THE PERFORMANCE ANALYSIS OF ULTRA HIGH SPEED PM TYPE SYNCHRONOUS MOTOR-GENERATOR FOR MICRO TURBINE

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This paper deals with loss analysis, structural, thermal-fluid and rotordynamics (critical speed and unbalance) which need in developing the motor-generator. This machine has designed of a generator of 800 W, 400 krpm and a starter of 400 W, 200 krpm. The generated losses of motor-generator are derived by magnetic analysis. Thermal-fluid analysis is performed using loss analysis result. The critical speed is extracted by Campbell diagram. Unbalance vibration response analysis enable to predict the expected vibration amplitude by unbalance. The motor-generator is well-developed using the applied several techniques of analysis.

Keywords: Stator loss; Rotor loss; Motor-Generator; Critical Speed; Unbalance Analysis; Thermal-Fluid analysis; Shrink fit.

1. Introduction

If ultra high speed motor-generator is applied to micro gas turbine, the system can be simplified. An electro-mechanical system can be made much smaller and lighter at the same power level by increasing its operating speed. The permanent magnet excited synchronous generator has many advantages as compared with existing synchronous generator, but it has been applied in limited field. However, the many interest and development is being done as power electronics and control method develop recently. The operating method of motor-generator for micro turbine is operated as synchronous motor in transient performance and also is acted as acceleration until turbine reaches in a certain speed [1],[2].

Finally, ultra high speed motor-generator which is rated a generator of 800 W, 400 krpm and a starter of 400 W, 200 krpm is well-developed using design, several techniques of analysis and manufactural technique. Fig. 1 shows prototype and parts. Table 1 shows proposed 3-phase Permanent Magnet Synchronous Motor (PMSM) dimension. Fig. 2 shows performance curve of motor-generator using EMCNM.

Fig. 1. The developed Permanent Magnet Synchronous Motor (PMSM)

Table 1. The specification of the developed motor-generator

Mode	Item	Value	Note
Generating	Rated power (W)	800	AC load
	Rated speed (rpm)	400,000	
	Rated voltage (V)	110	
	Rated current (A)	4.20	
	Current density (A/mm ²)	6.96	
	Efficiency (%)	94	Consider loss
	Phase resistance (mΩ)	4.385	Consider 150 °C
	Synchronous inductance (μH)	189.636	Consider DC
	Flux linkage (Vs/rad)	0.002491	Consider 150 °C
	BEMF(line) (mVrms/rpm)	0.31949	Consider 150 °C
Motoring	Torque constant (Nm/A)	0.005	Consider 150 °C
	Rated power (W)	400	
	Rated speed (rpm)	200,000	
	Rated voltage (V)	72.3	
	Rated current (A)	3.8

Fig. 2. Performance curve of motor-generator using Equivalent Magnetic Circuit Network Method (EMCNM).

2. Stator loss

Generally, stator losses can be divided into core loss and copper loss. Core loss which is generated in the laminated core is calculated as a constant of maximum flux density (B_m) by Steinmetz equation. In case of core losses, the total losses are commonly expressed by (1) for sinusoidally varying magnetic flux density B with frequency f and they are divided into hysteresis loss and eddy current loss. Each of losses is calculated by (1) [3],[4].

$$P_{core} = P_h + P_e + P_a = k_h B_m^n f + k_e B_m^2 f^2 + k_a B_m^{1.5} f^{1.5} \quad (1)$$

Where P_h , P_e and P_a is shown hysteresis loss, eddy current loss and strange eddy current loss. k_h , k_e and k_a is shown hysteresis loss coefficient, eddy current loss coefficient and strange eddy current loss coefficient. n is Steinmetz coefficient in the range 1.5 to 2.5

Core loss as a function of frequency and flux density is increased as a proportion and square in proportion to frequency. Fig. 3 shows core loss distribution and flux density distribution. The generated maximum flux density is 1.6 (T) in slot teeth.

Fig. 3. Core loss and flux density distribution

3. Rotor loss

Rotor loss is generated by eddy current loss in permanent magnet and sleeve with electrically conductive in Fig. 4. Rotor is heated by rotor loss because of thermal radiation difficulty although rotor loss is a small amount compared to stator loss. Also, thermal problem easily leads to demagnetization of permanent magnet.

