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On the Optimal Selection of Electrical Machines Fans

In this paper an analytic relationship for electrical machine fan design has been developed. In the particularly case of salient poles synchronous machine (with salient poles – for electromagnetic field excitation or surface mounded permanent magnet), this approach allowed to express the fan power as a function of machine middle axe air gap. This analytic foundation developed may leads to different optimization criteria as specific active materials or costs. Numerical simulations confirm our approach.

Keywords: PMSM, thermal flow, fan, design.

1. Introduction

Electrical machines may be founded in various modern applications where energy conversion systems take place. The usually field where electrical machines may founded are: conventional and electrical drive with high performances, energy generation in power plant, renewable energy conversion system, robotics, special applications [3]-[6], [11]-[12].

An important research field about conversion systems with electrical machines is about designing [1]-[5]. At this level, it is starting from rated data imposed design project, and are founded all important specific quantities: geometric dimensions and material data [2]-[5], [8]-[10], [13]-[18]. The effective design process is based on the already build machine, which use so-called design monograms. From this point of view, design procedure of electrical machines is an iterative process which means that the final solution is founded after more search.

In the present paper is performed a study on the dependence of air gap on middle axe from the perspective of optimization.

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

According to design requirements, the electrical stress as current density J[A/mm^2] and linear current density A[A/mm] , respectively, magnetic stress – air gap induction magnetic flux density B$_\delta$[T] must be located based of practice [2] [8]. Additional constraint may be added if is taking into consideration a thermal approach.

Electrical stress product must be contents in the next limits [13]-[14]:

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

with the help of this result can be predicted the thermal flow of losses in the in the active part of stator winding [13]-[14]:

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

where by $Q_{1T} = \rho_1 \cdot J_1 \cdot A_1\left[\frac{W}{m^2}\right]$ is denoted the analytical relationship of thermal flow; and the resistivity of the copper was considered at value $\rho_1 = \rho_{Cu_{115^oC}} = 2.46 \cdot 10^{-8}[\Omega m]$.

The task of every ele system which is not on the thermodynamic equilibrium is to assure an adeqvate to eliminate the power losses developed in the order to ensure a proper operation regime. This problem take place by using a cooler system designed according .

On the electrical machines the cooler is assured by fans. Depending on the application, there are several mods for fan design. In all adopted solution, the first step for fan computing is to find the heat flow .

The well-know relationship of heat flow required by cooling system is described by relatiopship [9]:

$$Q = \frac{\sum P}{c_p \gamma \vartheta}, \tag{1}$$

where ∑P represents the total power losses, c_p represents specific heat at constant pressure, γ represents the density of medium cooling and ϑ represents the temperature rise.

Starting for this relationship, it is fallows to determinate an adequate approach.

The total power losses may be expressed as function of utile power and efficiency by the next relationship [8]:

$$\sum P = P_2\left(\frac{1-\eta}{\eta}\right). \tag{2}$$

In the electrical designing machine, in the order to express a relationship between power and geometrical dimensions, it is used the inner apparent power relationship. There are two types of approach. The first one is the classical relationship [8]:

$$S_i = k_E S_n \,, \tag{3}$$

and the second one, related by energy transfer, is described according to Poynting vector [13]-[14]:

$$S_i = S_p \pi D L \,, \tag{4}$$

where the Poynting vector is computed according by relationship:

$$S_p = \frac{Q_{1T}}{p_{J1n}} k_{f1} \,, \tag{5}$$

where Q_{1T}[W/m2] is the thermal flow of losses of active part of stator winding, p_{J1n}[p.u.] represents the joule losses of winding.

Take into account relationship (4) and (5), the output electrical machines power can be expressed by:

$$P_2 = \frac{Q_{1T}}{p_{J1n}} \cos\varphi \frac{1}{k_E} k_{f1} \pi D L \,. \tag{6}$$

Now, the thermal flow of losses of active part of stator winding is represented as a function of thermal flow of slot insulation []:

$$Q_{1T} = \frac{Q_{1c}}{2(1-k_{z1})(1+\gamma_1)} \,. \tag{7}$$

Using the last relationship, the output power relationship becomes:

$$P_2 = \frac{1}{p_{j1n}} \cdot \frac{Q_{1c}}{2(1-k_{z1})(1+\gamma_1)} \cos\varphi \frac{1}{k_E} k_{f1} \pi D L \,, \tag{8}$$

and from relationship (2) and (8) the total power of losses becomes:

$$\sum P = \frac{1}{p_{j1n}} \cdot \frac{Q_{1c}}{2(1-k_{z1})(1+\gamma_1)} \cos\varphi \frac{1}{k_E} k_{f1} \pi D L . \left(\frac{1-\eta}{\eta} \right) . \tag{9}$$

This relationship is mainly related on thermal quantities because it is necessary to estimate the thermal flow of slot insulation. It is desirable to obtain a relationship expressed in well-known quantities which take place variations in certain limits based on practical design.

