OPTIMAL SELECTION OF SLOTS NUMBER PER POLE AND PHASE AT ROTATIONAL ELECTRICAL GENERATORS

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REZUMAT. Problematica generatoarelor sincrone excitate cu magneti permanenti, utilizate in conversia energiei –ca particularitati disticte de proiectare optimala - este una de actualitate. In lucrare se dezvolta o metoda noua de determinare a numarului de crestaturi pe pol si faza pe baza estimarii temperaturii la nivelul izolatiei crestaturii statorice, avand la baza algoritmul Poynting [14]. In functie de obiectivul urmarit, optimizarea numarului de crestaturi conduce la optimizarea concomitenta a consumului de materiale, sau a costului.

Cuvinte cheie: crestaturi pe pol si faza, generatoar sincron cu magneti permanenti, optimizare termica.

ABSTRACT. The issue of permanent magnet synchronous generators, used in wind energy conversion system, as distinct features of optimal design - is a current one. The paper develops a new method for determining the number of slots per phase and pole based on the estimation of stator slot insulation temperature, using Poynting vector algorithm [14]. Depending on the objective pursued, optimization of the number of slots per phase and pole leads to simultaneous optimization of active material consumption, or cost.

Keywords: slot per phase and pole, permanent magnet synchronous generator, thermal optimization

1. INTRODUCTION

Wind energy conversion systems have recently experienced a large development. In this direction have been developed new integrated technologies for all conversion structures involved.

The most viable option is given today by systems which are operating at variable speed. Thus, it follows a maximal extraction of power from wind energy.

The “heart” of these systems is given by electric generators which represents the most problematical execution element in this conversion system. Traditionally, the induction generator has the widespread development in the systems founded in exploitation [11].

Squirrel-cage induction generator presents, especially constructive advantages required for using in conversion systems. The great drawback is related by the impossibility of ensuring the magnetized power for iron with its own excitation. For this reason its operation required a power capacitor (for island operation) or grid connection. For these reasons the use of this generator, in practice, is reduced.

The generator which has the largest development in modern systems with variable speed (variable frequency) is the double fed induction one. This, it is required by a lot of advantages as: the control system through slip power which leads to lower converter size, and therefore lower price, simplifying of control schemes, a better adaptation to transient regimes, etc.

However, the presence of the ring-brush system leads to decrease generator reliability, and thus leads to other solutions. Both induction generator (squirrel cage and wound rotor) due to its construction, required invariably a gear box in order to adapt the speed required by shaft of wind speed turbine. These introduce a lot of drawbacks as: reduced reliability, periodic maintenance, produce shocks and vibrations that alter the overall performance of the conversion system, etc. For these reasons induction generators, lately, have lost significantly part of the market in favour of more efficient modern solutions.

All those shortcomings required by induction generators could be resolved, in part, by the technology of permanent magnet synchronous generators, especially at small and medium power. Biggest advantages are related to the possibility of direct coupling at the rotor of wind turbine, which leads to the development of multipolar structures. In addition, the iron magnetization made by its own excitation is another advantage.

Multipolar machine structures, required, yet for the early of XX century, for classic machine, leading to worsening of almost all performance [2] with increasing the numbers of pole pairs. From this point of view, permanent magnet excited synchronous generators face some specific problems due to the large number of poles involved in their construction.

Although, they were solved some problems of these machines, either through analytical approach (based on equivalent circuit diagrams, or fundamental equations of the electromagnetic field), either by numerical one (based on finite difference equations, using software dedicated software [12], the determining of the slots per pole and phase is less treated in literature survey.

In the solving of this problem should take into account both economic criteria (cost and / or consumption of active materials) and the thermal one, which is exclusively responsible with the lifetime of the machine.

