OPTIMUM POWER LOSS IN EIGHT POLE RADIAL MAGNETIC BEARING USING GA

Santosh Shelke[1] and Rapur Venkata Chalam[2]
[1&2]Mechanical Engineering Deptt., National Institute of Technology, Warangal, India.

ABSTRACT

This paper includes principle of working and design of eight pole active magnetic journal bearing (AMJB). A study of eight pole magnetic bearing design is done for peak load carrying capacity and with this condition stator dimensions, coil dimensions are obtained for finding different stator and rotor losses like copper loss, eddy current loss hysteresis loss, wind age loss . Also it includes study of these various stator and rotor losses with equations, loss dominating parameters. The objective function for optimum total energy loss is considered for four variables such as air gap length, magnetic flux density, rotor speed, lamination thickness. Suitable constraints and bounds are chosen for each loss and optimal loss is calculated using single objective genetic algorithm.

KEYWORDS: *Radial magnetic bearing, eight poles, optimum loss, genetic algorithm.*

I. INTRODUCTION

Active magnetic bearings (AMB) are experiencing an increased use in many rotating machines like compressors, milling spindles, flywheels, as an alternative to conventional mechanical bearings such as fluid film and rolling element bearings. An AMB provides a non-contact means of supporting a rotating shaft through an attractive magnetic levitation force and hence they offer many advantages over conventional bearings. Active magnetic bearings are a typical mechatronic product. They are composed of mechanical components combined with electronic elements such as sensors, power amplifiers and controllers which may be in the form of a microprocessor.

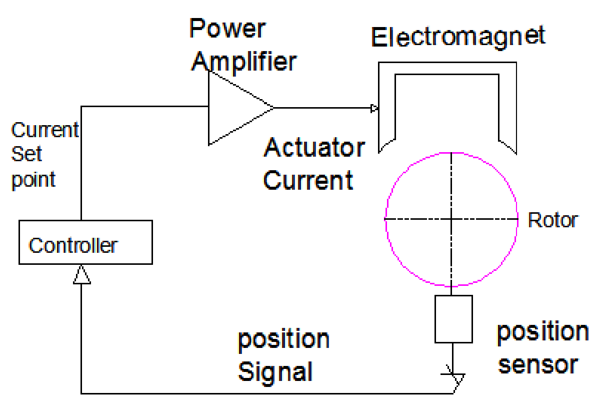

Figure 1. Block diagram of AMB system

Whenever a current carrying conductor is wound around a closed path magnetic field is created following right hand thumb rule. This magnetic field has strength to attract the rotor. Bearings provide support to rotating machinery by allowing relative movement in a plane of rotation. A body is said to be levitated if it is in a state of stable or of independent equilibrium relative to the earth, in which material contact between the body and its environment is not essential (Maslen, 2000). Magnetic bearing systems incorporate this feature, which makes its application possible in huge, weighted rotational systems having high rotational speeds.

The typical AMB system block diagram is illustrated in Fig.1. Besides the controller, the general control system also includes the sensor, A/D and D/A conversion and power amplifier.

The rotor' displacement along one of the axes is detected by these position sensors and converted into signals of standard voltage. Then compared with the setting value, the error signal enters the controller. After A/D conversion, the controller processes this digital signal according to a given regulating rule (control arithmetic) and generates a signal of current setting. After D/A conversion, this current signal enters the power amplifier, whose function is to maintain the current value in the electric magnet winding at the current level set by the controller. Therefore, if the rotor leaves its center position, the control system will change the electromagnet current in order to change its attraction force and, respectively, draws the rotor back to its balance position.[6]

In the present paper, a theoretical design of eight pole radial magnetic bearing and single objective total loss optimization procedure have been presented and illustrated. Objective functions have been considered, namely minimization total power loss considering four variables like air gap length, rotor speed, magnetic flux density and lamination thickness of rotor. The optimization model, the implementation algorithm, discussion of results and conclusions has been detailed in the following sections.

a. Eight pole active magnetic bearing

The active magnetic journal bearings are located in the AMB system shown in Fig. 2.The AMB system consists of two bearings with a rotor of length 1m and diameter 0.06 m, and weight of the rotor is 653.3 N. Total weight including auxiliary bearing is taken as 700 N. The radial bearing nominal air gap is 0.5 mm. Initially the rotor is kept on an auxiliary bearing at rest position with a gap of 0.25 mm.