The thermal flow of losses in slots is computing according to conduction low of heat transfer [13]:

$$Q_{1c} = \frac{\lambda_{iz1}}{\Delta_{iz1}} \cdot \theta_{iz1} \,. \tag{10}$$

An additional limitation of thermal flow of losses in slots, based on temperature approach, is related by localized in a certain range [13]:

$$\theta_{iz1} \cong \frac{\Delta_{iz1}}{\lambda_{iz1}} \cdot Q_{1c} \le \theta_{izad} (30^0 \div 40^0) \tag{11}$$

In the paper [7] has been established a global relationship on the slot number per pole and phase:

$$q_1 = \gamma_1 \cdot k_{z1} \cdot \frac{\pi D}{2 m_1 p h_{c1}} . \tag{12}$$

By using this relationship, the ration between high and width slots results:

$$\gamma_1 = \frac{q_1}{k_{z1}} \cdot \frac{2 m_1 p h_{c1}}{\pi D} . \tag{13}$$

This relationship may be expressed as a function of slot pitch:

$$\gamma_1 = q_1 \frac{1}{\tau \cdot k_{z1}} m_1 h_{c1} = f(\tau) \tag{14}$$

Now, this relationship may be expressed as a function of machine architecture factor:

$$\gamma_1 = q_1 \frac{\lambda}{L_i \cdot k_{z1}} m_1 h_{c1} = f(\lambda) \tag{15}$$

Take into account relation (1), (9) - (13) the total power of losses becomes as a function of slot pitch:

$$\sum P = \frac{1}{p_{j1n}} \cdot \theta_{iz1} \frac{\lambda_{iz1}}{\Delta_{iz1}} \frac{1}{2(1-k_{z1})\left(1 + q_1 \frac{1}{\tau \cdot k_{z1}} m_1 h_{c1}\right)} \ldots$$

$$\ldots \cos\varphi \frac{1}{k_E} k_{f1} \pi D L \left(\frac{1-\eta}{\eta}\right) = f(\tau) \; . \tag{16}$$

Now, by using the relationship (1) and (16) the thermal flow of losses becomes:

$$Q = \frac{1}{c_p \gamma \vartheta p_{j1n}} \cdot \theta_{iz1} \frac{\lambda_{iz1}}{\Delta_{iz1}} \frac{1}{2(1-k_{z1})\left(1 + q_1 \frac{1}{\tau \cdot k_{z1}} m_1 h_{c1}\right)} \ldots$$

$$\ldots \cos\varphi \frac{1}{k_E} k_{f1} \pi D L \left(\frac{1-\eta}{\eta}\right) = f(\tau) , \tag{17}$$

or by expressing as function of machine aspect ratio:

$$\sum P = \frac{1}{p_{j1n}} \cdot \theta_{iz1} \frac{\lambda_{iz1}}{\Delta_{iz1}} \frac{1}{2(1-k_{z1})\left(1 + q_1 \frac{\lambda}{L \cdot k_{z1}} m_1 h_{c1}\right)} \cos\varphi \frac{1}{k_E} k_{f1} \pi D L \left(\frac{1-\eta}{\eta}\right)$$

$$\ldots \cos\varphi \frac{1}{k_E} k_{f1} \pi D L \left(\frac{1-\eta}{\eta}\right) = f(\lambda) \tag{18}$$

$$Q=\frac{1}{c_p\gamma\vartheta p_{j1n}}\cdot\theta_{iz1}\frac{\lambda_{iz1}}{\Delta_{iz1}}\frac{1}{2(1-k_{z1})\left(1+q_1\frac{\lambda}{L\cdot k_{z1}}m_1h_{c1}\right)}\dots$$

$$\dots\cos\varphi\frac{1}{k_E}k_{f1}\pi DL\left(\frac{1-\eta}{\eta}\right)=f(\lambda) \tag{19}$$

All determination may be applied for all electrical machines with cylindrical symmetry. For induction machines the relationships deduced are finally.