2. ANALYTICAL DETERMINATION OF THE NUMBER OF SLOTS PER PHASE AND POLE. PRINCIPLES.

It is considered a permanent magnet synchronous generator with magnets mounted on the rotor surface, with radial magnetic flux. In this case the total number of slots of stator is determined by the relationship [8]:

$$Z_1 = 2 m_1 p q_1 \tag{1}$$

where often the generator is three phase one $m_1 = 3$, and the number of poles is imposed by the desired speed. The problem is to determining the optimal number of slots per phase and pole. In the work [12] it was showed that permanent magnet synchronous generators used in wind energy conversion system, in order to eliminate pull-out torque windings must be designed with fractional slot number per pole and phase. It was also established [12], that the number of slots per pole and phase must take into consideration the condition:

$$q_1 > 1.25 \tag{2}$$

Often around the value $q_1 \approx 1.5$ are obtained good performance [12]. It must to take into account that the number of slots per pole and phase can greatly increase due to mechanical considerations of teeth. This condition is a complex one. First, in the designing process of electrical machines are take into consideration that electrical demands as current density $J[A/mm^2]$ and linear current density $A[A/mm]$, and that magnetic – air gap induction magnetic flux density $B_\delta[T]$ must be incadrate in specific limits [9] according to in the nature and the destination electric machine. Because the current intensity is determined in the preliminary stage of design (directly from the rated data), geometric dimensions will determinated the losses thermal optimal flow.

Moreover, has been established that the amount of the product of the electrical demands, according to the degree of protection, must be incadrated between certain limits [13] - [14]:

$$A_1 \cdot J_1 \approx 3000(I.P.44) \div 3200(I.P.23)\left[\frac{A^2}{mm^2}\right] \tag{3}$$

This result has great practical importance because starting from this it can be predict the losses thermal flux in the in the active part of stator winding [13]:

$$Q_{1T} \approx 3000(I.P.44) \div 8000(I.P.23)\left[\frac{W}{m^2}\right] \tag{4}$$

where $Q_{1T} = \rho_1 \cdot J_1 \cdot A_1\left[\frac{W}{m^2}\right]$; and the resistivity of copper was considered at the value : $\rho_1 = \rho_{Cu_{115^o C}} = 2.46 \cdot 10^{-8}[\Omega m]$

Based on losses thermal flow in the active part of stator winding can be determinated the losses thermal flow of slot insulation with relationship [13]:

$$Q_{1c} = \frac{Q_{1T}}{2(1-k_{z1})(1-\gamma_1)} < Q_{1T}\left[\frac{W}{m}\right] \tag{5}$$

where the slot factor is included, in practice, between: $k_{z1} = \frac{b_{d1}}{k_{z1}} \approx 0.4 \div 0.6$ and the architectural elements of the right slot used are expressed by relations [13] - [14]:

$$h_{c1} \cong \frac{A_1}{J_1 k_{U1}(1-k_{z1})}[m] \tag{7}$$

$$\gamma_1 = \frac{h_{c1}}{b_{c1}} \geq 3 \tag{8}$$

In order to determine the optimum number of slots per phase and pole, it is starting from insulation drop temperature equation [13]:

$$\theta_{iz1} \cong \frac{\Delta_{iz1}}{\lambda_{iz1}} \cdot Q_{1c} \le \theta_{izad}(30^0 \div 40^0) \qquad (6)$$

If it imposed from the startig of the designing process the slot insulation temperature, and take into account the degree of protection (including insulation class), the losses thermal flow of slot result [13]:

$$Q_{1c} = \frac{\lambda_{iz1}}{\Delta_{iz1}} \cdot \theta_{iz1} \qquad (7)$$

The architecture factor of slot become [13]:

$$\gamma_1 = \frac{Q_{1T}}{2(1-k_{z1})Q_{1c}} - 1 \qquad (8)$$

If it is used the slot pitch relatioship [8]:

$$t_1 = \frac{\pi D}{Z} = \frac{\pi D}{2m_1 p q_1} \qquad (9)$$

The slot height results as inverse function of slot number per phase and pole:

$$h_{c1} = \gamma_1 \cdot k_{z1} \cdot \frac{\pi D}{2m_1 p q_1} = f\left(\frac{1}{q_1}\right) \qquad (10)$$

Number of slots become as follows:

$$q_1 = \gamma_1 \cdot k_{z1} \cdot \frac{\pi D}{2m_1 p h_{c1}} \qquad (11)$$

As has been shown in various works [13], [14], is very useful to express the all important geometric dimensions as a function of the geometry factor k_f (fig. 1).

