Design of a High-speed Solid-rotor Asynchronous Generator for an Expansion Turbine

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Abstract—In this paper, an electromagnetic design of a slitted solid-rotor high-speed generator is presented. Recommendations for an analytical preliminary design were summarized. The design was further optimized using 2-D finite element method. The power of the machine is 6.15 kW at 150 000 rpm and 2% slip. An efficiency of 90% was reached, despite of high eddy losses in the machine rotor. Our design may prove to be a cost-effective alternative to the permanent magnet synchronous machine in the cryogenics application after the thermal and mechanical analysis.

Keywords—Solid rotor, high-speed, slitted, design, FEA

1. INTRODUCTION

Cryogenics and gas liquefaction systems are well established fields of application for high-speed electrical machines. They involve compressors and turbines that require very high speeds to operate effectively. One of the critical components is an expansion turbine, where the energy of the gas is converted into the mechanical work. Coupling the turbine with electric generator enables to remove this energy from the system, thus preventing overheating. Increased efficiency of the process is another benefit. The design specification for this application was 150 000 min^{-1} and 10 kW. Based on the overview in [1] and the parameter $\text{rpm}\cdot\sqrt{\text{kW}}$, synchronous permanent magnet machine (PMSM) was previously selected and designed in [2]. The machine has very high efficiency, and meets the requirements, but the manufacturing of the machine rotor and sleeve is extremely complicated and expensive. Thus the second suitable option, an induction machine (IM) was chosen.

There are four main rotor variations (Figure 1) to be considered, when designing IM for a high speed application, namely solid steel rotor, solid steel rotor with axial slits, solid steel rotor coated with copper and squirrel cage rotor.

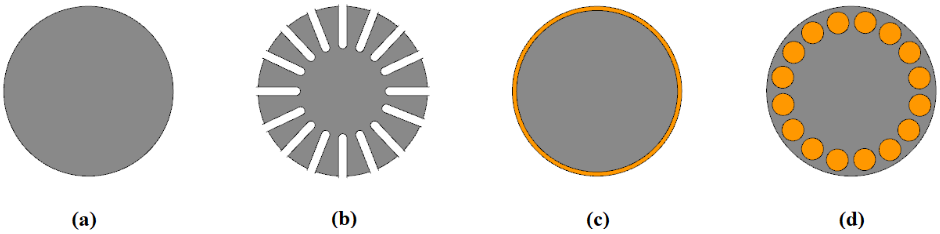


Figure 1: Common high-speed solid-rotor cross sections. (a) Smooth. (b) Slitted. (c) Coated. (d) Caged.

They are sorted with increasing electromagnetic performance with solid steel rotor gaining the worst efficiency and power factor. The mechanical properties go in an inverse order with solid steel rotor having the highest rigidity and resistance to centrifugal forces, thus achieving the highest circumferential speed. In this application a slitted solid steel rotor type was selected. It's electromagnetic performance is better that of the solid rotor. The slits act as barrier for the eddy currents flowing in the tangential direction and help the magnetic field to penetrate deeper into the rotor. Moreover, it is still machinable form a single piece of material, without the need of a special manufacturing technology. The downside is a slightly lower mechanical rigidity as the slits act as stress concentrators and increase windage losses.

2. MACHINE DESIGN

Optimal design of IM with slitted rotor is challenging, because magnetic and electric field share the same volume. It is impossible to define integration paths and simplify the problem, like in the caged IM. Methods used for smooth rotor, utilizing multi-layer transfer matrix [3] can not be used, because of the complex geometry of the slotted rotor. Nowadays, a finite element analysis (FEA) is commonly used to evaluate and optimize the performance of the machine. Solid rotor IM design was analyzed in detail in [4] and [5] and further optimized in [6]. Their design recommendations were considered in the preliminary design.

