Application of high-speed micro turbine generators in the electric industry

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Abstract. Among the particular features of high-speed micro turbine generators we can name output voltage instability when you change the value or load power factor; and difficulty of voltage regulation due to the absence of field winding. Authors of the article demonstrate a technical solution of several actual problems when using the high-speed synchronous generators in the system of an independent power supply. One of the proposed solutions is an original system of regulation and stabilization of the output voltage which helps to minimize flux leakage of the magnetic bias, and thereby minimize the energy consumption and increase the accuracy and speed of output voltage regulation. Owing to the new design ensuring regulation and stabilization of the output voltage we managed to minimize mass and dimension parameters of high-speed synchronous alternating-current generators with permanent magnet excitation. Several studies and a mathematic modeling confirm the efficiency of the new system of stabilization and regulation of the voltage ofthe high-speed micro turbine generators. Among the disadvantages of the proposed method we can name temperature increase in the stator magnetic circuit. Temperature increase is caused by the saturation of the magnetic circuit due to the stator back biasing. Experience has shown that the temperature influence on the main characteristics of permanent magnets NdFeB and on the induction in particular. With the increase in temperature, a decrease in the induction and capacity of non-contact magneto-electric generator was observed. To eliminate these disadvantages, the authors propose a patented design of stator winding with a direct cooling system.

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Introduction

The variety of energy consumers and the requirements for the type and quality of power supply gives a fresh look at the role of independent generating unitof mid-size(from tens of kilowatts to megawatts) in the energy sphere. Decentralized autonomous power supply along with the centralized power supply is a good prospect.In this case, the consumer does not depend on long power transmission lines and, consequently, possible accidents.An important argument in favor of independent power supply is the high cost of construction and maintenance of power transmission lines in severe climatic conditions of the Russian Federation even in the areas with developed electric power stations.Of special interest is the use of autonomous power supply units in remote sparsely populated areas, such as the Far North of Russia due to the large length of cable lines, complex landscape, and a small number of consumers. Moreover, autonomous power supply is used as backup on various objects.Today the major part of the electrical equipment expire service life or close to the date of expiration and will be taken out of operation. This will cause a reduction of heat and electricity production. Under conditions of economic crisis it is difficult enough to find sufficient sources for commissioning of new high-power stations in the coming years (except for completion of construction of earlier started objects).

Under conditions described, in the nearest future it is necessary to concentrate on relatively cheap independent low and medium power units. Necessary funds may be found in the local budget or private wealth. The main part of any autonomous power supply (APS) system is generator. To ensure economic efficiency of APS application, such a generator must have high performance, reliability while operating under extreme conditions, and have a simple design. Today, those requirements are best met by non-contact magneto-electric machines (NCMs) of low and medium power with rotation frequency from 12 000 up to 90 000 rpm, for example, high-speed micro turbine generators meet the stated requirements [1-3]. Among the particular features of high-speed micro turbine generators we can name output voltage instability when you change the value or load power factor; and difficulty of voltage regulation due to the absence of field winding.

Traditionally, output voltage regulation is achieved by inclusion of semiconductor converter or electric capacity in the electric circuit of stator winding. Method of DC magnetic bias is used as well to stabilize the output voltage of non-contact magneto-electric generator.Among the disadvantages of the first two methods we can name the presence of additional nodes with high specific mass and dimension parameters. A drawback of the method of magnetic bias of stator pack is flux leakage which negatively affects the overall efficiency of non-contact magneto-electric generator.

To solve the stated problems, we developed an original design of non-contact magneto-electric generator with biased stator pack [4], see Fig. 1

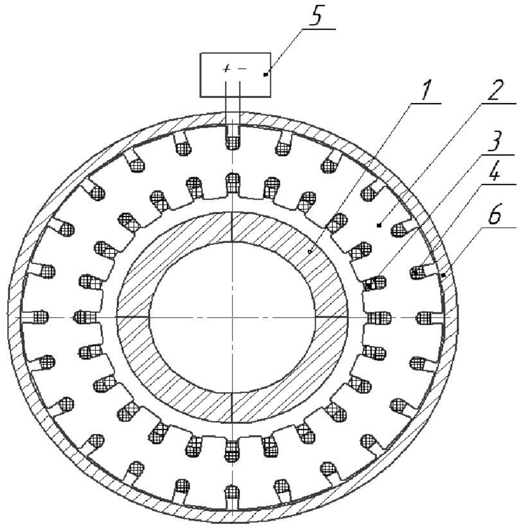

Figure 1: General view of non-contact magneto-electric generator according to patent illustrating where 1 is the rotor, 2 is the stator, 3 is the slot winding, 4 is the toroidal winding, 5 electrically-connected to DC power supply where stator is pressed into the ferromagnetic cylinder (6) with saturation flux density which is equal to the saturation induction of stator or exceeds it.

The idea is as follows: when the rotor 1 rotatesin the slot winding 2, the voltage is induced. If a load is applied the voltage drops. DC flows on the toroidal winding 3 of the stator.

