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ELECTRIC MACHINE TYPE SELECTION FOR HIGH-SPEED MEGAWATT-RANGE GENERATOR

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ABSTRACT

Previous researches have shown that number of high-speed machine applications in direct drives and generator units increases from year to year. This is due to obvious potential benefits of such power installations: reduced dimensions of high-speed electric machine, decreased total weight of installation, increased efficiency of energy conversion. The main purpose of this paper is to select optimal type of electromechanical convertor for such installation. Four types of electrical machines were considered: synchronous machine with permanent magnets, asynchronous machine, inductor machine, switch-reluctance machine. Comparative analysis of designed 4 MW 12,000 RPM generators was conducted for active materials weight and specific power value and conclusions were drawn.

Keywords: direct drives, synchronous machine, permanent magnets, asynchronous machine, inductor machine, switch-reluctance machine.

INTRODUCTION

In recent decades one may notice increased number of high-speed electric machine applications in direct drives and generator units. This is due to obvious potential benefits of such power installations: reduced dimensions of high-speed electric machine. Decreased of total weight of installation, increased efficiency of energy conversion [1-2]. Selection of optimal type of electromechanical convertor for such installation is an actual scientific and technical problem, which is considered in this article.

In general, high-speed turbomachines could be based on the following types of electric machines [3-6]:

- synchronous machines with permanent magnets (PMSM);
- asynchronous machines (AM);
- inductor machines (IM);
- switched-reluctance machines (SRM).

In order to investigate the feasibility of different electric machine types application for high-speed turbomachines the preliminary design of 4 MW, 12000 RPM turbogenerator was performed based on each of 4 types of abovementioned machines. In all cases, it was assumed that turbogenerator feeds infinite power electrical network through semiconductor power converter providing required quality of output electricity.

A. Synchronous generator with permanent magnets

High-speed 4 MW synchronous generator was designed in 2 versions - with 2-pole and 4-pole rotor. In each case conventional PMSM design was used: stator has a 3-phase distributed winding in laminated core slots and rotor has a number of surface mounted permanent magnets on a steel yoke.

2-pole synchronous generator has outer diameter D_a = 850 mm, core length L = 900 mm. Stator inner diameter is D_i = 400 mm. The air-gap between stator and rotor makes 16 mm. Hence rotor outer diameter is D = 368 mm. Stator core has z = 48 teeth which corresponds to the number of slots per phase per pole q = 8. Coil pitch is y = 16. Such winding has winding factor k_w = 0,8276. Stator slots of rectangular shape are semi-closed with slot opening b_c = 5 mm, slot opening height h_c = 1,5 mm, slot wedge width b_k = 16 mm, slot bottom width b_d = 16 mm, slot height h_z = 72 mm. Generator has stator slot skew or PM skew equal to 1 stator tooth pitch. Stator winding has 8 effective conductors per slot, 2 parallel branches; number of elementary conductors is equal to 2. Slot filling factor for selected conductors and slot insulation grade makes k_s = 0,678, series turns number per phase is w = 32.

Rotor has 2 permanent magnets of 25 mm high. Each PM's width is determined by pole angle α = 0,666 which yields in PM width b_m = 358,8 mm. PM material is characterized by residual flux density B_r = 1,17 T and coercive force H_c = 860 kA/m. The critical coercive force leading to PM total demagnetization makes 600 kA/m.

The 2-pole generator design is shown at Figure-1.

