

Total Loss Optimization in Varying Pole Pair Radial Magnetic Bearing Using Analytical and Genetic Algorithm Approach

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Abstract: A typical problem of radial magnetic bearing is chosen and bearing involving n -pole pairs, where $n = 2, 4, 6, 8$, are designed. The total losses in each case are computed for different rotor speeds. A comparative study of the total losses in each case is performed theoretically in order to arrive at possible optimum situations. The major dimensions required for the analysis of losses were obtained in all those cases. A loss analysis was performed and the results were presented. It was found that there was a drastic decrease in the total loss from two pole pair to four pole pair. On the whole, it appeared as though four pole pair gives the minimum total loss for all the speeds. Further a better analysis of total loss in four pole pair radial magnetic bearing was performed using genetic algorithms in two sections. Initially objective functions have been considered, namely minimization total power loss considering three variables like air gap length, rotor speed, and lamination thickness of rotor. Finally, same objective functions have been considered, namely minimization total power loss considering only two variables like air gap length and lamination thickness of rotor because in practical application machine should run at particular speed. The optimization model, the implementation algorithm, discussion of results and conclusions have been detailed.

Keywords: Radial magnetic bearing, pole pair, losses, air gap length, lamination thickness, rotor speed, genetic algorithm.

I. Introduction

An active magnetic bearing consists of a stator, which contains the electromagnets position sensors, and the rotor, which rotates with the shaft. When the magnetic bearing is operating, each magnetic bearing rotor is ideally centered in the corresponding stator so that contact does not occur. The position of the shaft is controlled using a closed-loop feedback system as shown in Figure 1.

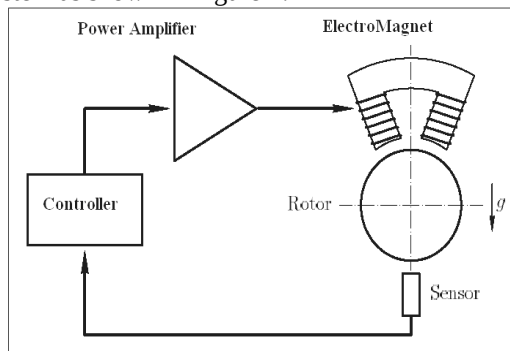


Figure 1 Working principle of magnetic bearing

The position sensors detect the local displacements from the shaft, and these signals are sent to a digital controller. The controller processes these signals and calculates to re-distribute the currents in the electromagnets to restore the shaft to its centered position. Power amplifiers then re-adjust the currents in the electromagnets according to these calculations.

II. Statement of a typical case

For the sake of the present study a rotor of length 3m and transmitting 90 kw power at 1000 rpm is considered. This specification is concern to the rotor of a pump studied.

A. Design of rigid rotor

From the power and speed, the torque being transmitted may be calculated as $T=859$ Nm. The diameter of shaft may then be calculated from,

$$d^3 = \frac{16}{\pi \tau_{\max}} (K_t T) \quad (1)$$

Taking $T=859\text{Nm}$, allowable shear stress 55N/mm^2 , and twisting factor, $k_t=2.5$, the diameter of shaft of rotor calculated as 60 mm for further calculations. Taking density of shaft material (steel) as 7850Kg/m^3 , the weight of rotor may be estimated as 700 N.

B. Design of radial magnetic bearing [1,2]

Let, r_r radius of shaft, r_j radius of journal, l_g air gap, w_p width of pole, l_p breadth of pole (along rotor axis), L_p pole length in radial direction, r_c and r_s inner and outer radii of stator, A_g gap area, h pole height, l_c coil length, t_c coil thickness, d_w be the wire diameter, V_e volume of electromagnet and l_s be the axial length of electromagnet.

