# DESIGN OF A HIGH-SPEED GENERATOR FOR A HELIUM EXPANSION TURBINE

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**Abstract**: This paper presents design of an ultra-high-speed generator, propelled by a helium expansion turbine. The power output of the presented generator is 5 kW at 160 000 rpm. Very high efficiency, over 95%, was achieved thanks to the use of permanent magnet synchronous machine type and proper material selection. Special care was taken during design of the machine rotor to meet both mechanical and electromagnetic requirements. Only high-strength materials can withstand the load. Stator sheets have to be very thin, to suppress the skin effect and eddy current losses, especially with the 4 pole configuration. It was shown that the design process for standard, low-speed machines can be used with the awareness of it's limitations. Weak points of the design, which should be further investigated, were pointed out.

**Keywords**: PMSM, high-speed, generator, turbine, design

## 1 INTRODUCTION

Due to the current demand for reduction of energy consumption and improvement of the overall efficiency among all industry sectors, new applications for high speed electric machines are being sought. One of them is an expansion turbine generator as a part of a Brayton cycle helium cryocooler. Vast amount of energy is lost during expansion phase of the cycle in conventional device. By expansion through the high-speed turbine this energy can be harvested. The gearless coupling between electric machine and turbine on a single shaft promises efficient and reliable operation of the device. Various high speed rotating machinery for different applications have been developed for long time. Based on the overview in [1], the achievable size and speed of particular machine type can be estimated using parameter $\mathrm{RPM}.\sqrt{\mathrm{kW}}$. The design specification in this application is 5 kW at $160000\,\mathrm{min}^{-1}$ corresponding with $3.5\mathrm{x}10^5\mathrm{min}^{-1}.\sqrt{\mathrm{kW}}$. Only permanent magnet synchronous machine (PMSM) and induction machine (IM) can reach this value, according to [1]. PM machine was selected since it has generally higher overall efficiency.

## 2 MECHANICAL DESIGN

Proper rotor dimensioning is a complex task as it has to meet both mechanical and electromagnetic loads. Tangential stress constant $\sigma_{Ftan}$ was used to determine the required rotor volume per given deign speed $\omega$ and power output $P$.

$$\sigma_{Ftan} = \frac{2P}{\omega\pi D_r^2 l'} \tag{1}$$

A value of 10 kPa was used after review of previously designed machines with similar parameters in [2][3]. This is below the typical range of tangential stress value for normal machines found in [5]. It is mainly cased by lower air gap flux density as well as increased windage and core losses of the high-speed machines.

The structure of the designed rotor is shown in Fig. 1. A solid, magnetic shaft is suspended between two bearings. The surface-mounted permanent magnets are secured in place by pressed-in sleeve to withstand high centrifugal forces. The sleeve is the most mechanically loaded component since the centrifugal force rises with square of diameter. It was modeled as rotating cylinder, loaded with pressure of PMs on the inner surface. Radial and tangential stress within the sleeve is expressed by equations

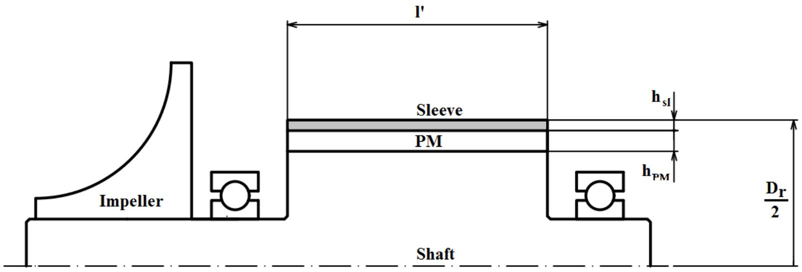

**Figure 1:** A cross-section view of the PMSM generator rotor.

$$\sigma_r = A - \frac{B}{r^2} - \frac{3+\mu}{8}\rho r^2\omega^2, \quad \sigma_t = A + \frac{B}{r^2} - \frac{1+\mu}{8}\rho r^2\omega^2, \tag{2}$$

where $\mu$ is Poisson's ratio and $\rho$ is material density. Constants A and B are derived from boundary conditions

$$r = \frac{D_r}{2} - h_{sl} : \sigma_r = -p_{PM} = 2\pi \rho_{PM} h_{PM} \omega^2 \left(r_{in} - \frac{h_{PM}}{2}\right)^2; \quad r = \frac{D_r}{2} : \sigma_r = 0 , \tag{3}$$

By solving equations (2) and (3), maximum stress within the sleeve for a given diameter, sleeve and PM thickness was obtained. With 1 mm thick Inconel 718 sleeve material and 2 mm of PM, yield strength of the sleeve (Tab. 1) is reached at 29 mm diameter. This calculation assumes that the radial stress between the shaft and PMs caused by the interference fit disappears due to the centrifugal forces at the nominal speed. Some radial stress is needed to transmit the torque, thus the sleeve diameter has to be smaller. Detailed calculation of the required sleeve interference can be found in [6].