The stator of the machine was designed using the calculation process presented in [7], as a standard, caged IM. Relatively low efficiency of the machine is expected, so the air gap power of the stator was increased to 12 kW to be able to cover the losses in rotor. In case of a solid rotor machine, the air gap length has to be significantly larger, in comparison with conventional squirrel cage rotor. Actual value is a compromise between high magnetization current and the eddy losses at the surface of the rotor. The stator bore was fixed at 37 mm due to compatibility with previous design and mechanical properties of the rotor. Because of the small bore diameter there are 12 stator slots to obtain reasonable tooth width. Long, narrow stator teeth would lack mechanical rigidity and pose manufacturing problems. Machine was designed as two-pole, in order to minimize iron losses in the stator sheet stack. With 150 000 rpm, the no-load supply frequency is 2500 Hz, thus special care must be taken when selecting the material. The thickness of the sheet must be kept below the depth of penetration of the changing magnetic field. Solid rotor IM are known for high eddy-current losses caused by higher-order harmonics in the rotor. They must be suppressed by all means. Because of this, a two-layer winding with 5/6 winding pitch was used. This has been proven in [4] to have the lowest higher-order harmonics in the air gap. The permanence harmonics, caused by stator slotting are suppressed by increasing the air gap length and adjusting the slot opening width.

There are only few rotor dimensions that need to be considered. According to [5], the optimal electromagnetic properties are reached when depth of the slit is 60% of the rotor diameter, but in practice it has to be limited to about 50% due to the mechanical constraints. The width of the slot should be as thin as possible, but during the manufacturing the thickness of the available machining tools is the limit. Tool thickness generally raises with its length and achievable depth of the slit. The number of the slits Q_r must be matched with number of stator slots Q_s in order to avoid vibrations, synchronous and asynchronous torques. The selection criteria can be found in [7]. To avoid synchronous harmonic torques, it is recommended that

$$Q_r < 1.25 Q_s \,. \tag{1}$$

For a high speed machine with fluid bearing, mechanical vibration is the biggest concern. It was found, that odd numbers of slits have high unbalanced forces [6]. These can destroy the bearings. The slot harmonics and synchronous torques will drop out the slot numbers matching conditions (2) and (3):

$$Q_r = 6 Q_s \pm 2p \,, \tag{2}$$

$$Q_r = 6pg \pm 2p \,, \tag{3}$$

where g is any integer and p number of poles. Due to small number of stator slots, all but 16 slots were disqualified, but 14 and 18 were also taken into consideration because of reasonable geometry. The last factors to be considered are length of the end-rings and the resistivity of the material. An overview of parameters of the preliminary machine design are shown in the Table I. The rotor material was provided by the customer. Operational temperature of the rotor and the material resistivity was estimated at 200 °C in this application.

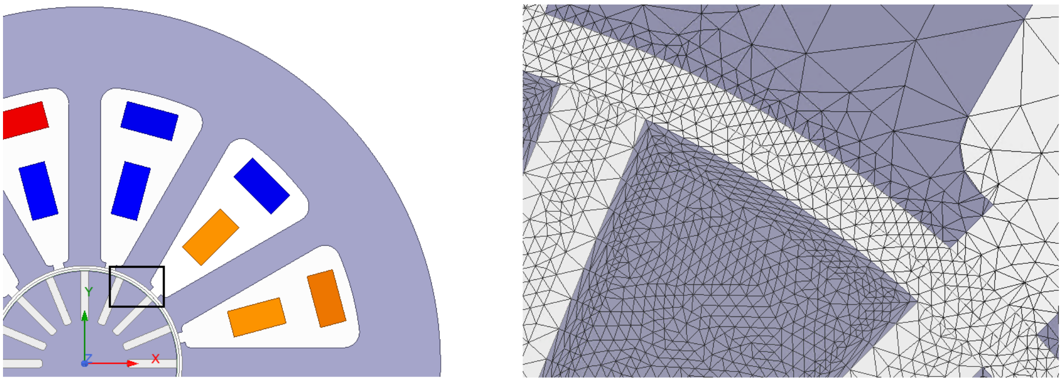
Table I: Preliminary electromagnetic design of the PMSM generator.

Rated voltage U	[V]	400
Stator winding connection		Star
Number of coil turns N		28
Single wire cross section S_{cs}	[mm^2]	3
Stator material		NO 10
Stator core length l	[mm]	45

Air gap δ	[mm]	1
Rotor diameter D_r	[mm]	35
Rotor length l_r	[mm]	50
Slot width W_{sl}	[mm]	1.5
Rotor material		Carbon steel
Rotor material resistivity	[MS/m]	3.5

3. DESIGN OPTIMIZATION

In order to optimize the number and depth of slots and to evaluate the performance of the final design, a parametric 2-D FEA model of the machine was created in Ansys Maxwell software (Figure 2a). The simulation was transient with eddy current calculation activated in the rotor volume. The rotor speed was constant and machine windings were supplied with a variable frequency sine voltage sources. The time step was set to $1\mu s$, which is enough to capture the effect of at least first eight space harmonics in the air gap. The mesh must be sufficiently refined in the air gap, and especially on the surface of the rotor, since the higher-order harmonics have low depth of penetration. The detail of the mesh is shown in Figure 2b.