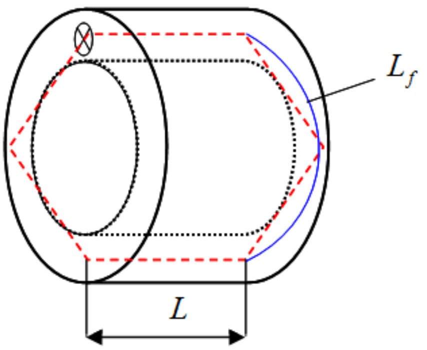

Fig. 1. Elements of geometric factor k_f

Geometry factor is defined as [13]:

$$k_f = 1 + \frac{L_f}{L} \qquad (12)$$

According to Poynting vector algorithm [14], both all the generator geometry and material costs and consumption can be of be represented as a function of the geometric factor k_f. Thus the number of slots per pole and pahase can be expressed as a function of geometry factor:

$$q_1 = \gamma_1 \cdot k_{z1} \cdot \frac{\pi D(k_{f1})}{2m_1 p h_1(k_{f1})} = f(k_{f1}) \qquad (13)$$

Thus, can be defined two optimization criteria. On the first criteria, the slots per phase and pole is determinated in parallel with active materials specific consumption optimization:

$$\begin{cases} q_1 = f(k_{f1}) \\ c_m[kg/VA] = f(k_{f1}) = \min \end{cases} \qquad (14)$$

The second criterion aims to determinate the number of slots per pole and phase in parallel with specific cost optimization:

$$\begin{cases} q_1 = f(k_{f1}) \\ k_m[kg/VA] = f(k_{f1}) = \min \end{cases} \qquad (15)$$

The work of this paper leads to improve the vector Poynting design algorithm [14], as can be seen in fig. 2