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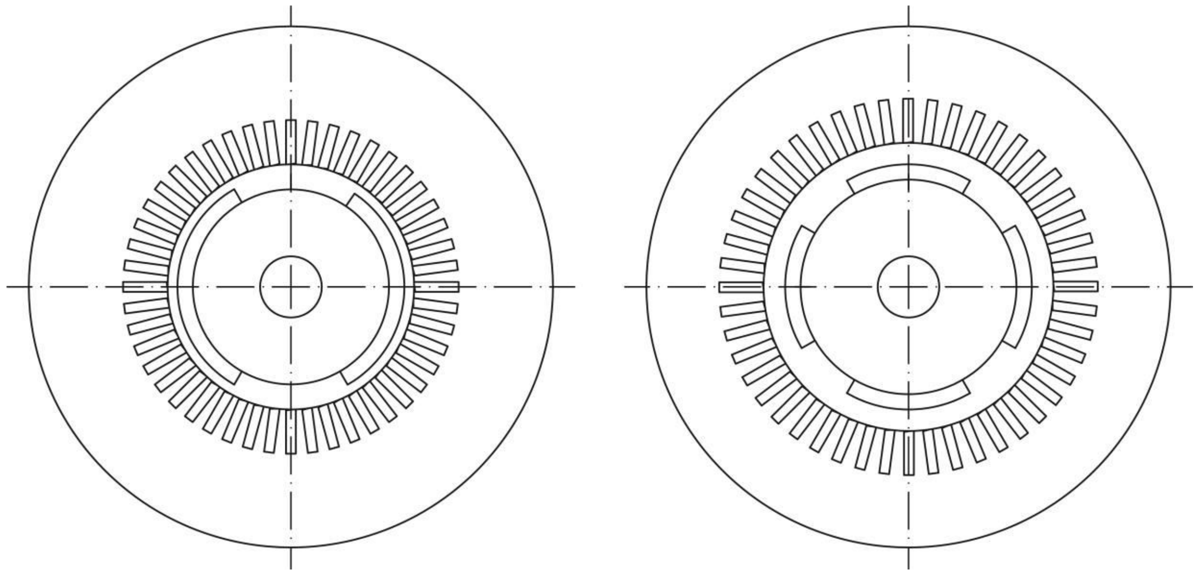

Figure-1. Synchronous generator with permanent magnets 2-pole and 4-pole designs.

Designed 2-pole synchronous generator has stator winding resistance at temperature 20°CR = 0,012916 Ohm, leakage reactance X_s = 0,85479 Ohm, total reactance on direct axis X_d = 9,2535 Ohm and total reactance on quadrature axis X_q = 9,2535 Ohm. The last two values show that PM rotor could be treated like none-salient-pole rotor. This is due to surface location of permanent magnets over steel yoke while PM permeability is almost like an air.

Machine total weight could be estimated via active material weight as follows: steel of stator teeth and yoke weight makes M_{Fe} = 2718 kg, copper of stator winding weight makes M_{Cu} = 306 kg, permanent magnet weight makes M_{PM} = 119 kg. The total weight of active materials makes M = 3143 kg. Hence, specific power of synchronous permanent magnet generator relative to active materials makes 1,273 kW/kg.

Stator core losses makes P_{Fe} = 22303 W, stator winding losses makes P_{Cu} = 5491 W, mechanical losses could be estimated as P_v = 10000 W which yields in total power losses of P_{sum} = 37807 W. Hence, generator efficiency makes η = 99,064%.

The rated current of 3-phase 4 MW generator at phase voltage 4 kV is equal to 319 A. The maximum power can be achieved at load angle 0,7845 rad. or 44,94 deg. and makes 4,245 MW. The voltage under maximum power makes 3,6 kV. The output voltage frequency of 2-pole generator is equal to f = 200 Hz.

4-pole synchronous generator with permanent magnets has the same rated voltage of U_1 = 4 kV and frequency f = 400 Hz for the rated speed of n = 12,000 RPM. Stator main dimensions were kept at the same level: stator outer diameter D_a = 850 mm, stator core length L = 900 mm. the designed 4-pole generator has stator inner diameter D_i = 470 mm, air-gap between stator and permanent magnets 35 mm and rotor outer diameter D = 400 mm.

The stator teeth number is z = 48 which means the number of teeth per phase per pole is equal to q = 4. Stator coil pitch is y = 10. Stator winding factor k_w = 0,925. Stator slots of rectangular shape are semi-closed with slot opening b_c = 5 mm, slot opening height h_c = 1,5 mm, slot wedge width b_k = 16 mm, slot bottom width b_d = 16 mm, slot height h_z = 72 mm. Generator has stator slot skew or PM skew equal to 1 stator tooth pitch. Stator winding has 8 effective conductors per slot, 2 parallel branches; number of elementary conductors is equal to 2. Slot filling factor for selected conductors and slot insulation makes k_s = 0,678, number of subsequent turns per phase is w = 32.

Rotor has 4 permanent magnets of 25 mm high. Each PM's width is determined by pole angle α = 0,666 which yields in PM width b_m = 196,15 mm. PM material is characterized by residual flux density B_r = 1,17 T and coercive force H_c = 860 kA/m. The critical coercive force leading to PM total demagnetization makes 600 kA/m.