(a)

(b)

Figure 2: (a) Machine model (b) Mesh detail

The effect of end rings can not be modeled with 2-D model. The resistivity of rotor material is increased by a coefficient k_{Russel} to take the resistance of the end rings into account.

$$k_{Russel} = 1 - \frac{2\tau_p}{\pi l_r} \tanh\left(\frac{\pi l_r}{2\tau_p}\right), \tag{4}$$

where τ_p is the pole pitch. The rotor resistivity was corrected to 1.29 MS/m.

4. RESULTS

A series of model variations with slit depth ranging from 6 - 10 mm (34 - 57 %) for each number of slots were simulated. Slip of the machine was fixed to 2%. The optimization criteria was maximum electromagnetic torque and mechanical power, that can be removed from the system. Results of the optimization are shown in Figure 3. Maximum power was removed with 16 slit and 9 mm slit depth. The performance of the 14 slit rotor is comparable and could be better choice from mechanical point of view. The 18 slit rotor performs much worse and achieves the peak power at lower slit depth. This might be due to magnetic saturation at the root of the slit. Relatively wide slits take up too much from the rotor cross-section. Another selection aspect was torque ripple of the rotor. The findings are in accordance with the recommendations (1) – (3). The 16 slit rotor has about a half ripple compared to other two options. Thus, the 6 slit and 9 mm depth combination was chosen as the final design.

Magnetic flux density distribution of the selected design is shown in Figure 4a. Whole magnetic

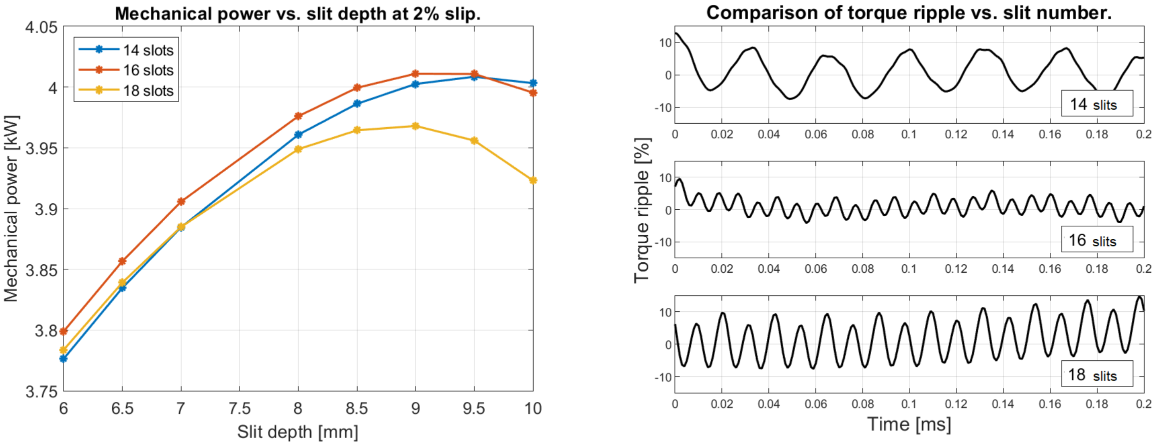


Figure 3: Optimization results at 2% slip: (a) Power optimization (b) Torque ripple

circuit is designed to have low saturation (below 0.8 T) to limit the losses. Figure 4b shows a very strong localization of the eddy currents on the rotor surface and explains the need of mesh refinement in this area.