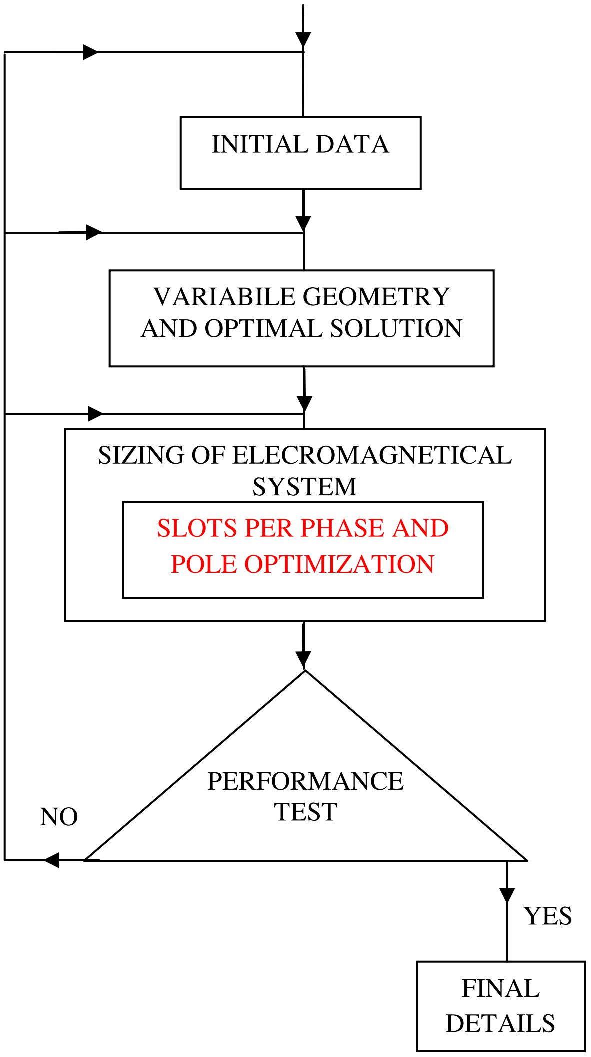

Fig. 2. Improved algorithme for generator design

In electromagnetic sizing block was introduced the criteria developed in this work (red color) as system (14), or (15).

3. ANALYTICAL DETERMINATION OF SLOT NUMBER PER POLE AND PHASE. CASE STUDY.

It is considered the following data required by the design theme for a the permanent magnet synchronous generator with radial flux:

- Rated power: $P_n = 50 \ [kW]$
- Rated voltage: $U_n = 400 \ [V]$
- Rated frequency: $f_n = 50 \ [Hz]$
- Rated power factor: $\cos\varphi_n = 0.9$
- Rated efficiency: $\eta_n = 0.92$
- Pairs poles number: $p = 12$
- Maximal torque: $M_m = 2.5$

The type of generator used is a permanent magnet synchronous with magnets mounted on the surface of the rotor. A cross section of the generator it was represented in fig. 2, where was presented all defitning geometric elements.

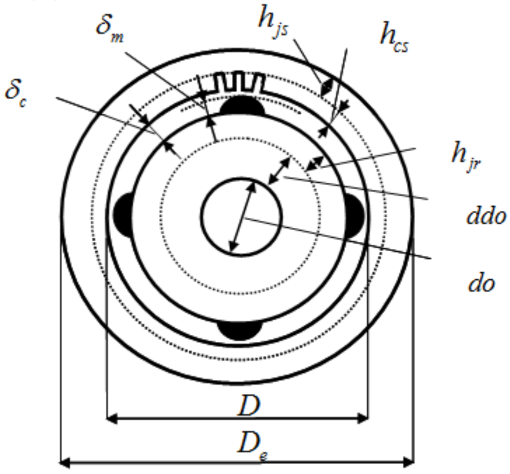

Fig. 3. Cross section of generator

Class F insulation is chosen, the thermal conductivity of copper was considered at value $\lambda_{iz1} = 0.16\left[\dfrac{W}{m^o K}\right]$, and the thickness of insulation is $\Delta_{iz1} = 0.5[mm]$ (low voltage). The imposed drop temperature on the slot insulation was considered at value $\theta_{iz1} = 20^o C$, according to class F of insulation. The optimization was done take into account the Poynting vector algorithm developed in detail in [14].

Based on the rated data and on stator leakage reactance (estimated) - expressed in per unit - were determined in a first stage the universal characteristics of the generator. Were represented both characteristics based on the scheme equivalent circuit (denoted by $''T''$) and those based on analytical relations which allow losses separate (denoted by $''P''$) [14]. In fig.4, electromechanical characteristics were represented:

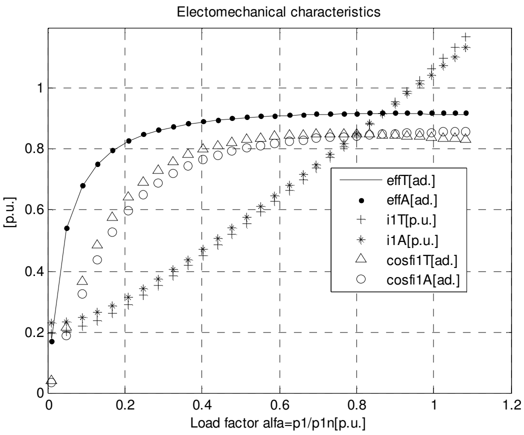

Fig. 4. Estimated electromechanical characteristics

Angular characteristics were represented in fig. 5. At this stage was established the rated internal angle as: the torque based on echivalent circuit scheme *T* and the one based on Portier relationships must be equal to the rated one (1 *p.u.*); also simultaneously, voltage u_m<1. Thus, the resulting value of internal angle is $\theta \approx 30^o$.