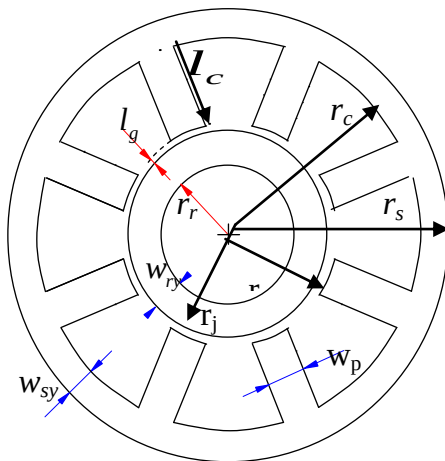
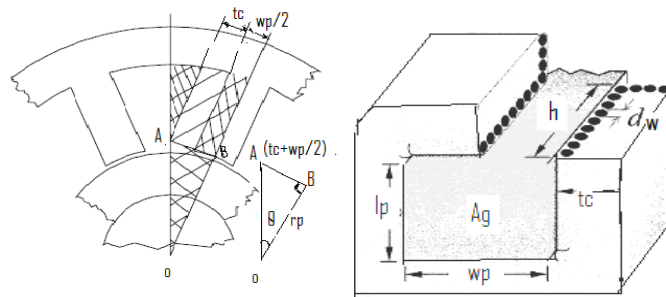


Figure 2 Stator geometry of RMB



(a) (b)
Figure 3 Coil geometry

The rotor is supported by two bearings and they are assumed to shear the load equally. Hence, the static load to be supported by each bearing may be 350 N. In the present case the maximum load $F_{\max}$ is taken as 3500 N and the dynamic load F_{dy} is taken as 3000 N. An air gap l_g of 0.5 mm is considered. Saturation flux density, $B_{\text{sat}} = 2.2\text{T}$ (for Vanadium permendur)

Table I Dimensional details calculated for different pole pairs of RMB

n	--	2	4	6	8
A_g	cm^2	18.16	9.82	6.63	6.66
w_p	cm	1.86	1.17	0.85	0.86
l_p	cm	9.76	8.35	7.71	7.74
d_j	cm	9.72	8.35	7.72	7.72
t_c	cm	3.98	1.16	0.61	0.61
l_c	cm	39.16	23.71	19.6	19.66
A_{coil}	cm^2	1.36	3.41	3.08	1.399
r_c	cm	7.23	7.36	8.96	6.26
L_p	cm	2.32	2.45	5.05	2.35
h	cm	2.32	2.45	5.05	2.35
r_s	cm	9.09	8.54	9.81	7.12
l_s	cm	17.72	10.68	8.95	8.97
$V_e \times 10^4$	cm^3	4.07	0.91	0.94	0.44
model	--	30A20	20A14	30A8	25A8
d_w	cm	0.25	0.30	0.25	0.23
$A_w \times 10^{-4}$	cm^2	5	7.3	5	4.16
N_t	--	30	44	30	35

III. Analysis of losses

In this section various losses and the methods of evaluating are discussed. The total loss is summation of copper loss eddy current hysteresis windage loss.

$$P_T = P_{cu} + P_e + P_h + P_w \quad (2)$$

$$P_T = (\rho_{cu} \eta J^2 V_c) + \left(\frac{\sigma \pi^2 f_e^2 B_{\max}^2 t^2}{6} \right) V_e + (K_h B^{1.8} f_h \times V_e) + (K_f C_f \rho_r \pi l_s \omega^3 r^4) \quad (3)$$

Taking appropriate values from Table II and constant given in Table IV, each loss is calculated.

Table II Summary of each loss in (watt)				
n	2	4	6	8
P_{cu}	169	91	264	336
$P_e \times 10^4$	$97.6 f_e^2$	$53.56 f_e^2$	$82.56 f_e^2$	$52.8 f_e^2$
P_h	$0.26 f_h$	$0.12 f_h$	$0.18 f_h$	$1.16 f_h$
$P_w \times 10^{10}$	$2.53 N^3$	$1.52 N^3$	$1.3 N^3$	$1.3 N^3$

