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SUBSTANTIATION OF THE STARTER-GENERATOR TYPE FOR MOVING OBJECTS WITH SELF-CONTAINED POWER SUPPLY SYSTEMS

ABSTRACT *In this article a comparative analysis of two types of brushless switched electric machines, induction and permanent-magnet machines is presented. These machines are selected as the most allowable for starter-generator operation of independent mobile objects. It is shown that permanent-magnet machines are more perspective for using in the capacity of starter-generator.*

Keywords: *asynchronous machines, brushless machines, dc machines*

1. INTRODUCTION

One of the main problems at designing of electric starting and generation systems for any self-contained moving object is a selection of electrical machine (EM) type and its subsequent calculation. In practice, in many cases various EM types are used as a starter and generator for self-contained moving objects, but also the variant of combination of starter and generator functions in one EM exists. During power unit starting such EM works as a starter, after starting it functions as a generator [1]. One of possible block schemes of the starter-generator (SG) on the basis of magnetoelectric machine (MEM) with the matrix converter [2] and microprocessor control is shown in Figure 1.

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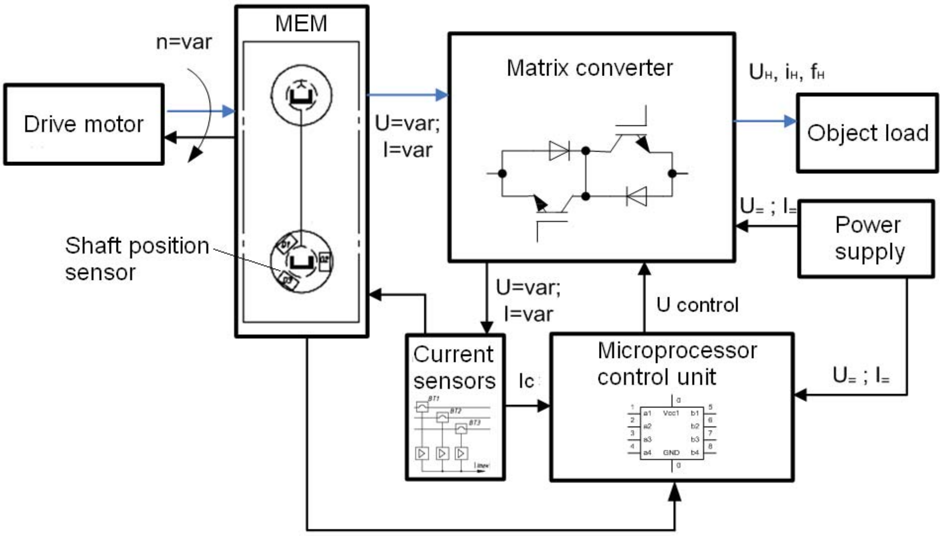


Fig. 1. Block scheme of the starter-generator system

Contradictory requirements of start and generation modes transfer the task of SG creation in series of multiparametric ones with a great number of restrictions. In addition to the requirements executable at designing of every EM, the following demands caused by exploitation features are distinguished:

- trouble-free operation in all conditions of application;
- survivability, autonomy and simplicity of service;
- minimum mass and overall dimensions;
- high mechanical strength;
- low radio interference level;
- protection against water, fuel and other liquids applied on the object [1].

Till the end of 1990s, DC power supply systems were widely applied in the self-contained moving objects. In aviation of that time the unique electromechanical DC electric power source was DC commutator-type generator of series ГСР and starters-generators of series ГС realized on its basis [3]. Technical characteristics of some aviation DC commutator generators and SG of these series are summarized in Table 1.

When a new generation of altitude supersonic aircrafts appeared, application of DC commutator machines (including their using as bulk power supplies) became problematic [3], because they had ceased to satisfy the needs of a new airborne equipment of self-contained moving objects in accordance with many parameters (generally it concerns reliability) [4].

Implementation of AC power supply system with usage of contactless AC electric machine as an electromechanical power source was output from this situation. Implementation of AC power supply system in the self-contained moving objects is also explained by other reasons [3].

TABLE 1
Technical characteristics of commutator-type generators and starter-generators

Parameter	Generator or starter-generator type								
	ГСР-СТ12000	ГСР-12КИС	ГС-12ТО	ГСР-СТ12/40А	СТГ-12ТМО	ГСР-18000М	СТГ-18ТМ	ГСР-18ТО	ГСР-СТ18/70 КИС
Power, kW	12	12	12	12	12	18	18	18	18
Current, A	400	420	400	400	400	600	600	600	600
Speed, 10^3 rpm	4.2-9	4-9	5.68-7	4-9	4.2-9	4-9	4.5-9	4-9	4-7.8
Overall dimensions, mm	179x380	-	187x385	180x393	187x437	198x485	200x517	-	198x391
Mass, kg	31	32.5	30	32	35	41.5	44	40	42.5

For usage as a starter-generator in the system of engine starting and electrical power generation on the object the following types of contactless EMs have been considered: synchronous contactless machine, contactless AC machine, asynchronous machine, contactless machine with claw pole rotor, contactless machine with combined excitation, inductor machine, switched reluctance machine, brushless magnetoelectric machine.