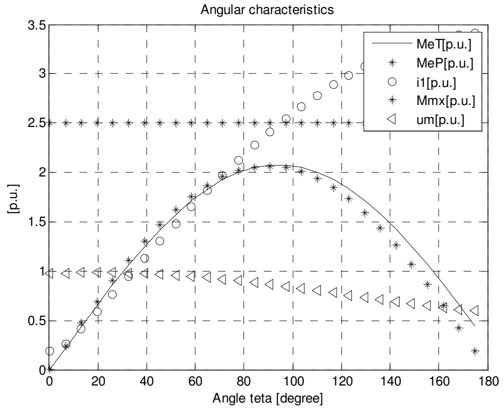

Fig. 5. Estimated angular characteristics

In fig.6 were represented the geometrical dimensions of stator.

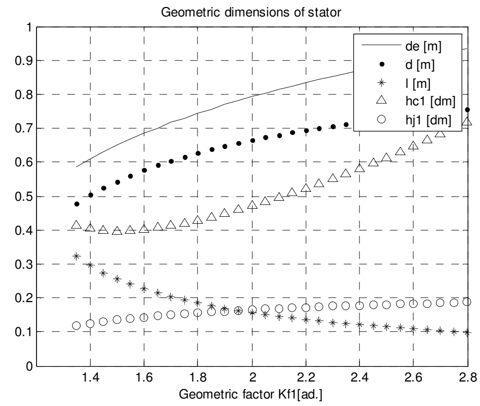

Fig. 6. Geometric dimensions of stator

Geometric dimensions of rotor were representeted in fig.7.

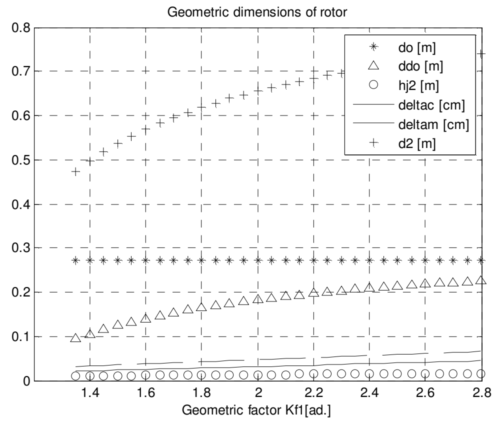

Fig. 7. Geometric dimensions of rotor

In fig. 8 were represented the specfic statoric consumption of active material (*Cu*, *Fe*, total one), and specific statoric cost.

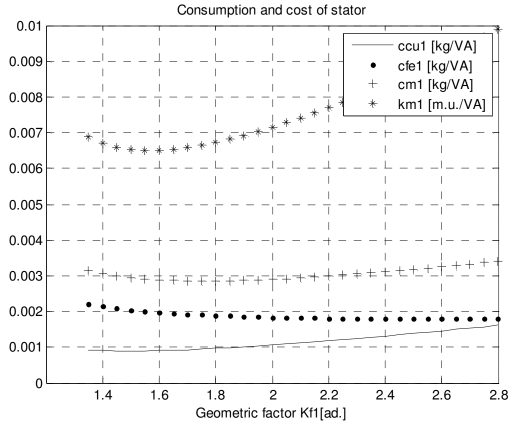

Fig. 8. Consumption and cost of stator

Total specific consumption of active material (Fe, Cu and PM), and total specific cost were represented in fig. 9.