The main parameters of the magnetic bearings are mentioned below.

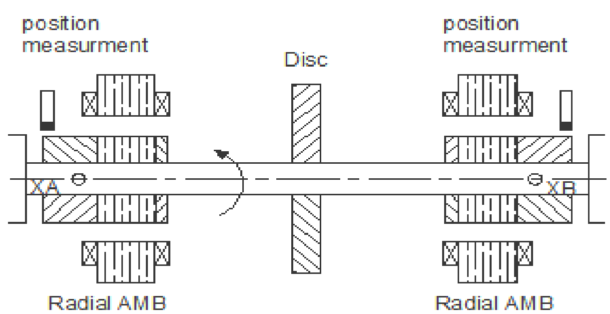

Figure 2. Radial Magnetic Bearing with rotor arrangement

II. DESIGN OF RADIAL MAGNETIC BEARING

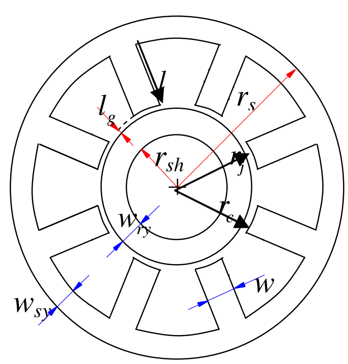

Figure 3. Stator geometry showing eight poles.

2.1. Design Steps for Eight Pole Bearing

Following are design steps for eight pole magnetic bearing [6],

2.1.1 Calculation of gap area, (A_g) :

We know that maximum force, $F_{\max}$ carried by AMB

$$F_{\max} = \frac{\sigma' B_{sat}^2 n_p A_g}{2\mu_0} \tag{1}$$

Where,

$A_g = w_p.l_p$, (w_p -width of pole, l_p -length of pole) , μ_0 -Permeability of Vacuum (4π×10^{-7} H/m), stress,

n_p -Number of poles, $const.\sigma'$ -0.24 (for 8 number of legs of actuator),

$A_g = 0.003398 m^2$

2.1.2 Journal dimensions: Journal radial dimension at least 0.5 or 1.0 times width to avoid saturation.

$$r_j > r_r + f_s.w_p \tag{2}$$

Where, f_s –split flux(0.5)

r_j -Radius of journal, r_r –radius of rotor

$$A_g = 2\gamma w_p (r_r + f_s w_p) \tag{3}$$

Solving equation (3) , the width and length of pole are 0.81cm and 11.6 cm .

Diameter of journal, $d_j = 2(r_r + f_s w_p)$

$d_j = 11.62 cm$

So, radius of journal, $r_j = 5.81 cm$

2.1.3 Bias point selection: $\frac{F_{dy}}{F_{\max}} = \frac{\beta^2}{\sigma'}$

Where, Dynamic load capacity , F_{dy} = 300 Nm

we get, β =0.46

2.1.4 Coil design: For available coil space thickness of coil is calculated as,

$$t_c = r_p \tan\left(\frac{\pi}{n_p}\right) + \left(\frac{w_p}{2}\right) \tag{4}$$

Where,

t_c –Thickness of coil, r_p – pole tip radius,

$r_p = r_j + l_g$

$r_p = 10.81 cm$

$t_c = 10.81 \tan\left(\frac{3.14}{8}\right) + \left(\frac{0.81}{2}\right) = 0.47 cm$

a) Required Coil Area (A_c) :

$$A_c = \left(\frac{\beta B_{sat} l_g}{f_c J \mu_0}\right)\sqrt{1 + \left(\frac{F dy \sigma}{F_{\max}\beta}\right)^2} \tag{5}$$

Where,

Saturation flux density, B_{sat} = 1.2T, Copper current density, $J = 600\, {}^{A}\!/\!{}_{mm^2}$

A_c =0.00167m²

b) **length of coil**: Comparing available coil area to the required coil area,

$A_v = \eta A_c$ when $1 \le \eta \le 2$

$A_v = 2A_c = 8cm^2$

$A_v = t_c l_c$

t_c –Thickness of coil, l_c – length of coil

$l_c = 20.4cm$

$$l_c = \sqrt{r_c^2 - \left(\frac{w_p}{2} + t_c\right)^2} - r_p \quad (6)$$

Putting, r_p, t_c, l_c, w_p, in (6),coil space radius, r_c is calculated .