However, for DC and synchronous machines –due to particulary construction - there appear some important particularities.

The length of air gap on the DC and synchronous machines has a general computing relationship [9]:

$$\delta_0=\gamma_\delta\tau\frac{A}{B_\delta} \tag{20}$$

From this relationship results:

$$\frac{B_\delta}{\tau}=\gamma_\delta\frac{A}{\delta_0} \tag{21}$$

From relationships (14) and (21) results:

$$\gamma_1=q_1\frac{1}{B_{z1}}\gamma_\delta\frac{A}{\delta_0}m_1h_{c1}=f(\delta_0) \tag{22}$$

Thus, take into account relation (1), (9) and (13) the total power of losses and becomes as a function of air gap in pole axis:

$$\sum P=\frac{1}{p_{j1n}}\cdot\theta_{iz1}\frac{\lambda_{iz1}}{\Delta_{iz1}}\frac{1}{2(1-k_{z1})\left(1+\frac{q_1\gamma_\delta}{B_{z1}}\frac{A}{\delta_0}m_1h_{c1}\right)}\dots$$

$$\dots\cos\varphi\frac{1}{k_E}k_{f1}\pi DL\left(\frac{1-\eta}{\eta}\right)=f(\delta_0) \tag{23}$$

$$Q=\frac{1}{c_p\gamma\vartheta p_{j1n}}\cdot\theta_{iz1}\frac{\lambda_{iz1}}{\Delta_{iz1}}\frac{1}{2(1-k_{z1})\left(1+\frac{q_1\gamma_\delta}{B_{z1}}\frac{A}{\delta_0}m_1h_{c1}\right)}\dots$$

$$\dots\cos\varphi\frac{1}{k_E}k_{f1}\pi DL\left(\frac{1-\eta}{\eta}\right)=f(\delta_0) \tag{24}$$

Based on the above relationship and with the help of vector Poynting algorithm [13], [14] two main criteria may be defined. In the first one, the machine is designed on low cost:

$$k_m[mu/VA] = f(k_{f1}) = \min\ , \tag{25}$$

expressed in [mu]- monetary unity
The second one is about low consumption of active materials:

$$c_m[kg/VA] = f(k_{f1}) = \min\ . \tag{26}$$

3. Case study on simulation of permanent magnet synchronous generator

Based on the above approach, in this paper section has been considerate a case study of design of permanent magnet synchronous machine with design theme defined by the next requirements:

- Rated power: P_n=450 [kW];
- Rated voltage: U_n=400[V];
- Rated efficiency: η_n=0.93[ad.];
- Rated power factor: $\cos\varphi_n$=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.
In Figure 1 has been represented the efficiency, stator current and power factor for machine considerate.

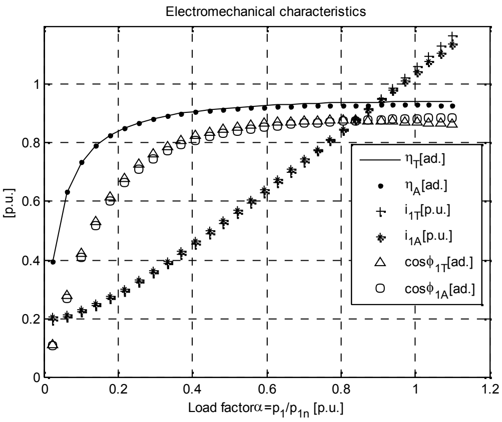

Figure 1. Efficiency, stator current and power factor

The geometric dimensions of stator are represented in Figure 2, while the rotor one is represented in Figure 3.

