rho_{12}}\cdot\frac{\theta_{in12}}{\theta_{in11}} \tag{28}$$

Knowing the electromagnetic stress or the dependence between them, now mechanical stress developed by electromagnetic forces may be computed.

The apparent efforts are described by [13]-[15]:

$$\sigma_{11} = \frac{1}{\sqrt{2}}A_{11}B_{\delta 11} \tag{29}$$

$$\sigma_{12} = \frac{1}{\sqrt{2}}A_{12}B_{\delta 12} \tag{30}$$

where $B_{\delta 1}$ is magnetic flux density on air gap.

From relationships (26)-(29) is obtained the apparent effort:

$$\sigma_{12} = \sigma_{11}\cdot\frac{\theta_{in12}}{\theta_{in11}}\cdot\frac{\rho_{11}}{\rho_{12}}\cdot\frac{J_{11}}{J_{12}}\cdot\frac{B_{d12}}{B_{d11}}, \tag{31}$$

where B_{d1} is magnetic flux density on teeth.

Or if is used the relationship of specific power losses:

$$p_{J_{11}} = \rho_{11}J_{11}^2 \tag{32}$$

$$p_{J_{22}} = \rho_{22}J_{22}^2, \tag{33}$$

is obtained:

$$\sigma_{12} = \sigma_{11}\cdot\frac{\theta_{in12}}{\theta_{in11}}\cdot\frac{p_{J11}}{p_{J12}}\cdot\frac{J_{12}}{J_{11}}\cdot\frac{B_{d12}}{B_{d11}}. \tag{34}$$

Now, starting from relationship of tangential density of force:

$$f_t = \frac{1}{\sqrt{2}}\cdot J\cdot B_\delta\cdot\frac{1}{\mu_d k_{z1}} = \frac{1}{\sqrt{2}}\cdot J\cdot B_d\cdot\frac{1}{\mu_d}, \tag{35}$$

the relationship (34) becomes:

$$\sigma_{12} = \sigma_{11}\cdot\frac{\theta_{in12}}{\theta_{in11}}\cdot\frac{p_{J11}}{p_{J12}}\cdot\frac{f_{t12}}{f_{t11}}\cdot\frac{\mu_{d12}}{\mu_{d11}}. \tag{36}$$

If we want to find a relationship of tangential force of teeth, we will start from relationship [13]-[14]:

$$p_{J1} = \frac{Q_{1T}}{V_1\sigma_1}k_{f1}, \tag{37}$$

where $k_{f1}=1+L_{f1}/L$ is a global geometric factor (L-ideal machine length and L_{f1}-frontal length of stator winding).

The ratio of Joule losses results:

$$\frac{p_{J11}}{p_{J12}} = \frac{f_{t12}}{f_{t11}}\cdot\frac{V_{12}}{V_{11}}\cdot\frac{\sigma_{11}}{\sigma_{12}}\cdot\frac{k_{f11}}{k_{f_{12}}}. \tag{38}$$

Because the stator remains the same ($k_{f11}=k_{f12}$), results:

$$\frac{p_{J11}}{p_{J12}} = \frac{f_{t12}}{f_{t11}} \cdot \frac{V_{12}}{V_{11}} \cdot \frac{\sigma_{11}}{\sigma_{12}} . \tag{39}$$

Based on the least relation, the tangential force density becomes:

$$f_{t12} = f_{t11} \cdot \frac{\theta_{in12}}{\theta_{in11}} \cdot \frac{Q_{12T}}{Q_{11T}} \cdot \frac{V_{12}}{V_{11}} \cdot \frac{\mu_{d11}}{\mu_{d12}} . \tag{40}$$

The last relationship may be expressed as a dependence of speeds:

$$f_{t12} = f_{t11} \cdot \frac{\theta_{in12}}{\theta_{in11}} \cdot \frac{Q_{12T}}{Q_{11T}} \cdot \frac{n_{12}}{n_{11}} \cdot \frac{\mu_{d11}}{\mu_{d12}} . \tag{41}$$

From this relation may be deduced a speed dependence of speed by electromagnetic stress:

$$n_{12} = n_{11} \cdot \frac{f_{t12}}{f_{t11}} \cdot \frac{\theta_{in11}}{\theta_{in12}} \cdot \frac{Q_{11T}}{Q_{12T}} \cdot \frac{\mu_{d12}}{\mu_{d11}} . \tag{42}$$