$r_c = 27.84cm$ (Stator inner radius or coil space radius.)

c) Pole length in radial direction: Subtracting pole tip radius $r_p = 10.81cm$ through coil space radius $r_c = 27.84cm$ we get radial pole length, $l_p = r_c - r_p$ =17.03 cm

d) Stator outer radius:

$$r_s = r_c + f_s w \quad (7)$$

r_s = 28.65 cm

e) Stator axial length, l_s : It is sum of Iron length, l_i and coil thickness, t_c

$$l_s = l_i + 2t_c \quad (8)$$

l_s =11.6 +2x0. 47 =12.54 cm

f) Amplifier capacity: It is detected by slew rate requirement, $\left|\frac{dF}{dT}\right|_{\max}$

$$\left|\frac{dF}{dT}\right|_{\max} = \frac{2I_b V_{\max}}{l_g} \quad (9)$$

Where, I_b –Bias current, $V_{\max}$ – maximum voltage

$$\frac{2I_b V_{\max}}{l_g} = \frac{2\times0.5\times200}{0.005} = 4000 \text{ N/s}$$

$$VA_{\max} = \left|\frac{dF}{dt}\right|_{\max}\left(\frac{\eta l_g}{\beta n}\right) = 4000\left(\frac{4\times0.0005}{0.46\times8}\right)$$

$$VA_{\max} = 2.17KVA(select\,2.4KVA)$$

From user manual[6], for available amplifier capacity 2.4 KVA,we choose amplifier of peak current 30A and peak voltage 80 V, for model 30A8 available in market.

$$NI_{sat} = NI_{\max} = 30N = \frac{B_{sat} l_g}{\mu_0} \quad (10)$$

$N = 29.17\ (\approx 30turns)$

Table I. Designed dimensions of eight pole bearing.

parameters	symbol	value
Gap area, m^2	A_g	0.00339
Width of pole, cm	w_p	0.81
Length of pole ,cm	L_p	11.6
Diameter of Journal ,cm	d_j	11.62
Bias ratio	β	0.46
Thickness of coil, cm	t_c	0.47
Pole tip radius ,cm	r_p	10.81
Length of coil ,cm	l_c	20.4
Coil space radius , cm	r_c	27.84
C/s area of coil, m^2	A_c	0.0016
Radial Pole length, cm	l	17.03
Stator outer radius, cm	r_s	28.65
Overall stator diameter, cm	d_s	57.3
Stator axial length, cm	l_s	12.54
No. of turns	N	30
Amplifier capacity, KVA	$VI_{\max}$	2.4

III. LOSSES IN RADIAL MAGNETIC BEARING

Ha-Yong Kim and Lee (2002) proposed an analytical expression based on eddy current brake model for eddy current loss. Hetropolar and homopolar AMB with non laminated cores and rotor are compared for verification of test result. Sun Y. and Yu, (2002) studied power loss using drag force acted on rotor and stiffness including eddy current effect from radial force. Sun Y.and Yu, (2002) indicates loss is promotional to lamination thickness and flux density. Finally rotational loss is calculated by integrating resistance loss over volume of lamination. Hu T., Lin Z., and Allaire P. E.(2004) investigate the fundamental reasons behind the performance degradation under actuator allocation strategy. For laminated rotor Meeker D., Filatov A. and Maslen H.(2004) used thin plate assumption to simplify the magnetic field calculation in lamination of journal and power loss could be calculated if the flux density at the journal surface is known. Bakay L., and Dubois M., (2007) studied effect of Cu and Iron losses of optimized eight pole radial AMB on discharge time of no load long term flywheel energy storage. NSSN configuration is used. It concludes that for high discharge time for low loss AMB mass is smaller than in case of low discharge time. Optimal solution is for class of sinusoidal force signal. Also presented static allocation strategy for suboptimal power loss. Hyun and Kang (2008) studied magnetic force to current input relation for new bearing is analyzed with 1D magnetic circuit and 3D magnetic field modeling. A novel permanent magnet biased heteropolar type magnetic bearing is developed. Bakay L., Dubois M., and Ruel J., (2009) optimized AMB to minimize Cu and Iron loss for different magnitude of external force. For the purpose of reducing eddy current loss laminated material is used. For this reason steel M19-29 Ga material has been chosen in both stator and rotor lamination while 304 stainless steel material has been chosen for shaft.