Designed 4-pole synchronous generator has stator winding resistance at temperature 20°CR = 0,013174 Ohm, leakage reactance X_s = 1,6885 Ohm, total reactance on direct axis X_d = 6,1556 Ohm and total reactance on quadrature axis X_q = 6,1556 Ohm.

Machine active material weight is as follows: steel of stator teeth and yoke weight makes M_{Fe} = 2382 kg, copper of stator winding weight makes M_{Cu} = 312 kg, permanent magnet weight makes M_{PM} = 130 kg. The total weight of active materials makes M = 2824 kg which is 11% less than 2-pole generator weight. The specific power of 4-pole generator relative to active materials makes 1,416 kW/kg.

Stator core losses makes P_{Fe} = 21304 W, stator winding losses makes P_{Cu} = 6076 W, mechanical losses could be estimated as P_v = 10000 W which yields in total power losses of P_{sum} = 37393 W. Comparing to 2-pole design magnetic losses become slightly less, electric losses become slightly higher and generator efficiency makes η = 99,07%.

B. Asynchronous generator

Asynchronous generator was designed based on 4 MW induction motor design which is operating in generator mode with rated voltage 4, 8 kV and frequency 200 Hz leading to the same synchronous speed of 12,000 RPM. Stator has 3-phase distributed winding with one pole pair. Rotor has conventional squirrel-cage winding with slot copper bars welded to end rings.

Stator dimensions: outer diameter D_a = 850 mm, inner diameter D_i= 400 mm, core length L = 900 mm (main dimensions were selected similar to synchronous generator). Number of stator slots z = 48. Stator winding and stator tooth zone is almost like ones of synchronous generator. Rotor with squirel-cage winding has the same length as stator, rotor teeth number is z_r= 40.

Asynchronous generator design is shown at Figure-2.

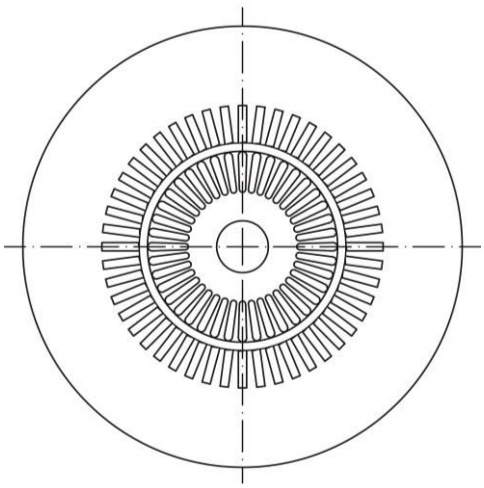

Figure-2. Asynchronous generator design.

Stator winding resistance at temperature 20°C makes R_S = 0,013 Ohm, leakage reactance makes X_S= 0,971 Ohm, adjusted value of rotor winding resistance makes R'_R = 0,018 Ohm, adjusted value of rotor winding leakage reactance makes X'_R = 0,893 Ohm.

Asynchronous generator should consume reactive power. Its rated power factor is equal to cosφ = 0,925.

The designed asynchronous generator has efficiency η = 98,4% which is slightly less than efficiency of PM synchronous generator.

Stator steel weight makes 2560 kg, rotor steel weight makes 499 kg, stator winding copper weight makes 307 kg, rotor winding copper weight makes 152 kg. the total steel weight makes 3059 kg, copper weight makes 459 kg which leads to the total weight of active materials equal to M = 3518. And the specific power of asynchronous generator makes 1,137 kW/kg. The specific power is less than one of PM synchronous generator. At that the total cost of asynchronous generator active materials will be twice lower than PM synchronous generator material cost because of very high cost of permanent magnets. And manufacturability of asynchronous generator is much better which will decrease the total generator cost even more.

One of the useful features of asynchronous generator is its ability to operate in motor mode in order to start gas turbine of the power unit. Designed machine starting torque factor makes k_{Ts} = 0,508.

Asynchronous generator has rated phase current equal to 284 A at rated slip s_r = 0,1%. Overload capacity makes k_T = 4,9.

C. Inductor generator

The third type of electric machine which was used for design of high-speed generator is an inductor generator with hybrid excitation. Inductor generators with stator voice-coil for exciting axial magnetic field are well known. Design method is described in [7] with main attention on field analysis.