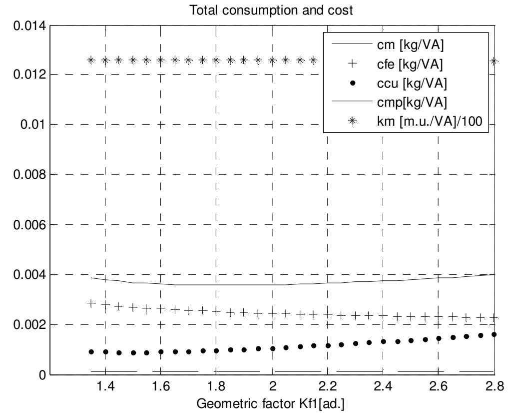

Fig. 9. Total consumption and cost

The optimization of the slot number number was made by criteria (13) and (14). There are two options:

can be deterеminated the number of slots per phase and pole depending on the specific consumption of active materials, or according to specific cost. During this stage, the imposed temperature remains constant. All require optimization features for slot per phase and pole take into account active material consumtion were represented in fig.10.

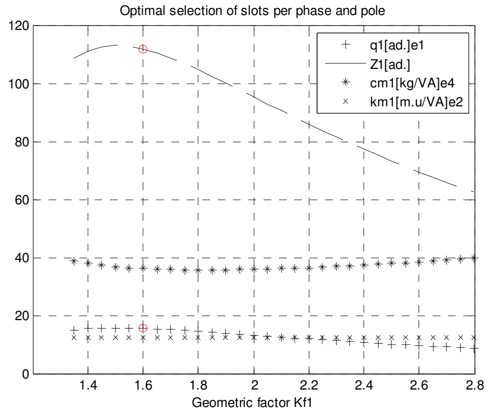

Fig. 10. Optimal selection of slots per phase and pole

In the case of cost optimization, the characteristics were represented in fig. 11.

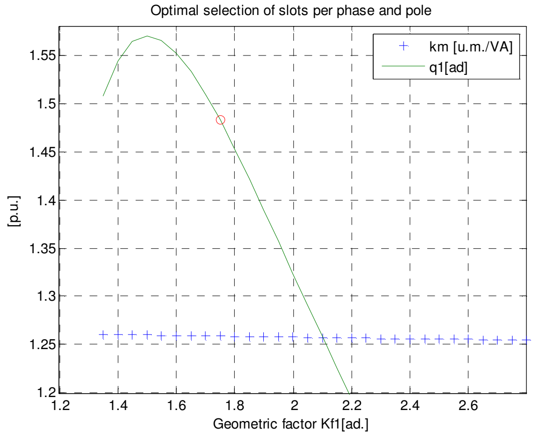

Fig. 11. Real angular characteristics for consumption optimization

Optimization criteria is a graphic-analytical one. The results obtained from optimization procces are presented in table. no. 1.

Table no. 1. Optimization characteristics

Parameter	Consumption optimization	Cost optimization
k_{f1}	1.7	1.6
γ_1	4	4
q_1	$1.55 \approx \frac{19}{12}$	$1.48 \approx \frac{18}{12}$
Z_1	112	106
$c_{m1}[kg/VA]$	0.0036	0.0030
$k_m[m.u/VA]$	0.0036	1.2591

Note that the results obtained from optimization are very close.

Circuit parameters, and some performances were given in table no. 2. Power factor resulting is lower because of large number of pole pairs involved of generator.

Table no. 2. Optimization parameters

Parameter	Estimated	Consumption optimization	Cost optimization
$r_1[p.u.]$	0.413	0.0346	0.0329
$x_{\sigma 1}[p.u.]$	0.12	0.171	0.136
$\cos\varphi$	0.9	0.86	0.86
η	0.92	0.919	0.922

In fig. 11 and fig. 12 were represented the characteristics obtained from optimal design of active materials consumption.