The loss components of the magnetic journal bearing can be summarized as

$$P_{loss} = (P_{cu}) + (P_{iron}) + (P_{mech}) \tag{11}$$

$$P_{loss} = (p_{cu}) + (P_{eddy} + P_{hys}) + (P_{windage} + P_{friction}) \tag{12}$$

Where,

P_{loss} - Total power loss in Watt,

P_{cu} - Copper loss,

P_{iron} - Stator core (iron) loss,

P_{mech} - Mechanical loss,

P_{eddy} - Rotor eddy current loss,

P_{hys} – Hysteresis loss,

$P_{windage}$ - Windage loss.

$P_{friction}$ - Frictional loss(negligible)

3.1. Copper Loss Analysis

Copper loss occurs due to resistance to flow of current through coil. Copper loss equation is given by[10]

$$P_{cu,\max} = R_{cu} I_{\max}^2 \tag{13}$$

$$P_{cu,\max} = \rho \eta J^2 A_c V_c \tag{14}$$

Where,

Resistivity, $\rho = 2\times 10^{-5}\,\Omega m$; coil packing factor, $\eta = 0.85$;

$$\text{Current density, } J_{\max,\min} = \left(\frac{K_a l_{g_{\max,\min}}}{K_i \eta A_c}\right)\sqrt{\frac{4F_{\max,\min}}{\mu_0 A_g}} \tag{15}$$

$$F_{\max,\min} = (0.25\mu_0 A_g)\left(\frac{K_i n_p i_{\max,\min}}{K_a l_{g_{\max,\min}}}\right) \tag{16}$$

$$l_{g_{\max,\min}} = (l_g \pm x_{\max,\min}) \tag{17}$$

Maximum displacement of rotor in terms of force and displacement stiffness,

$$x_{\max} = (F_{\max} - F) / K_x \tag{18}$$

cross sectional area and the volume of the coil are expressed as

$$A_c = t_c(r_c - r_p) \ ; \ V_c = A_c l_c \tag{19}$$

Hence, constraint becomes,

$$J_{sat} \geq J_{\max} ; J_{\min} \geq 0 \tag{20}$$

3.2. Iron Core loss

These occur due to variation of flux density in electro-magnetic material. The flux variation create eddy current and magnetic hysteresis in the iron lamination. (a) Eddy current loss depends on time rate of change of flux density. (b) Magnetic hysteresis loss in laminating layer depends on peak value and frequency of flux density. Under alternating flux conditions, the stator core loss density P_{f_e} in W/kg can be separated into a hysteresis P_h and an eddy current component P_e , and can be written in terms of the Steinmetz (2007) equation as given below.

$$P_{f_e} = P_h + P_e = K_h B^n f + K_e B^2 f^2 \tag{21}$$

Where,

K_h , K_e and n are constants. For silicon Iron laminates n =1.8-2.0, K_h = 40-55 Ws/T^{2}m^3, K_e =0.004-0.007 Ws/T^{2}m^3

3.2.1. Eddy current loss

In high-speed permanent-magnet machine applications, rotor losses generated by induced eddy currents may amount to a major part of the total losses. The eddy currents are mainly induced in the permanent magnets, which are highly conductive, and also in the rotor steel. The eddy current problem can be

solved one-dimensionally by using Maxwell equations[5].
Taking time average of energy, $E_{(t)^2}$ over one period, The eddy current power loss per unit volume is,

$$P_{eddy} = \frac{\sigma\pi^2 f^2 B_{\max}^2 t^2}{6} \tag{22}$$

3.2.2. Hysteresis Loss

Since, energy loss in each cycle is proportional to area enclosed by BH curve .i. e. area inside of hystersis curve increases with frequency. Every portion of rotating core passes under S ,N polarity alternatively[7].
Hysteresis loss p_h is directly proportional to frequency of magnetic reversal,

$$P_h = K_h B^n f \tag{23}$$

Where,
For silicon Iron laminates n=1.8-2.0, K_h = 45 Ws/T^{2}m^{3,}

3.3 Mechanical loss

3.3.1 Windage loss[9]

In a simple rotor-stator system if speed increases, Taylor vortices disappear shear stress, τ_r

$$\tau_r = \frac{1}{2} C_f \rho_1 V^2$$

Where,
C_f Friction coefficient, ρ_1 ,density of rotor material.
Tangential frictional force on rotor is given as below,

$$F_r = C_f \rho_1 \omega^2 \pi r^3 L \tag{24}$$

Where,
L, length of rotor, r, radius of rotor.
This frictional force balanced by electromagnetic torque,

$$T_{f_r} = C_f \rho_1 \pi L \omega^2 r^4$$

Using this friction torque of a rotating cylinder we can calculate Wind age loss, $P_w = T_{f_r}\omega$