DC flows through the windings 4 and produces a magnetic field. Lines of the magnetic field close on the stator 2 and ferromagnetic cylinder 6 stabilizing the stress curve where the saturation induction of the ferromagnetic cylinder must be equal or must exceed the saturation induction of the stator.Introduction of the ferromagnetic disk helps to minimize flux leakage and thus enhance the effectiveness of voltage regulation through the magnetic bias of the stator back.

For practical implementation of the proposed solution it is necessary to develop a mathematical tool adequately describing the processes in the non-contact magneto-electric generator when magnetic bias of the stator back is applied. With reference to the works [5-7] you can see different mathematical models of such systems created for non-contact magneto-electric generators with permanent magnets SmCo or AlNiCo. Today it is best to use the NdFeB type magnets because they differ from SmCo and AlNiCo magnets in temperature stability, and accordingly the application of well-known mathematical models can cause significant errors in calculations. In this regard, the urgent task to be solved in this article is to develop a mathematical tool describing the processes of voltage regulation in the non-contact magneto-electric generators with permanent magnets AlNiCo.

Main level heading

The essence of the proposed method lies in impact on reluctance of non-contact magneto-electric generator [5] that is:

$$R_m = R_{mag} + R_\delta + R_{st}, \qquad (1)$$

Where R_{mag} is permanent magnet reluctance, R_δ is gap reluctance, R_{st} is reluctance in a magnetic core which depends on degree of iron saturation.

Given that $R_{mag} = \text{const}, R_\delta = \text{const}$, than the change of the reluctance in the magnetic core will lead to changes in the reluctance of the non-contact magneto-electric generator.

Total magnetic flux Θ goes through a permanent magnet. Part of this flux Θ_{em} is dispersed by the magnet. An operating flux Θ_δ passes through the gap. It follows different paths in the back of the armature: Θ_{jb} is the flux in the section of the back of the armature where the flux of the bias winding is directed oppositely with the full magnetic flux; Θ_{jc} is the flux in the section of the back of the armature where the flux of bias winding is directed in accordance with the full magnetic flux.

Since the flux at different sections is constant, then the magnetizing force of the armature winding at different sections is determined by the formula:

$$F_p' = \frac{\alpha_i}{4p} F_p, \qquad (2)$$

Where F_p is the magnetizing force; F_p' is the magnetizing force of the armature winding at sections 1 and 3; α_i is the coefficient of pole overlapping;$p$is a number of poles.

For section 2:

$$F_p'' = \frac{1-\alpha_i}{2p} F_p, \qquad (3)$$

Where F_p is the magnetizing force; F_p'' is the magnetizing force of the armature winding at section 2; α_i is the coefficient of pole overlapping; p is a number of poles.

Magnetizing force of the armature winding is expressed as follows:

$$F_p = Iw, \qquad (4)$$

Where I is stator current; w is a number of stator turns.

Voltage regulation by magnetic bias of the stator pack leads to an increase of heat loss in copper and in the stator pack.

According to preliminary calculations maximal increase in the stator pack caused by the increase of magnetic induction in the stator back does not exceed 19%. Overall copper loss may be expressed as follows:

$$P = mI^2 r + I_p^2 r_p, \qquad (5)$$

Then, the total efficiency of non-contact magneto-electric generator (magnetic bias of the stator back is applied) is determined by the formula:

$$\eta = \left[1 - \frac{(mI^2 r + I_p^2 r_p + P_r)}{P}\right] 100, \qquad (6)$$

From earlier studies [8-10] it is know that the temperature increase will lead to the decrease of the NdFeB permanent magnets performance.

Mathematically, temperature influence on the performance of permanent magnets is described by the introduction of heat coefficients. Dependence of the high-coercivity permanent magnets characteristics on operating temperature is described by the introduction of temperature coefficients of high-coercivity permanent magnets (k_{Br} is for residual induction, k_{Hc} is for coercivity. For the NdFeB type k_{Br}=-0,11; while k_{Hc}=-0,6). Taking into account these coefficients, residual induction and the coercivity of the high-coercivity permanent magnets is expressed as follows:

$$B_r(T) = B_r\left(1 - \frac{k_{Br}(T_{pm} - 23)}{100}\right)$$

$$H_c(T) = H_c\left(1 - \frac{k_{Hc}(T_{pm} - 23)}{100}\right) \qquad (7)$$

Where $B_r(T)$, $H_C(T)$are the value of residual induction and coercive force stated in technical requirements respectively; T_{pm} is temperature of the high-coercivity permanent magnet; k_{Br} is temperature coefficient of residual induction; $k_{Hc}$is temperature coefficient of coercivity. Useful power and efficiency of the high-coercivity permanent magnet changes as well.

Useful power in this case is as follows:

$$P = 3.06 V_m k_m k_{rm} k_{ad} k_{ud} f k_f B_{m0} H_c \sqrt{1 - \frac{\cos^2\varphi}{k^2} - \frac{\sin\varphi}{k}}, \quad (8)$$

where P is the capacity of the generator with the high-coercivity permanent magnet; V_m is the volume of the magnet; k_f is the field form coefficient; f is the current frequency; k_m is the coefficient reflecting the drop in magnetic intensity in the magnetic circuit; k_{ad} is the coefficient reflecting dependence of the MMF of direct-axis armature reaction on the rotor MMF; k_{ud} is the striking short circuit current ratio; k is the ratio of the nominal current to the short circuit current; k_{rm} is the leakage coefficient; B_{m0} is the induction on the surface of the high-coercivity permanent magnet.