Inductor generator of conventional design has an active zone with an excitation voice-coil in the central part while rotor poles at each side of the voice-coil are shifted by pole pitch. Such rotor configuration provides summing of electromotive forces of each armature coil side, while electromotive force is induced by variable part of air-gap magnetic field due to rotor rotation. Figure-3 shows average magnetic flux line within one section of inductor generator.

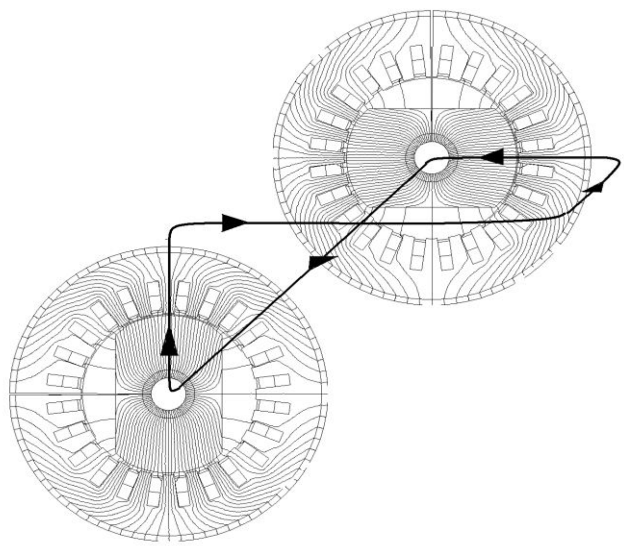

Figure-3. Average magnetic flux line within one section of inductor generator.

Inductor machines of brushless design has no winding on rotor. Rotor made of solid steel has a very high mechanical strength suitable for high-speed applications. On the other hand, all inductor machines obtain constant component of magnetic flux density which is not used in

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electromechanical power conversion. This leads to increased core cross-section and increased weight. Besides, active zone of induction machine has passive regions located between rotor poles which should be enlarged for increasing variable component of magnetic flux density.

Designed inductor generator with hybrid excitation is equipped with permanent magnets in the inter-pole rotor regions (Figure-4). These side permanent magnets have radial magnetization. To retain permanent magnets thin cylindrical bandage sleeves could be used on rotor surface. Such sleeves will provide smooth rotor surface leading to decreased aerodynamic losses.

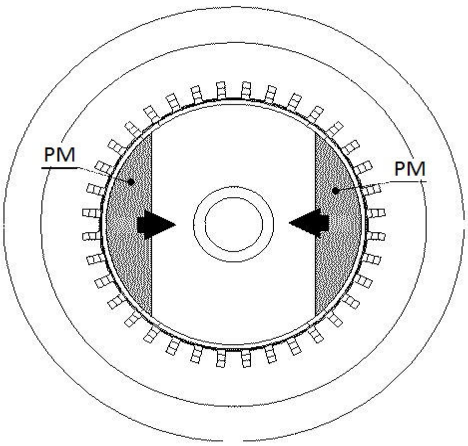

Figure-4. Inductor generator with permanent magnets on rotor side.

Additional side permanent magnets provide increased specific power of inductor generator. And its interaction with main excitation magnetic field allows decreasing excitation current and excitation losses.

Inductor generator with hybrid excitation is shown at Figure-5. Designed 4 MW inductor generator has only one section with one voice-coil and two rotor 2-pole parts.

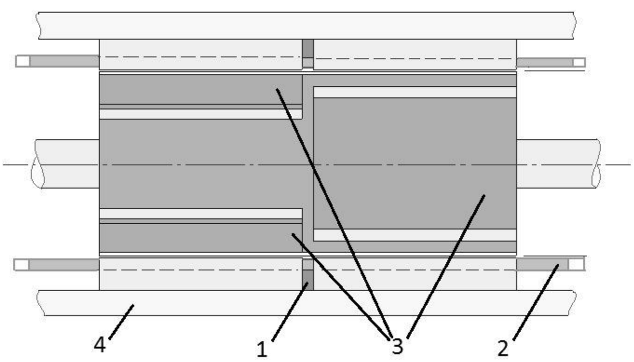

Figure-5. Inductor generator with hybrid excitation. 1 - excitation voice-coil; 2 - armature winding; 3 - permanent magnets; 4 - outer yoke.