Load	PM loss (W)	Sleeve loss (W)
AC	0.261	3.43
DC	1.312	4.831

Fig. 4. Eddy current loss of rotor (PM and Sleeve)

4. Shrink fit analysis according to interference

It is necessary for structural analysis of rotor to select sleeve thickness in ultra high speed. The PM condition (compression or tensile) of shrink-fitted rotor should be checked. The shrink-fitted PM should be always in a state of compression in ultra high speed because of tensile condition is very weak. Maximum equivalent stress increases as a growing sleeve thickness. Fig. 5 shows von-Mises stress distribution in interference 0.003 mm for shrink fit (operating condition : 200,000 rpm, 210 °C). Inconel which has yield stress, 1100 MPa is used for sleeve material.

The generated maximum von-Mises stress is 114.85 MPa in case of sleeve thickness 0.8 mm and interference 0.003 mm. The safety factor is 9.58(=1100/114.85). The PM is in a state of compression according to sleeve thickness [1].

Fig. 5. von-Mises stress(σ_{eqv}) distribution(200 krpm, 210 °C)

The von Mises criterion is also known as the maximum distortion strain energy criterion. The von Mises stress, σ_e , is computed with the principal stresses ($\sigma_1, \sigma_2, \sigma_3$) as follows:

$$\sigma_e = ([(\sigma_1- \sigma_2)^2+(\sigma_2- \sigma_3)^2+(\sigma_3- \sigma_2)^2]/2)^{1/2}$$
 (2)

5. Critical speed

The supported bearing stiffness of ceramic bearings used 1e8 N/m in simulation. The bending critical speed of rotor should be above operating speed, 200,000 rpm. Fig. 6 shows Campbell diagram. The crossing points are critical speed. The critical speed of 1st forward whirling of the developed model is 255,777 rpm. The separation margin between the operating speed and the bending whirling critical speed needs to be large. An appropriate separation margin is typically 20~30 % in the bending whirling critical speed [6]. The developed model has 27.88 % separation margin.

Fig. 6. Campbell diagram (sleeve thickness = 0.8 mm)

6. Unbalance analysis

Table 2. Unbalance (G0.4) and its applied location (sleeve thickness = 0.8 mm)

U_{max} : consider bending mode		Unbalance (g·mm)	Location
0.000595	c
— B : ceramic ball bearing — a ~ e : vibration response position			
Rotor weight : 31.1 g			
Supported stiffness of ceramic ball bearing : 1e8 (N/m)

Fig. 7. Unbalance response according to unbalance location and phase (sleeve thickness = 0.8 mm, G 0.4)

Unbalance vibration response analysis enable to predict the expected vibration amplitude by unbalance in ultra high speed [5],[6]. Then it needs to check and review rubbing problem between rotor and stator of motor.

The calculated unbalance is like below [5].

$$U_{Max} = 9549 \cdot G \cdot M / N \text{ (g·mm)} \quad (3)$$

Where, G is G grade, M is weight of rotor, N is rotational speed and $U_{\max}$ is unbalance.

Unbalance magnitude (G0.4) is applied to rotor in this paper. The applied unbalance location and response position to check generated vibration displacement is shown in Table 2. Unbalance response results are shown in Fig. 7 and Table 3 according to unbalance applied location and phase.

Table 3. Vibration displacement result of rotor by unbalance analysis (200,000 rpm, unbalance G 0.4)

Unbalance model	Location number [vibration displacement (μm_{p-p})]				
	<i>a</i>	<i>b</i>	<i>c</i>	<i>d</i>	<i>e</i>
<i>c</i>	90.5	1.59	62.46	6.38	10.03

7. Conclusion

This paper deals with several analyses which need in developing motor-generator which is rated a generator of 800 W, 400 krpm and a starter of 400 W, 200 krpm. This paper is performed loss analysis, structural, thermal-fluid and rotordynamics (critical speed and unbalance) which need in developing the motor-generator. Ultra high speed motor-generator is well-developed using design, several techniques of analysis and manufacture technique.

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