Given that the induction on the surface of high-coercivity permanent magnet is calculated as follows:

$$B_{m0} = \frac{B_r}{\left(1 + \frac{\delta_{oe} B_r k_\delta}{\mu_0 l'_m k_{rm} H_c}\right) k_{rm}}, \qquad (9)$$

Where $\delta_{OE}=2\delta/D$ is the relative air gap; δ is the air gap of the generator; D is the diameter of the rotor; l_m is the relative length of the rotor; k_δ is the coefficient of the air gap.

The electromechanical energy converter capacity is as follows:

$$P = 3.06 V_m k_m k_{ad} k_{ud} f k_f \frac{B_r}{\left(1 + \frac{\delta_{oe} B_r k_\delta}{\mu_0 l'_m k_{rm} H_c}\right)} H_c \sqrt{1 - \frac{\cos^2\varphi}{k^2} - \frac{\sin\varphi}{k}}, \quad (10)$$

According to the eqn. (10) and taking into account the eqn. (7), we demonstrated the dependence of the capacity and the air gap induction of the NCM on the temperature of the high-coercivity permanent magnet, fig.2, fig.3. When calculating, we used the following parameters of the NCM: rotation frequency 12000 rpm, B_r=1,32 T, H_c=947 кА/м, δ=1,5, $\cos\varphi$=0,9, D=130 mm, k_{rm} =1,2.

In order to check the accuracy of our calculations, we carried out a computer simulation (using Maxwell) of power and magnetic induction in NCM the air gap changing characteristics of the high-coercivity permanent magnets. (see eqn. 10). Computer simulation results are also shown in fig. 2, fig. 3.

This analysis, fig.3, shows that with an increase in temperature in 2 times, the generator capacity is reduced by 27%. Induction in the air gap is reduced to 15-17%. The difference between the calculated and computer data does not exceed 10% for magnetic induction and 12% for the power. This confirms the possibility of using the above mentioned formulas for the design of generators with high-coercivity permanent magnets.

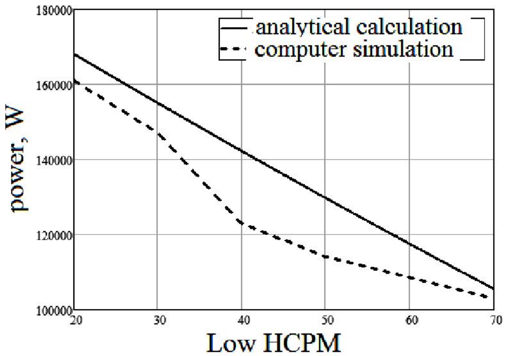

Figure 2: Dependence of capacity of the generator with the high-coercivity permanent magnets on the temperature of the permanent magnets.

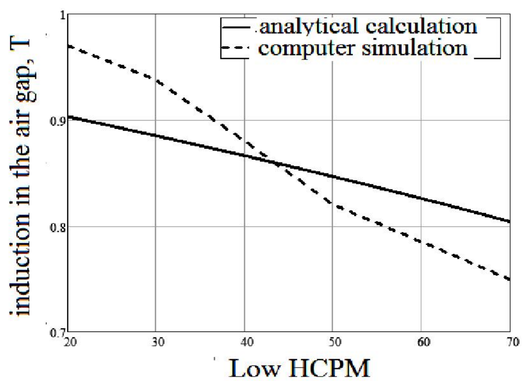

Figure 3: Dependence of the air gap induction of the generator with the high-coercivity permanent magnets on the temperature of the permanent magnet.

Thus, to ensure efficient use of the system of voltage regulation in the NCM it is necessary to increase the cooling rate. To solve the stated problem, we propose a novel design of intensive cooling system [11].

Design developed for intensive cooling of NMC represents the stator windings which are hollow tubes in the form of profiled slots with direct cooling. These tubes are interconnected by a common hollow ring, wherein the base of each tube has a coolant outlet system, gas expelling system and electrical leads.

The advantage of the developed design is that it allows you to simplify the repair of the NCM winding, as well as to increase the reliability of intensive cooling of the NCM.

Conclusions

A novel technical solution to increase the effectiveness of voltage regulation in the NCM without additional semiconductor block is presented in this article. For practical application of the presented solution it is necessary to increase the cooling rate of the electrical machine. We also designed a novel scheme for this.It is established that with the increase in temperature of the rotor magnet in the NCM (rotation frequency 12000 rpm, B_r=1,32 T, H_c=947 kA / m, δ=1,5, cosφ = 0,9, D = 130 mm, l_M=142 mm, σ = 1,2.) in 2 times, its power is reduced by 27%. Induction in the air gap is reduced to 15-17%.

The results obtained can be used for designing the autonomous power supply systems with the NCMs.

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