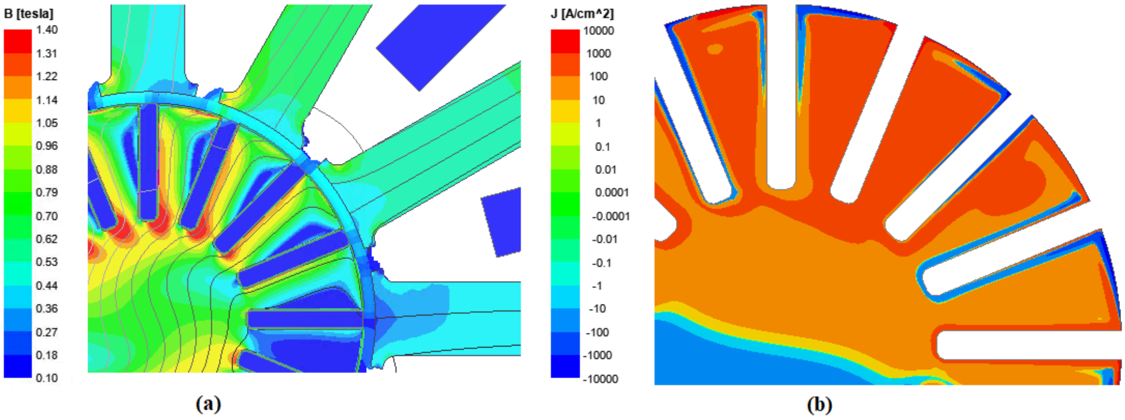


Figure 4: Final design, fields distribution: (a) magnetic flux density (b) eddy current density

The torque and losses of the designed machine as a function of slip are shown in Figure 5. The machine would achieve the specified power at 5% slip, but the rotor losses seem excessive. Because of this the nominal slip was set to only 3%.

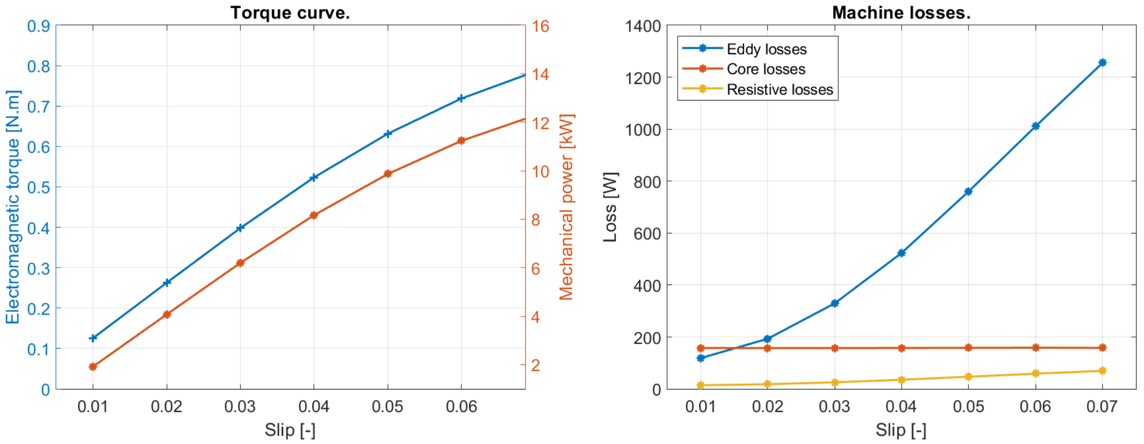


Figure 5: Characteristics of the selected machine design.

Overview of performance characteristics at this set-point are listed in Table II. Analytical equations assuming smooth rotor surface in [7] were used to calculate the windage losses. Based on the findings in [8], the roughness coefficient was raised to 2.5 to consider the effect of the slits.

Table II: Rated performance parameters of the designed induction generator at 3% slip.

RMS phase current I_s	[A]	18.7
Rotor eddy current loss	[W]	329
Windage loss P_ρ	[W]	98
Iron core loss P_{Fe}	[W]	158
Copper loss P_{Cu}	[W]	26
Efficiency η	[%]	90.5
Mechanical power P_{max}	[W]	6 150

5. CONCLUSION

An induction machine with slitted solid rotor may be a suitable and economical solution for an expansion turbine application. It was shown, that the preliminary, analytical and guessed design was very close to the optimized result. From the electromagnetic point of view, the machine is capable of removing specified mechanical power from the cryogenic circuit with a very high efficiency. The main culprit, which may reduce the performance of the machine, is that the vast majority of losses is dissipated into the rotor. This could be solved by increasing air gap length as a tradeoff between the rotor losses and magnetization current and copper losses. Only the thermal analysis and prototype testing will show, if the liquefied gas can provide sufficient rotor cooling capacity. It may be enhanced by a flow analysis and optimal skewing of the rotor slits. A mechanical analysis is necessary to validate the rotor material selection, calculate sufficient rotor teeth strength and critical speed of the whole rotating assembly.

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