| Material | Density $\rho$ | Yield strength | Young's modulus $E$ | Poisson's ratio $\mu$ | Use |
|---|---|---|---|---|---|
| Inconel 718 | 8190 kg/m$^3$ | 1100 Mpa | 205 GPa | 0.31 | sleeve |
| 41CrMo4 | 7800 kg/m$^3$ | 800 Mpa | 205 GPa | 0.29 | shaft |
| Recoma 35E | 8300 kg/m$^3$ | N/A | 140 GPa | N/A | PM |

**Table 1:** Mechanical properties of used rotor materials.

Another phenomenon limiting the length of the rotor is mechanical resonance. A critical speed occurs when the rotation of shaft excites its first normal mode of vibration. The speed of the machine usually has to be kept below this limit to avoid catastrophic failure. An empirical estimation of the maximum length of rotor to avoid resonance for a given design speed was described by Wiarth [4]

$$l'^2_{max} = \frac{\pi}{k\,\omega}\sqrt{\frac{E\,J}{\rho S}}\ , \tag{4}$$

where $J$ is the quadratic moment of the shaft's cross-section area. For 41CrMo4 steel shaft with a diameter of 20 mm the maximum length is 69 mm. Since the shaft has complex structure, FEA analysis should be carried out, including the effect of additional weight of the impeller and bearings.

| | |
|---|---|
| Rotor diameter $D_r$ [mm] | 28 |
| Rotor lenght $l'$ [mm] | 25 |
| Sleeve thickness $h_{sl}$ [mm] | 1 |
| PM thickness $h_{PM}$ [mm] | 2 |

**Table 2:** Parameters of designed PMSM generator rotor.

## 3 ELECTROMAGNETIC DESIGN

The design process accommodated from [5] starts by defining the air gap $\delta$ and the air gap magnetic flux density $B_\delta$ as these imply the rest of magnetic circuit dimensions. Since relative permeability of Inconel 718 material, used for the retaining sleeve is close to 1, it's increasing the apparent thickness of the air gap. Increasing the thickness of PMs to gain sufficient magnetomotive force results in higher centrifugal forces acting on the sleeve. Thus the magnetic circuit design has to be carried out iteratively, together with the mechanical.

A simplified calculation can be used as an initial guess of the required PM thickness by omitting the magnetic voltages over the majority of reluctance is caused by the air gap.

$$h_{PM} = \frac{\frac{B_\delta}{\mu_0}\,\delta}{H_c - \frac{H_c}{B_r}\,B_{PM}} \tag{5}$$

The machine was designed as four-pole, with 12 stator slots, giving 1 slot per pole and phase. A minimum number of slots was chosen, because of small diameter of the stator bore. With 24 slots and 2 slots per pole and phase, more sinusoidal EMF would be obtained, but very narrow stator teeth are problematic to manufacture. Two-pole machine would lead to a higher stator yoke and copper volume, increasing the losses.

To determine necessary stator tooth width and height, the winding slot cross-section area has to be evaluated.

$$N = \frac{e_{PM}}{p\,\omega_m\,k_w\,\alpha_{PM}\,B_\delta\,\tau_p\,l'}\,, \tag{6}$$

where $e_{PM}$ is effective value of induced voltage, $k_w$ is winding factor, and $\alpha_{PM}$ relative effective PM width. The cross section of a single wire is determined from the mean power output requirement and the permitted current density $J_s$

$$I_s = \frac{P}{m\,\eta\,U_s\cos\varphi};\quad S_{Cs} = \frac{I_s}{a\,J_s}\,, \tag{7}$$

where $m$ is number of phases and $a$ number of parallel branches. High current density has to be selected to obtain reasonable shape of the stator teeth. Widening the slots leads to thin teeth, resulting in high tooth flux density and increased losses. Tall slot compromises mechanical rigidity of the teeth and increases its magnetic voltage. The minimal cross-section area of the stator slot $S_{Cus}$ is obtained by multiplying the number of conductors per slot $z_Q$ by required cross section of a single conductor $S_{cs}$.

$$z_Q = 2\,a\,m\frac{N}{Q},\quad S_{Cus} = \frac{z_Q\,S_{cs}}{k_{Cu}} \tag{8}$$

Proposed dimensions and parameters of the machine stator are shown in Table 3. A FEMM software was used to verify the calculations. Figure 2 shows flux density distribution within the magnetic circuit at nominal load angle and current (Tab. 4). The current is supplied by a current sources into the q-axis of the machine.