The comparative analysis of foregoing EM types has shown that the most acceptable SG variant is an asynchronous or magnetoelectric EM. In this connection the comparative analysis of these two EM types is of interest.

2. ASYNCHRONOUS STARTER-GENERATORS

Squirrel-cage SG can find application in the self-contained moving objects having wide range of rotary speed of the drive engine. Principal advantage of asynchronous machine (AM) is a construction simplicity, high reliability, high rotary speed and operation in field reduction mode. Thanks to these qualities the area of AM application constantly extends [5].

AM application as the starter-generator with usage of the frequency converter is rather expedient [6, 7]. In the elementary case of frequency regulation the shaft speed control is carried out by means of change of the frequency and amplitude of three-phase voltage supplied to EM winding. It is known that full controllability of the electric drive is provided by control of the electromagnetic torque of the electric motor. This possibility is given by the vector control determined by obviously expressed vector character of controlled variables (currents, flux linkages, torque of the induction motor). It is allowed to provide rotary speed accuracy with sliding compensation (even without speed feedback), wide control range, fast response to loading change, high efficiency of the electric motor at low frequencies.

Despite the marked advantages of asynchronous SGs, their application in generating mode is limited by necessity of reactive power consumption. In other words, asynchronous SG is capable to work only in system with reactive power source.

Reactive power expended on creating of AM magnetic field is estimated in the following way. If the amplitude of flux density B_m in air gap is defined then appropriate specific energy of the magnetic field is equal

$$w_M = [1/(2 \cdot \mu_0)] \cdot B_m^2, \tag{1}$$

where μ_o is permeability of vacuum.

For the full volume of air gap V_δ reactive power is approximately equal

$$Q \approx \omega \cdot w_M = 2 \cdot \pi \cdot f \cdot w_M = [\pi \cdot f / \mu_0] \cdot B_m^2 \cdot V_\delta \tag{2}$$

where ω is angular frequency, s^{-1}; f is frequency, Hz.

The reactive power providing AM excitation in generating mode can be received at the expense of application of capacitors or controlled semiconductor converters (inverters) which enclose the circuit of reactive power generating.

It is known that the voltage inverter has a rigid external characteristic (similar to AC mains characteristic). At active load it gives the active power and at inductive one the active power is equal to zero. When AM works in generating mode, the inverter is just reactive power source (3), required for creation of the main magnetic flux

$$Q \approx m \cdot U \cdot I \cdot \sin(\beta - 0{,}5\gamma) \tag{3}$$

where

m – number of phases,
U – voltage, V,
I – loading current,
A, β – advance angle (in this case $\beta < 0$),
γ – overlap angle.

Rotary speed of magnetic field of the stator is defined by switching frequency of inverter transistors. The wattful current of the stator is rectified by means of the diode bridge of reverse current and is transmitted in an aircraft electrical system [6].

AM application with the semiconductor converter as SG demands the complex control algorithms and software.

According to the analysis the asynchronous SG is contactless, constructive reliable, simple, low-cost, effective machine, i.e. it provides requirements presented to SG of independent objects. In addition this SG has a possibility of control of currents and torque. It allows to improve energy characteristics noticeably.

But, in comparison with MEM, AM has the following disadvantages: larger mass and overall, low energetic, dynamic coefficients and overload capacity because of low thermal limit at identical power and other equal conditions. Moreover the form of mechanical and adjusting characteristics of AM isn't favorable from the point of view of speed control and start-up conditions. They essentially yield in it to MEM. Mechanical characteristics of magnetoelectric (1) and asynchronous (2) EMs in motor mode (expressed in relative units) are shown in Figure 2

3. BRUSHLESS MAGNETOELECTRIC STARTER-GENERATORS

Magnetoelectric SG, possessing advantages of the contactless EM, has benefits in comparison with SG, fulfilled on the AM base, namely:

- high efficiency (up to 0,95 and more) and raised thermal loading of the stator due to absence of losses on excitation and losses in the rotor;
- higher overload capacity (short-time ratio of the maximum torque is 5 and more);
- reduced reactance and rigid speed-torque characteristic;
- high response speed;
- high service reliability (failure rate is no more $1x10^{-6}$ 1/h);
- high power density in generating mode at the expense of rotary speed selection, electromagnetic loadings and application of new materials of the magnetic circuit [8].