Designed inductor generator has stator outer diameter equal to D_a = 548 mm, internal stator diameter equal to D_i = 408 mm. Two halves of stator core are located inside steel housing which also provides path for axial magnetic field. Outer diameter of housing is equal to D_k = 656 mm.

The total length of two stator core halves is equal to 884 mm, the width of excitation voice-coil located between two stator halves is equal to 33 mm. so, the total length of inductor generator was set L = 920 mm.

Each stator core has 36 slots of rectangular shape. Slot width is equal to b_s = 11 mm, slot height is equal to h_s = 29 mm.

For air-gap δ = 4 mm rotor outer diameter is equal to D_r = 460 mm. Each rotor half-section with 2 salient poles has permanent magnets located in the inter-pole region. These magnets are retained by bandage sleeve of 8 mm width. Permanent magnets are made of NdFeB grade 40.

4 MW inductor generator was designed for rated phase voltage U_1 = 3.70 kV, phase current I_1 = 397 A at unit power factor. Stator winding number of turns is equal to w_1 = 12 with parallel branches a = 1. Stator winding current density was selected at J_a = 6 A/mm^2, excitation voice-coil current density is the same J_f = 6 A/mm^2.

Weight estimation: stator yoke – 445 kg, stator teeth - 200 kg, stator winding copper weight makes 97,1 kg, field winding copper weight makes 11,4 kg, rotor core - 535 kg and rotor shaft 92 kg, machine frame weight makes 1219 kg and permanent magnets weight makes 176.7 kg. This estimation of active materials gives the value of specific power 1.441 kW/kg (while weight of the magnetic frame is accounted for) which is better than PMSM and AM results.

D. Switched-reluctance generator

In order to design switched-reluctance generator the modified procedure of SRD design was used [8]. At that the basic configuration 12/8 was selected which means combination of 12 stator teeth with 8 rotor teeth at each of 4 iterance. The total number of stator teeth is equal to 48, number of rotor teeth is equal to 32 (Figure-6). Stator winding has number of phases m = 3. Stator coils of each phase are located at each third stator tooth and has alternating polarity. Stator phase sequence along stator circle is as usual: A - B - C. Such low number of phases allows to use relatively simple topology of semiconductor switch converter.

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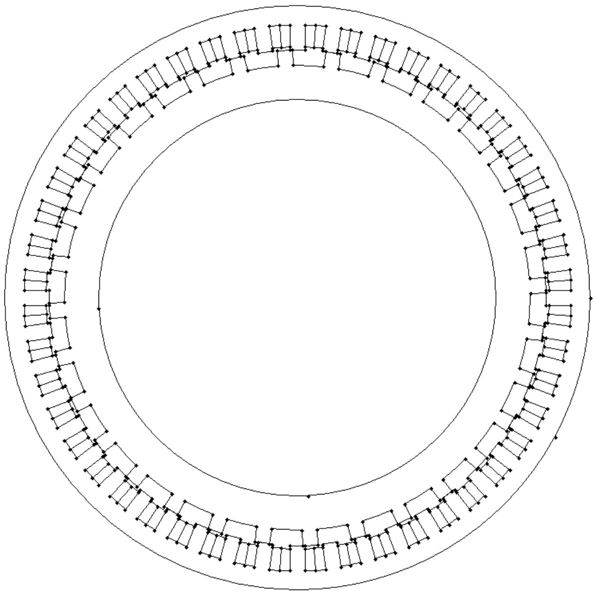

Figure-6. Switched-reluctance generator design.

Designed switched-reluctance generator has stator outer diameter equal to 590 mm, stator inner diameter equal to 500 mm, stator and rotor core length is equal to 1335 mm. Air-gap is equal to 0.5 mm, hence rotor outer diameter makes 499 mm. Rotor inner diameter is equal to 400 mm. Stator tooth width is equal to 15 mm, tooth height is equal to 25 mm, minimal stator slot width is equal to 17,7 mm. Rotor tooth width is equal to 15 mm, tooth height is equal to 15 mm, maximum rotor slot width is equal to 34 mm.

Phase current of designed switched-reluctance generator makes 1000 A, phase coils are series connected. At that stator winding current density is selected at the level of 6,5 A/mm^2 which is suitable for indirect air cooling. Stator core weight makes 549, 6 kg, rotor core weight makes 554,5 kg, stator winding copper weight makes 272,9 kg. So, the total generator active materials weight makes 1377 kg which corresponds to specific power of 2,9 kW/kg.