The last relationship shows, through other things, that on each speed variation a reaction of magnetically material is being $n_{12}=f(n_{11},\mu_{d12}/\mu_{d11})$. From this relationship may be deduced the expression of magnetic permeability of teeth for a speed variation:

$$\mu_{d12} = \mu_{d11} \cdot \frac{\theta_{in12}}{\theta_{in11}} \cdot \frac{Q_{12T}}{Q_{11T}} \cdot \frac{n_{12}}{n_{11}} \cdot \frac{f_{t11}}{f_{t12}} , \tag{43}$$

and based on relationship of speed [8]:

$$n = \frac{60 f}{p} , \tag{44}$$

is obtained:

$$\mu_{d12} = \mu_{d11} \cdot \frac{\theta_{in12}}{\theta_{in11}} \cdot \frac{Q_{12T}}{Q_{11T}} \cdot \frac{p_{11}}{p_{12}} \cdot \frac{f_{t11}}{f_{t12}} . \tag{45}$$

3. Case study on simulation of permanent magnet synchronous machine

In the above section have been deduced different relationships for assessment of stress for the case of adjustable speed with poles commutation method. For this situation, in this section has been considerate a case study of permanent magnet synchronous machine design with the next requirements imposed by project design theme:

- Rated power: P_n=500 [kW];
- Rated voltage: U_n=400[V];

- Rated efficiency: η_n=0.93[ad.];
- Rated power factor: cosφ_n=0.92 [ad.];
- Pairs of poles: p=6 and p=8[ad.] (for two different speeds);
- Protection degree: IP 44;
- Insulation class: F.

The excitation has been design according to NeFeBr PM which has the next characteristics:

- Remnant magnetic flux density: B_r=1,1 [T];
- Coercitive magnetic field strength: H_c=1049[A/m];
- Relative permeability: μ_{rPM} = 1.049;
- Electric conductivity σ= 0.667 [MS/m].

The topology of permanent magnet synchronous machine with permanent magnets mounted on the rotor surface is depicted on the Figure 1.

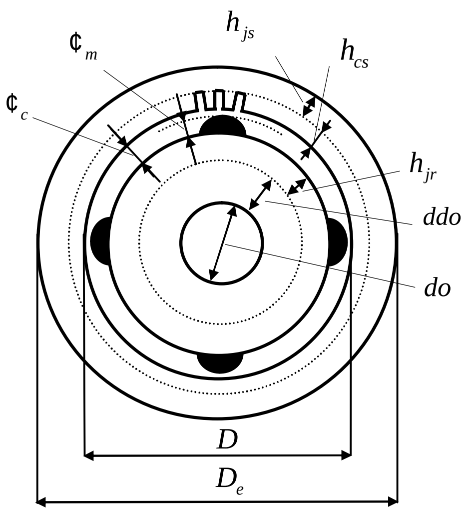


Figure 1. Topology of permanent magnet synchronous machine

In the above figure has been hightailed the main geometric dimensions of the machine.

In the order to assessment the electromagnetic stress, we will perform two simulations according to design methodology [13] and [14], when magnetic flux densities and current density are de same with different poles pairs. The once geometry is identified by the same geometric factor k_{f1}.

The main characteristics of magnetic steel are represented in the below Figure as a function of magnetic flux density.

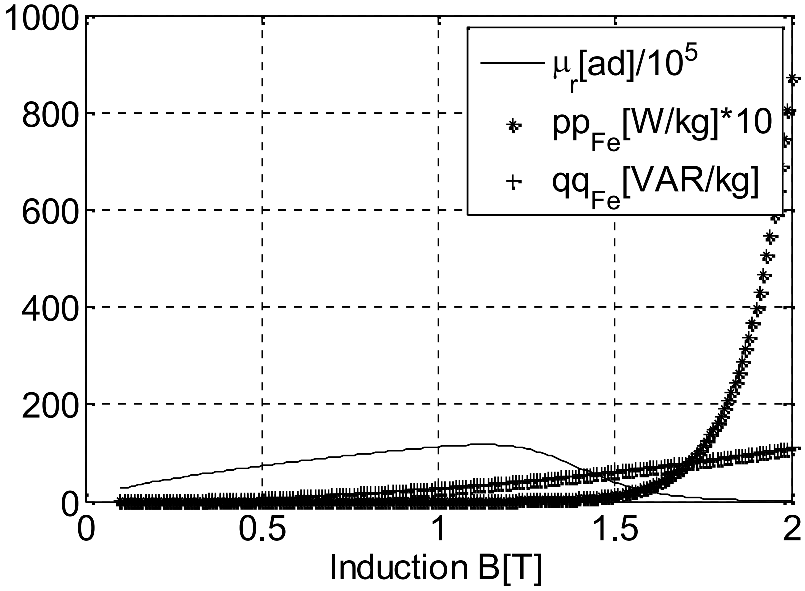
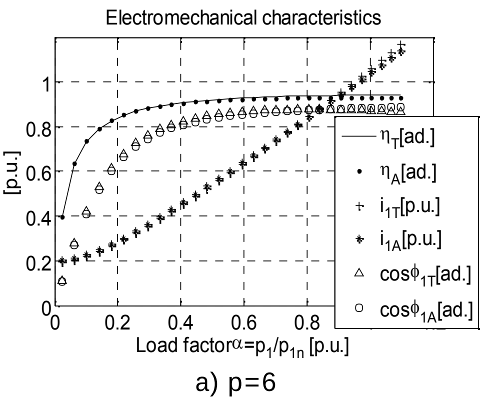


Figure 2. Efficiency, stator current and power factor.