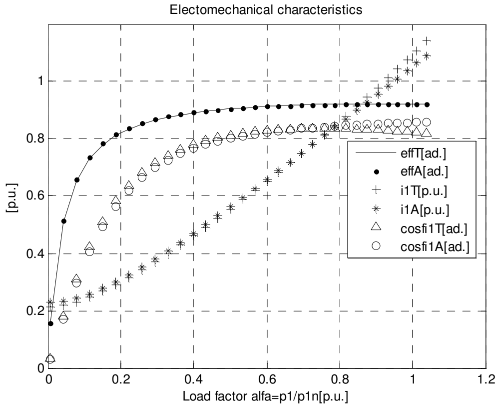

Fig. 12. Real electromechanical characteristics for consumption optimization

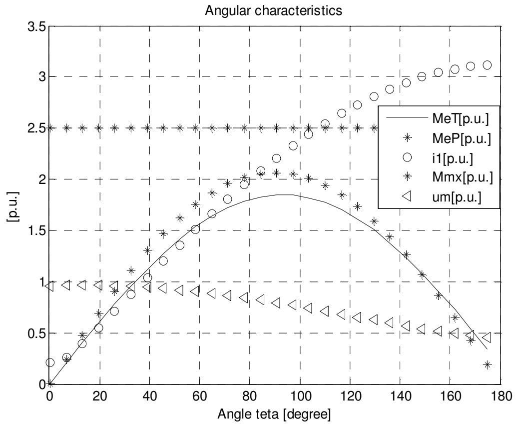

Fig. 13. Real angular characteristics for consumption optimization

Performance characteristics for optimization case of specific costs were represented in fig. 13 and fig. 14.

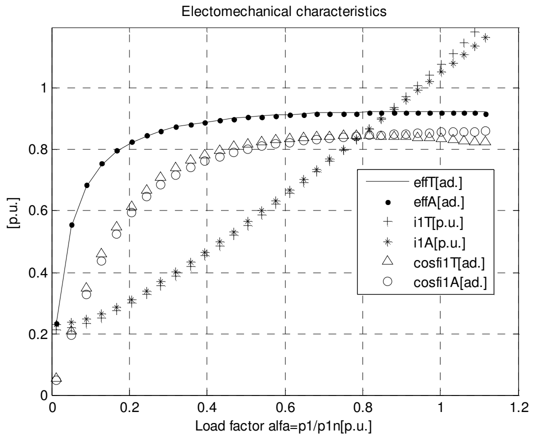

Fig. 14. Real electromechanical characteristics for cost optimization

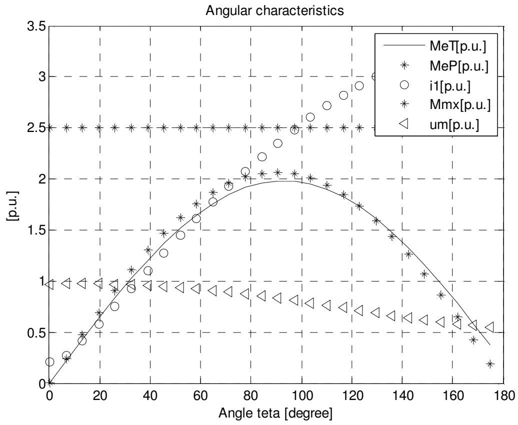

Fig. 15. Real angular characteristics for cost optimization

4. CONCLUSIONS

The optimization of slots number per phase and pole, with a multi-criteria approach, as economic criteria, respectively, thermal one leads to a rapid convergence in the order to determinate the solution.

The great advantage of the new method proposed in this work paper consists in the possibility of direct monitoring of temperature insulation by the number of slots per phase and pole which is an obligatory condition for ensuring a long life of the generator.

An approach as the one proposed in this work is an alternative one at the traditional methods (which are often solved by intelligent systems), providing a quick, practical and simple optimal solution.

The universality of the proposed method can be recommended for all the other types of classical and special rotating machine, either with fractional or integer winding, where the number of slots per phase and pole has a great influence on the performance characteristics.

Future work involve a complete analyze of the machine take into account the thermal influence of frontal part of winding to output performance of machine.

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