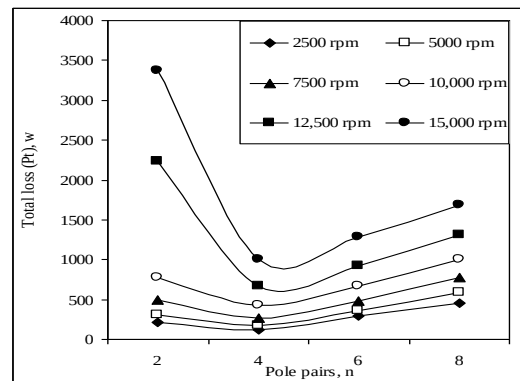


Figure 4 Total power losses versus pole pairs

IV. Optimum total loss analysis using Genetic Algorithm[7-8]

A. Design variables and their bounds

The design variables chosen with their upper and lower bounds are rotor speed, air gap length and lamination thickness given in Table 4.

Table III Lower and upper bounds for the design parameters		
Design parameter	Lower bound	Upper bound
Rotor speed, N (rpm)	2,000	15,000
Air gap length, l_g (m)	0.0005	0.0011
Lamination thickness, t (m)	0.0003	0.0009

B. Objective function

Some of the parameters in the expression (3) are influenced by

$$J = \left(\frac{K_a l_g}{K_i \eta t_c (r_c - r_p)} \right) \sqrt{\frac{4F}{\mu_0 A_g}} \quad (4)$$

$$f_e = \frac{N}{60} \quad \text{and} \quad f_h = \left(\frac{n_p N}{120} \right) \quad (5)$$

The total power loss may be expressed in terms of the design variables as,

$$P_T = \left(\frac{K_a l_g}{K_i \eta t_c (r_c - r_p)} \right)^2 \left(\frac{4 \rho_{cu} \eta V_c F}{\mu_0 A_g} \right) + \left(\frac{\sigma \pi^2 N^2 B_{\max}^2 t^2}{6 \times 3600} \right) V_e + \left(\frac{2nN K_h B^{1.8} V_e}{120} \right) + K_f C_f \rho_r \pi l_s \left(\frac{2\pi N}{60} \right)^3 r^4 \quad (6)$$

C. Constraints

Suitable constraints may be imposed on current density, magnetic flux density and maximum power loss as

$$g_1 : J_{sat} - J_{\max} \geq 0 \quad (7)$$

$$g_2 : J_{\min} \geq 0 \quad (8)$$

$$g_3 : \alpha_{\max} B_{sat} - \left(\frac{\mu_0 K_i \eta (A_c J)}{2 K_a l_g} \right) \geq 0 \quad (9)$$

$$g_4 : \left(\frac{\mu_0 K_i \eta (A_c J)}{2 K_a l_g} \right) - \alpha_{\min} B_{sat} \geq 0 \quad (10)$$

$$g_5 : P_{\max} - P_T \geq 0 \quad (11)$$

Table IV Constant and input parameters

Permeability of vacuum,	$\mu_0 = 4\pi \times 10^{-7} \text{ H / m}$
Resistivity of copper,	$\rho_{cu} = 2 \times 10^{-8} \Omega m$
Lamination conductivity,	$\sigma = 7.46 \times 10^6 (\Omega m)^{-1}$
Radius of rotor,	$r = 0.03 \text{ m}$
Saturated flux density,	$B_{sat} = 2.2 \text{ T}$
Coil m.m.f. loss factor,	$K_i = 1.394$
Actuator loss factor,	$K_a = 1.072$
Coil packing factor,	$\eta = 0.85$
Electromagnetic force,	$F = 3500 \text{ N}$
Volume of electromagnet,	$V_e = 0.000734 \text{ m}^3$
Maximum volume of coil,	$V_{\max} = 0.00039 \text{ m}^3$
Number of turns,	$N_t = 44$
Hysteresis constant,	$K_h = 40 \text{ Ws / T}^2 \text{ m}^2$
Axial length of bearing,	$l_s = 0.106 \text{ m}$
Coefficient of friction,	$C_f = 0.00005$
Drag factor,	$K_f = 1.25$
Maximum copper loss,	$P_{\max} = 500 \text{ w}$
Iron saturation factor,	$\alpha = 0.5$
Weight density of coil,	$\rho_c = 8910 \text{ Kg/m}^3$
Weight density of rotor,	$\rho_r = 7850 \text{ Kg/m}^3$
Current density,	$J = 600000 \text{ A/m}^2$
Number of pole pairs,	$n = 4$