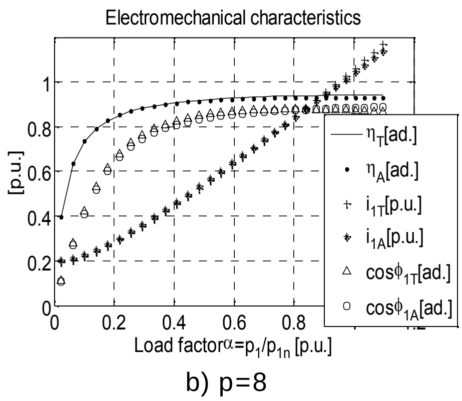
Thus, where hightailed the next quantities: specific active power losses pp_{Fe}[W/kg], specific reactive power losses qq_{Fe}[VAR/kg] and relative magnetic permeability μ_r. As be seen, once with increasing of magnetic flux density, the specific losses increasing too.

Now, will be represented, alternatively, the characteristics obtained for the two cases of different pairs poles.

The Efficiency, stator current and power factor are represented in Figure 3.



a) p=6

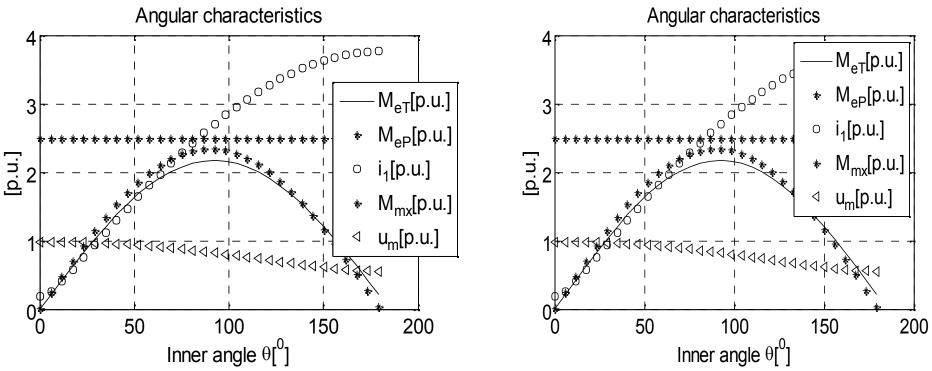


b) p=8

Figure 3. Efficiency, stator current and power factor

From the above figure, a slight difference may be highlighted.

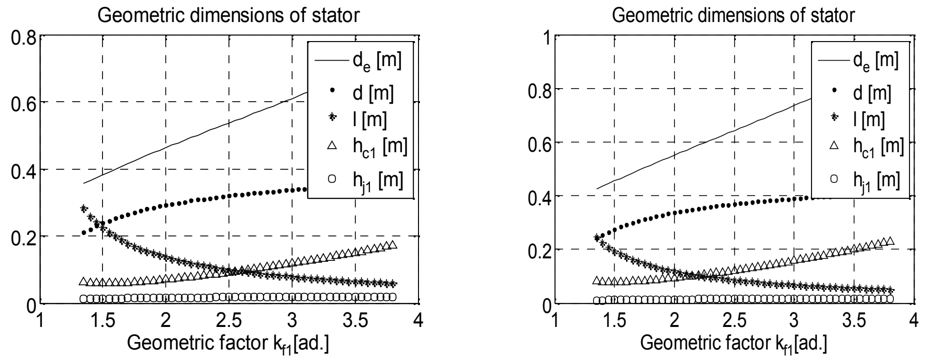
Important characteristics dependent on internal angle were represented in the Figure 4.



a) p=6 b) p=8

Figure 4. Characteristics dependent of internal angle

The stator geometric dimensions were represented as a function of factor k_{f1} in Figure 5. The curve allure is the same, but there are some slight variations according to different number of pairs poles involved.