One of the main disadvantages of switched-reluctance generator is a high frequency of steel magnetization reversal leading to high steel losses. For the designed generator in case of simplest converter topology with single switching the frequency of stator tooth magnetization reversal makes

$$f = \frac{Z_R n}{60} = 6{,}400\ \text{Hz}.$$

In case of paired switching the convertor topology became more complicated, but the frequency of tooth magnetization reversal becomes twice lower

$$f = \frac{1}{2}\frac{Z_R n}{60} = 3{,}200\ \text{Hz}.$$

Even in latter case frequency of steel magnetization reversal is still very high which leads to high level of power losses. For example, the conventional 2-pole synchronous generator with rotating speed of 12,000 RPM has stator core magnetization reversal frequency equal to only 200 Hz.

E. Comparison of designed high-speed generators

Comparison of main parameters of designed high-speed generators of different types are made in Table-1.

Table-1. Comparison of designed high-speed generators.

Parameter	PMSM		AM	IM	SRM
	2p=1	2p=2			
Rated power, MW	4	4	4	4	4
Rated voltage, kV	4	4	4,8	3,70	4
Output frequency, Hz	200	400	200	400	0
Rotor speed, RPM	12 000				
Outed diameter, mm	850	850	850	656	590
Core length, mm	900	900	900	917	1335
Active materials weight, kg	3143	2824	3518	2776	1377
Specific power, kW/kg	1,273	1,416	1,137	1,441	2,9

CONCLUSIONS

a) Permanent magnet synchronous machines used to have higher specific power and higher efficiency comparing to asynchronous machines and switched-reluctance machines, but this type of machine possesses some significant drawbacks which restricts its implementation in high-speed applications [9]. In particular, one should carefully select rotor design and magnets location and watch on mechanical stress on fragile material of permanent magnets at high circumferential speed. Robust rotor design provides bandage sleeves to retain magnets on rotor surface. Such sleeves are made of non-magnetic materials in order to decrease permanent magnet leakage fields, but such sleeves increase non-magnetic air-gap. In case of conductive material of rotor sleeve there are eddy currents induced by higher harmonics of air-gap magnetic field which leads to increases losses and rotor with permanent magnets overheating. Many papers like [10] discuss rotor sleeve material selection which combines maximum mechanical strength with minimal eddy current losses.

b) Switched-reluctance machines features simple and reliable rotor design which makes it attractive for high-speed applications [11-13]. Such machines have no winding no permanent magnets on rotor. However, in comparison to PM synchronous machines SRM consumes significant magnetizing current due to high values of effective air-gap between stator and rotor teeth. Such factors decrease SRM power factor and leads to decreasing total efficiency. Moreover, SRM has high cogging torque which influence negative on general machine efficiency and quality [14].

c) While selecting high-speed electric machine type one should take into account not only technical values but also cost of production and maintenance. Paper [15] describes the design of embedded high-speed drive for industrial turbocharger. Besides of squirrel cage induction motor authors consider PM synchronous motor and switched-reluctance motor of the same dimensions. The comparison of all 4 electric machine types showed that induction motor is twice cheaper than PM synchronous motor and 40% cheaper than switched-reluctance motor.

d) Finally, asynchronous generator seems to be the most robust and cheap design, furthermore it could be easily manufactured at many Russian plants of electrotechnical industry.

The second feasible design of high-speed high-power generator is an inductor generator with brushless unipolar excitation and additional excitation from permanent magnets. Conventional inductor generator has passive rotor with minimum power losses. Aerodynamic losses of salient-pole design at high speed could be significantly decreased by outer sleeve while eddy currents due to higher harmonics could be decreased by selection of non-conductive material and rotor lamination.

The last place is occupied by synchronous generators with electromagnet excitation and rotating rectifiers, synchronous generators with permanent magnets and switched-reluctance generators. Electromagnet excitation of synchronous generator leads to complex problems with mechanical strength of rotating coil and rotating rectifier. Synchronous generators with permanent magnets are very risky for high-power long-term operation. Till now there are no statistics of permanent magnet behavior during dozens of years of exploitation. Finally, switched-reluctance generator obtains not only expensive semiconductor converter but also extremely high magnetic losses which raises doubts in high efficiency values of the whole installation.

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