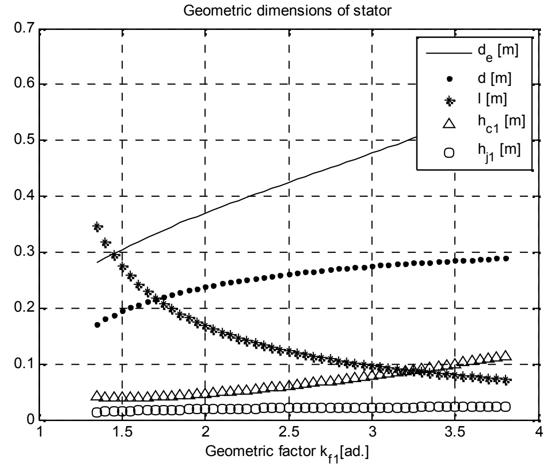

Figure 2. Efficiency, stator current and power factor

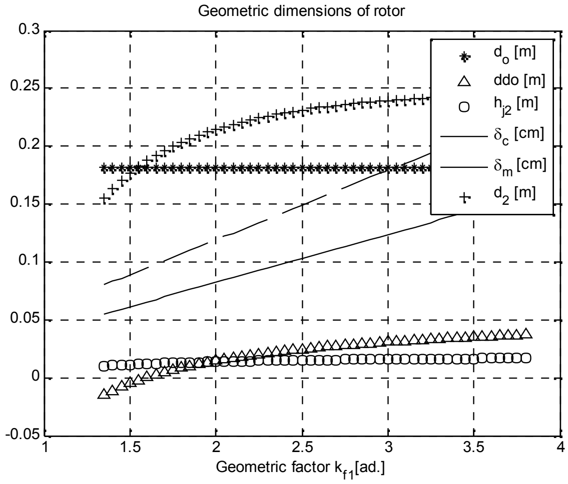

Figure 3. Efficiency, stator current and power factor

In Figure 4 are represented the main curves of economic optimization (k-costs and c –consumptions of active materials: Fe, Cu and PM).

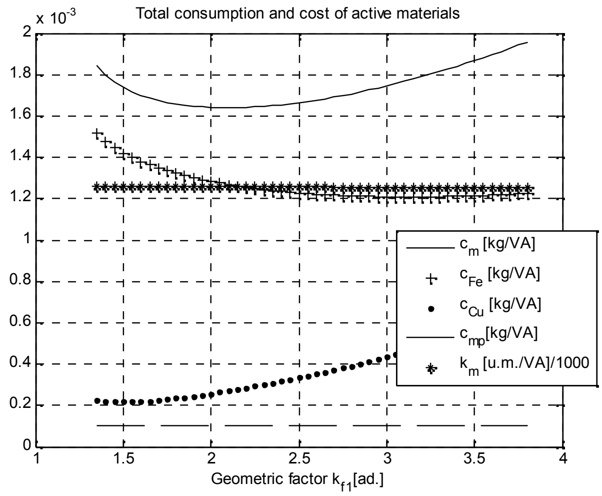

Figure 4. Costs and consumptions of active materials

In the least figure is represented, according to relationship (24) the curve of thermal flow of fan as a dependence of air gap on the middle axe of pole.

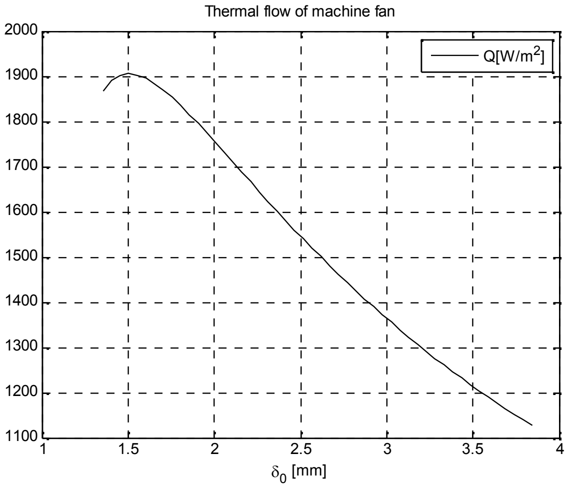

Figure 5. Thermal flow of fan as a dependence of air gap

Once with increasing of air gap on middle axe of pole, the thermal floe required by fan is decreasing too. In the design, for a proper solution, a correlation between Figure 4 and 5 must be done.

4. Conclusion

At an imposed thermal flow on the active part of stator winding and losses imposed too (from the extimated curve of efficiency), the thermal flow required by fan design has a particullary depndence on air gap on middle axe of pole. If the air gap on middle axe of pole is increasing, the the thermal flow required by fan design is strong decreasing. This particularly situation must be taken into account on machine design.

The approach of the paper maybe completed by take into consideration the effect of nonlinear curve of magnetic core.

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