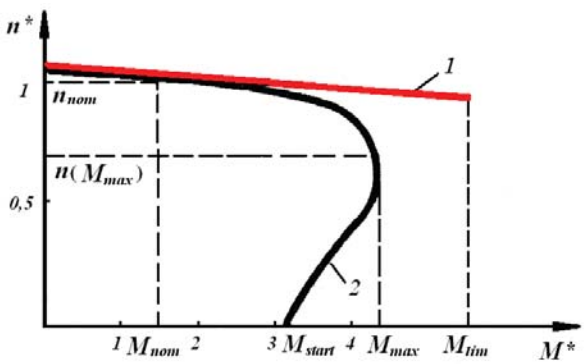


Fig. 2. Mechanical characteristics of MEM and AM motor mode

Application of new permanent magnet materials allows to develop the high-speed SG with mass and overall coefficients, which exceed identical coefficients of asynchronous SG [8].

Mass and overall, energy and dynamic coefficients of MEM depend not only on the magnetic material sort, but also on the magnetic system construction. The modern programs of magnetic fields modeling on the basis of the finite-element method permit to optimize flux density distribution in working volume of the system, to provide the maximum flux in air gap in the given or minimum volume.

Torque of the magnetoelectric SG is limited by the value of maximum admissible current as armature current (or phase current) doesn't create the main magnetic flux i.e. magnetoelectric SG doesn't contain a magnetizing reactive current as asynchronous SG. In this connection, under identical heating conditions restricting the current value, the torque defined by magnetoelectric SG current will be greater.

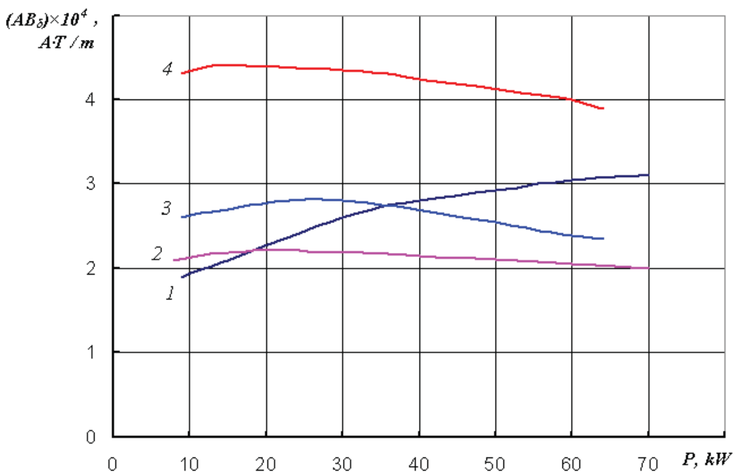
Using classical electromagnetic torque representation through tangent force applied to a surface unit of the rotor it is possible to write the following ratio:

$$M = (\pi/2)\cdot D^2 \cdot L \cdot F_k = (\pi/2)\cdot k \cdot D^2 \cdot L \cdot A \cdot B_\delta, \tag{4}$$

where

$F_k = k\cdot A\cdot B_\delta$ – specific tangent force, N/m^2;
D, L – boring diameter and length of thestator (rotor) pack;
A, B_δ – ampere density and amplitude of flux density in the air gap;
k – the non-dimensional coefficient depended on EM design features and distribution of induction.

According to (4) the electromagnetic torque of EM rises with magnification of electromagnetic and specific loadings (A, B_δ and F_k). Besides, by comparison of EMs with identical overall dimensions the electromagnetic torque of that EM will be more whose values of electromagnetic loadings (A, B_δ) will be higher. Thanks to absence of electrical and magnetic losses in the rotor, in MEM the greater values of electromagnetic loadings can be accepted as compared with AM (see Fig. 3) [8]. This explains higher value of electromagnetic torque of MEM in comparison with AM according to the formula (4). The great values of electromagnetic loadings in MEM (under identical working conditions and equal capacity) result in reduction of the active materials volume and EM mass.



1 – AM with cosφ = 0,8; 2 – MEM with cosφ = 0;
3 – MEM with cosφ = 0,8; 4 – MEM with cosφ = 1

Fig. 3. Curves of electromagnetic loads product AB_δ for AM and MEM

The rotary speed range of magnetoelectric SGs is restricted to mechanical strength of the rotor and maximum supply voltage of the converter [9].

Hence, the torque range and rotary speed of MEM is wider than ones of variable-frequency AM [10]. MEMs have almost unlimited control range of rotary speed (1:50000 and more).

Thanks to appropriate adjustment of rotor position sensors the power factor of brushless MEM is close to unity. It promotes reduction of losses in a stator winding.