V. Statement of optimization problem

Renaming the design variables as $x_1 = l_g$, $x_2 = t$ and $x_3 = N$, the optimization problem may be stated as

$$\text{Find } \mathbf{x} = \{x_1 \ x_2 \ x_3\} \quad (12)$$

which minimizes the objective function $f(\mathbf{X})$

Subject to constraints $g_i(\mathbf{X}) \geq 0; i = 1, 2, \dots, 5.$

The objective functions and the constraints may be expressed using x_i as

$$f(\mathbf{x}) = \left(\frac{K_d x_1}{K_i \eta t_c (r_c - r_p)} \right)^2 \left(\frac{4 \rho_{cu} \eta V_c F}{\mu_0 A_g} \right) + \left(\frac{\sigma \pi^2 x_3^2 B_{\max}^2 x_2^2}{6 \times 3600} \right) V_e + \left(\frac{2n x_3 K_h B^{1.8} V_e}{120} \right) + K_f C_f \rho_r \pi l_s \left(\frac{2\pi x_3}{60} \right)^3 r^4 \quad (13)$$

VI. Results and Discussion

The non-dominated sorting genetic algorithm is employed[7]. For the optimization, the simulated binary crossover parameters, namely, the probability of the crossover, the probability of the mutation, the crossover distribution index, the mutation distribution index and basic seed are chosen as 0.6, 0.005, 5.0, 10.0 and 0.1, respectively. A population of size 100 is taken with 1000 generations.

Table V Final Lower and upper bounds for the design parameters

Design parameter	Lower bound	Upper bound	Optimum Value
$N(\text{rpm})$	2,000	4284	2,525
l_g (m)	0.0005	0.00543	0.00500
t (m)	0.0003	0.000468	0.000306

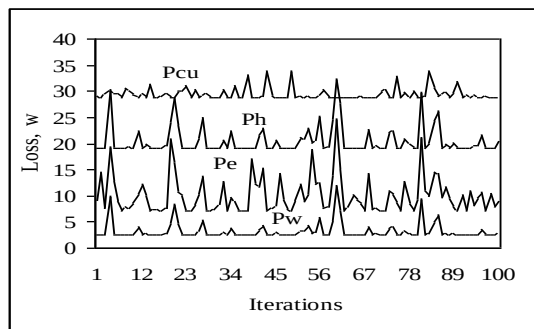


Figure 5 Optimum results of each loss

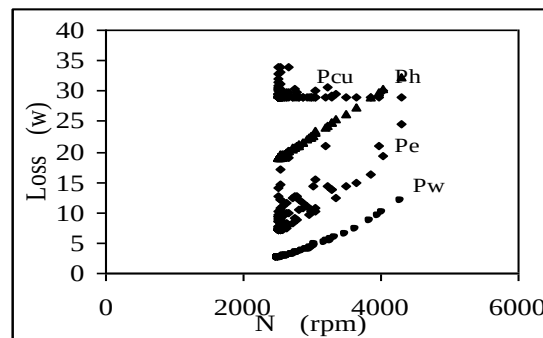


Figure 6 Results of optimization process

Figure 5 show the variations of optimum copper loss, eddy current loss, hysteresis loss and windage loss. Figure 6 shows the values of copper loss plotted against speed of the rotor. Except for few scattered points, the figure shows the optimum copper loss does not depend on speed. In the eddy current loss versus speed an increasing trend may be observed. The hysteresis loss plotted against speeds. A linear variation may be observed. The windage loss plotted against speeds. The figure shows a parabolic variation as per the Equation (7).