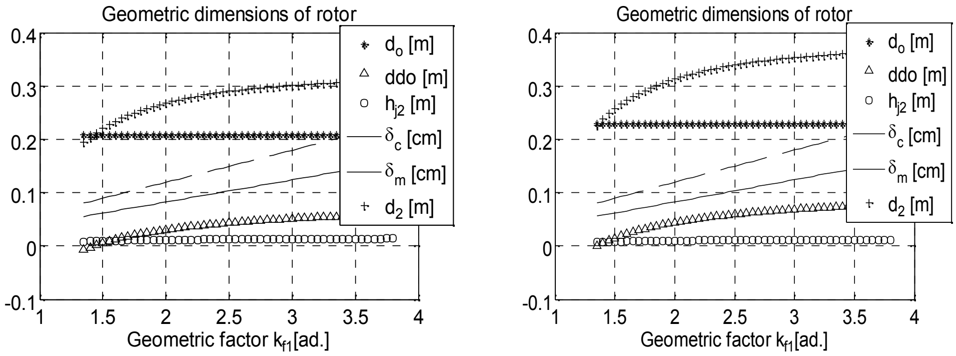


a) p=6 b) p=8

Figure 5. Stator geometric dimensions

In Figure 6 are represented the rotor geometric dimensions as a function of geometric factor.

All geometric dimensions, represented in Figure 5 and 6 keep the notations from Figure 1 of cross section of machine.

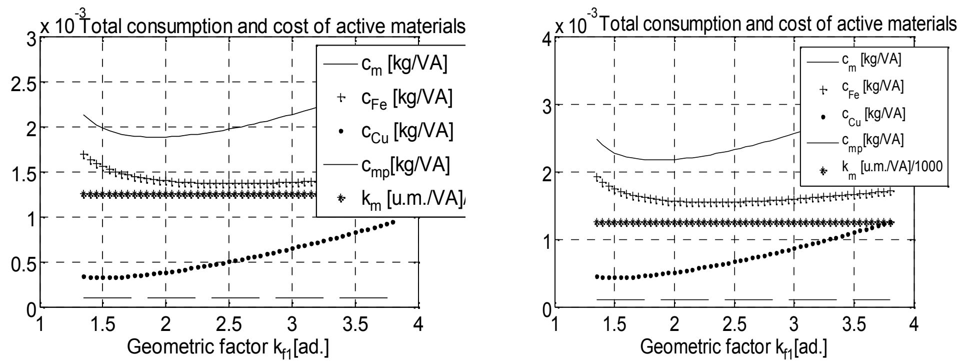


a) p=6 b) p=8

Figure 6. Rotor geometric dimensions

In the order to define economic criteria for cost optimization, in Figure 7 has been represented the main curve of cost and consumption of active materials (Fe, Cu and PM).

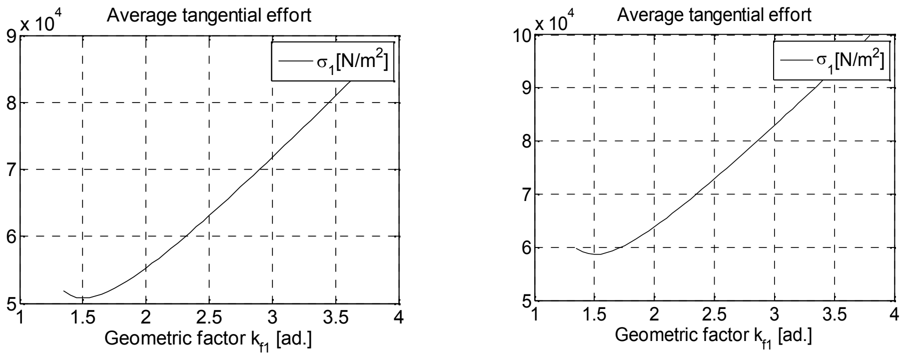
The minimal point of total consumption c_m, which will be considerate in this study, is different (different k_{f1}).



a) p=6 b) p=8

Figure 7. Specific cost and consumptions of active materials

Finally, the average tangential effort is presented in Figure 8. The allure of the curve is the same, but there are slight differences.



a) p=6

b) p=8

Figure 8. Average tangential effort

In this simulation case poles commutation leads to increase the average tangential efforts. All important quantities may de computed according to relationships (31), (34), (36), (40)-(43).

4. Conclusion

Speed variation, by pole commutation, generate in the intrinsic structure of electrical machines different aspect related by: stress, thermal loses and magnetic permeability variation. This aspect must be taking into account in the designing phase of electrical machines where as additional constrains must be added.

The study performed, for the case of a permanent magnet synchronous machine, shows a link between main quantities as: stress, thermal losses and magnetic permeability variation. The increasing of poles pairs leads to increasing the average tangential effort when the specific power losses (Joule one) imposed are the same

The future approach is based on the assessment of electromagnetic stress with different stator winding types.

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