Mechanical characteristic of AM depends nonlinear on the torque and has a falling character. Actually mechanical characteristic of MEM looks like the mechanical characteristic of the independent excitation DC motor (see Fig. 2) and is rather convenient at creation of controlled systems of the electric drive [10]. The external characteristic of magnetoelectric SG has rigid character in generating mode. According to experimental data a voltage variation from idling to rated value is approximately 7-10% and it allows to eliminate voltage regulator usage in a number of cases.

In start mode of drive engine of the self-contained moving object AM essentially yields to MEM as AM has the worst dynamic indexes and the inertia moment of AM rotor (owing to increased mass) considerably exceeds inertia moment of MEM rotor. In this connection the electromechanical time constant of AM (5) will be more than electromechanical time constant of MEM. This testifies to deterioration of AM dynamics.

$$T_{м} = J_m \dot{\varphi}^0 / M_{sc}\,, \tag{5}$$

where

J_m – inertia moment of EM;
$\varphi°$ – angular frequency of rotation at ideal idling;
M_{sc} – short circuit torque.

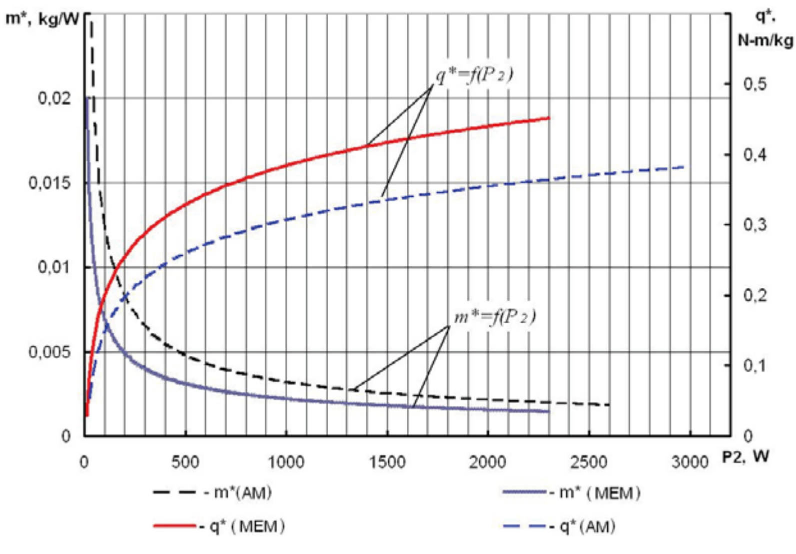


Fig. 4. Aircraft AM and brushless MEM dependences *m, *q** = *f*(P_2)**

MEM has disadvantages and the primary lack is a regulation complexity and stabilizing of output voltage as the magnetic flux of permanent magnets doesn't change largely. Another imperfection of MEM is the raised cost due to permanent magnets using. Besides, characteristics of MEM depend on changing of ambient temperature. Especially it concerns MEM with Nd-Fe-B magnets having temperature stability much lower than temperature stability of samarium-cobalt magnets.

The quantitative estimation of EMs engineering level gives the most accurate account of their application for SG.

For the quantitative estimation of AM and MEM engineering level it is necessary to use concepts of relative density m^* and a specified torque q*. The relative density is a ratio of EM mass to its rated power $m^* = G/P2$ (kg/W), and specified torque is the ratio of the nominal torque to EM mass $q^*=M_n/G$ (Nm/kg). Figure 4 shows dependences m^*, $q^* = f(P2)$ of aircraft AM and brushless MEM at identical operation modes, method of cooling and equal rotary speed. From schedule comparison (Fig. 4) it follows that AM yields to brushless MEM at every index.

4. CONCLUSION

The carried out analysis shows that MEM meets the requirements of the modern power supply systems and surpasses AM by all main indexes: critical and overload capacity, efficiency, reliability, specific mass (specific mass of EM average power is higher than one of AM in 2.3 – 2.6 times), specified torque (specified torque of EM average power is higher than one of AM in 1.2 – 1.3 times). Thus, MEM is more perspective for usage as SG of self-contained moving objects.

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Manuscript submitted 20.06.2013

MASZYNY ELEKTRYCZNE DO NAPĘDU PRZEMIESZCZAJĄCYCH SIĘ OBIEKTÓW Z AUTONOMICZNYM SYSTEMEM ZASILANIA

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STRESZCZENIE *W artykule omówiono i przeanalizowano dwa rodzaje maszyn elektrycznych: indukcyjną i bezszczotkową prądu stałego o magnesach trwałych. Zostały one wybrane jako najlepiej nadające się do pracy prądnicowo-silnikowej. Wykazano, że bezszczotkowe maszyny prądu stałego o magnesach trwałych są rozwiązaniem lepszym pod względem właściwości i niezawodności.*

Słowa kluczowe: *maszyny asynchroniczne, maszyny bezszczotkowe, maszyny prądu stałego*