Table VI Comparison of loss analysis

Losses, w	P_{cu}	P_e	P_h	P_w	P_T
GA	29	7	19	2	57
TA	91	9	20	2	122

There is a drastic decrease of about 53 percent in the total loss. The copper loss still continues to be a major component. There is a decrease of 60 percent in the copper loss. The optimum total loss is 57 w. Table 6 gives values of various losses which together made the optimum total loss by genetic and theoretical analysis.

VII. Optimization of the total loss for different speeds

In section 3, an optimization was performed with an objective to minimize the total loss. Speed was taken as one of the design variables. It was found that the optimization process was yielding a value of the speed closer to its lower bound. However in a practical application the machine should run at a particular speed. Therefore, taking the speed as the design variable is not proper. However, it has established the fact that the low speeds give rise to minimum loss. Now it is intended to minimize the total loss with respect to only two variables namely, air gap length and lamination thickness, keeping the speed constant. Taking $x_1 = l_g$ and $x_2 = t$, the optimization problem may be stated as

$$\text{Find } \mathbf{X} = \{x_1, x_2\} \quad (14)$$

which minimizes the objective function $f(\mathbf{X})$

subject to constraints $g_i(\mathbf{X}) \geq 0; i = 1, 2, \dots, 5.$

The objective function Equation (13) and the constraints Equations (7) to (11) reused keeping N as constant parameter.

VIII. Results and Discussion

Employing the GA with the same values of simulated binary crossover parameters, the optimization is performed for different speeds.

Table VII Optimum values of the loss using genetic algorithm (GA) and its comparison with theoretical analysis(TA)

Loss	5,000 rpm		10,000 rpm		15,000 rpm	
	TA	GA	TA	GA	TA	GA
P_{cu}	91	29	91	29	91	29
P_e	37	10	148	40	333	90
P_h	40	38	80	75	120	113
P_w	19	18	152	151	513	512
P_T	187	96	471	296	1057	744

From the results presented in Table 7, the genetic algorithm is showing the optimum losses nearly 50 percent of those predicted theoretically. Copper loss is independent of speed. It is observed that the copper loss given by the genetic algorithm is less than the theoretical values predicted in section 4. This may be because genetic algorithm is adjusting the other two parameters namely, air gap length and lamination thickness. The eddy current loss given by genetic algorithm is much less than those predicted by theoretical analysis. The reason may be same as that indicated for copper loss. It is to be observed that the eddy current loss is increasing with speed. The hysteresis loss is tallying with the values predicted by the theoretical analysis. It is also to be observed that the hysteresis loss is increasing with speed. The windage loss given by genetic algorithm is almost tallying with that given by theoretical analysis. It is observed that the windage loss is also increasing with speed. The total loss on the whole is almost 50 percent of that predicted by theoretical analysis. It was observed in section 4, that copper loss was the major component in the total loss. However, from the values given by genetic algorithm, it is noted that the hysteresis loss is forming a major component in the total loss. This may be because the copper loss and eddy current loss are influenced by design variables where as the hysteresis loss and windage loss are purely dependent on the speed. This may also be the reason for tallying closely with the theoretical values predicted. On the whole the total loss is increasing with speed.

IX. Conclusion

The individual losses and total losses are examined and it was found that four pole pair bearing offers minimum total loss. This was demonstrated in Figures 4 and 5.

Taking only air gap length and lamination thickness as the design variables, the total loss minimization is performed using genetic algorithms for different speeds. It is observed that the copper loss and eddy current loss are less than those predicted by theoretical analysis. The reason may be that the other design parameters are constantly getting adjusted and making these losses as less as possible. The hysteresis loss and windage loss are closer to the theoretical predicted values. The reason could be that these losses are not influenced by the design parameters and they are dependent purely on the speed of the rotor. On the whole all losses are having increasing trend with speed. The analysis hinted that the design parameters, namely, the air gap length and the thickness of lamination are playing a major role in decreasing the total loss.

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