| | | | | | |
|---|---|---|---|---|---|
| Number of coil turns $N$ | | 32 | Stator tooth height $h_d$ | [mm] | 4 |
| Number of slot conductors $z_Q$ | | 16 | Stator tooth flux density $B_d$ | [T] | 1.4 |
| Slots per pole per phase $q$ | | 1 | Stator yoke height $h_{ys}$ | [mm] | 8 |
| Single wire cross section $S_{cs}$ | [mm$^2$] | 1.18 | Stator yoke flux density $B_{ys}$ | [T] | 0.8 |
| Winding space factor $k_{Cu}$ | | 0.5 | Stator outer diameter $D_{re}$ | [mm] | 70 |
| Stator winding connection | | Star | Stator material | | NO10 |
| Linear current density $J$ | [A/mm$^2$] | 4.0 | Rotor flux density $B_r$ | [T] | 0.57 |
| Stator tooth width $b_d$ | [mm] | 12 | Tangential stress$\sigma_{Ftan}$ | [kPa] | 10 |

**Table 3:** Electromagnetic design of the PMSM generator.

It is important to take the skin effect into account, when choosing materials for the machine rotor. Penetration depth at 5333 Hz is approximately 0.14 mm for electrical steel and 1.26 mm for copper. As a result, winding has to be made of multiple parallel branches or Litz wire. Very common M230-35A electrical steel with 0.35 mm thickness is not suitable choice. Only advanced, thin electrical steel, like NO10-1270N can be used in order to achieve satisfactory performance and losses.

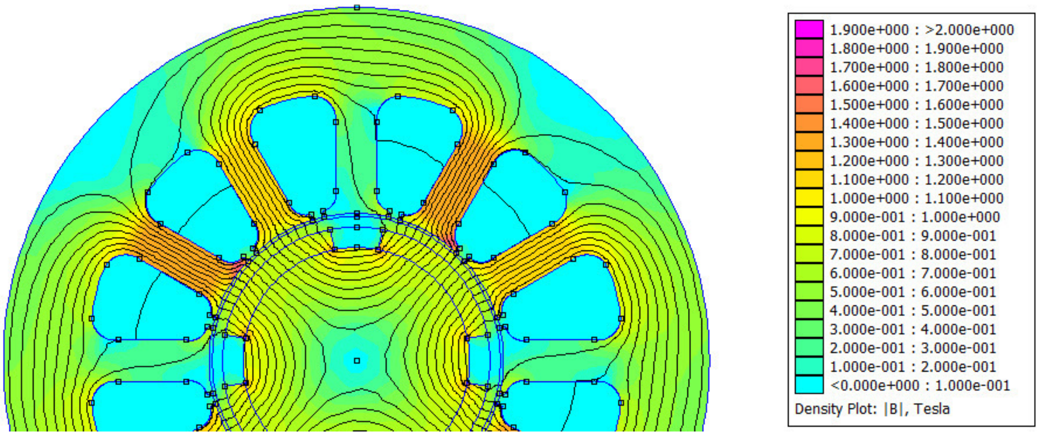

**Figure 2:** Magnetic flux density distribution within machine cross-section geometry at nominal load.

## 4 RMXPRT SIMULATION RESULTS

Properties of the designed machine were evaluated by Ansys RMxprt software. The most important parameters are listed in Table 4. The machine has large power reserve and reaches the nominal power with relatively low load angle. With proper cooling, it may be possible to reduce the machine volume. Winding resistance and inductance are both very low and should not cause problems with the control of the machine. The windage losses $P_\rho$ were calculated by equations (9.8) – (9.18) in [5], assuming air at 100 °C as surrounding medium and surface roughness 1.2. The efficiency of the machine is very high, but the bearing mechanical losses as well as eddy current losses in the sleeve and PMs were not taken into account.

## 5 CONCLUSION

Permanent magnet synchronous machine is a suitable solution for the helium expansion turbine generator. It is possible to meet required power output and speed of the turbine. Proposed machine can withstand the extreme mechanical loading and operate with reasonable efficiency. This can be

| | | |
|---|---|---|
| Max. line voltage $U$ | [V] | 231 |
| RMS phase current $I_s$ | [A] | 19.2 |
| Armature resistance $R$ | [mΩ] | 9.5 |
| Synchronous inductance $L_d = L_q$ | [$\mu$H] | 33.4 |
| Torque angle $\delta_{load}$ | | 19.5° |
| Windage loss $P_\rho$ | [W] | 68 |
| Iron core loss $P_{Fe}$ | [W] | 125 |
| Copper loss $P_{Cu}$ | [W] | 11 |
| Efficiency $\eta$ | [%] | 96 |
| Peak output power $P_{max}$ | [W] | 23 400 |

**Table 4:** Rated performance parameters of the designed PMSM generator.

achieved only by the use of high-end materials. It was shown that the standard, analytic design process used in low-speed applications can be used with limited accuracy. Further FEM modeling is necessary to guarantee reliable operation. Rotor dynamics analysis should be carried out to prevent mechanical failure. The effect of slot permeance harmonics, inducing eddy currents into retaining sleeve and PM, should be analyzed to avoid problems with overheating of the rotor.

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