Hence,
$$P_w = C_f \rho_1 \pi L \omega^3 r^4 \tag{25}$$

3.3.2 Frictional power loss

$$P_f = F\left[0.02\left(\frac{\omega}{100}\right) + 0.005B\left(\frac{\omega}{100}\right)^2\right] \tag{26}$$

IV. OPTIMUM TOTAL LOSS ANALYSIS USING GENETIC ALGORITHM

The parameters most contribute to evolution in genetic algorithm are crossover and fitness based selection/reproduction. Mutation also plays a role in this process[14].
Unlike the standard search techniques, genetic algorithms search among a population of points, work with a coding of the parameter set and use probabilistic transition rules. Populations of m points are chosen initially at random in the search space. The objective function values are calculated at all points and compared. From these points, two points are selected randomly, giving better points higher chances. The selected two points are subsequently used to generate a new point in a certain random manner with occasionally added random disturbance. This is repeated until new points are generated. The generated populations of points are expected to be more concentrated in the vicinity of optima

than the original points. The new population of points, which can again be used to generate another population and so on, yields points more and more concentrated in the vicinity of the optima.

4.1 Input parameters

Permeability of vacuum, $\mu_0 = 4\pi \times 10^{-7} H / m$;
Area of gap, $A_g = 0.003 m^2$;
Area of coil, $A_c = 0.0016 m^2$;
Resistivity, $\rho = 2 \times 10^{-5} \Omega m$;
Lamination conductivity, $\sigma = 7460000 W / mc$;
Radius of rotor, $r = 0.03 m$;
Length of rotor, $L = 1 m$;
Friction coefficient, $C_f = 0.005 m$;
Saturated flux density, $B_{sat} = 1.2 T$;
Coil mmf .loss factor, $K_i = 1.394$;
Actuator loss factor, $K_a = 1.072$;
Coil packing factor, $\eta = 0.85$;
Electromagnetic force, $F = 350 N$;
Maximum volume of coil, $V_{\max} = 100 \times 10^{-6} m^3$;
Maximum copper loss, $P_{\max} = 5000 W$;
Iron saturation factor, $\alpha = 0.5$;
Current density, $J_{ub} = 600000 A / m^2$;
Basic seed=0.01;
Crossover =0.1;
Mutations=0.01.

4.2 Bounds of the variables

$l_{g_{\min}} = 0.0005 m, l_{g_{\max}} = 0.004 m$;
$f_{\min} = 50 rev / s, f_{\max} = 250 rev / s$;
$t_{\min} = 0.001 m, t_{\max} = 0.004 m$;
$B_{\min} = 0.2 T, B_{\max} = 1.2 T$;

4.3 The summary of the formulation of the magnetic bearing design for the single objective optimization

Minimize; $f_i(x) = 1$ where x = $\{l_{g,} f, t, B\}$
Subject to;
$g_i(x) \geq 0;\ i = 0,1,...9;\ h_k(x) = 0,\ k = 1,2;\ x^p \leq x_p \leq x^p;\ p = 1,....,4.$
Where,
$f(x) = P_{Total}.$
$g_0(x) = J_{sat} - J_{\max};$
$g_1(x) = J_{\min};$
$g_2(x) = V_{\max} - V_c;$
$g_3(x) = B_{\min} - \alpha_{\min} B_{sat};$
$g_4(x) = \alpha_{\max} B_{sat} - B_{\max};$
$g_5(x) = P_{cu};$

$g_6(x) = P_{eddy};$

$g_7(x) = P_{hys};$

$g_8(x) = Pw;$

$g_9(x) = P_f;$

$h_1(x) = F_{\max} - F(l_{g_{\max}}, i_{\max});$

$h_2(x) = F_{\min} - F(l_{g_{\min}}, i_{\min});$

V. Results

Results are obtained for following conditions:
Initial population size=100;
Final population=1000;
Generation=1000
Optimum value of copper loss, eddy current loss, hysteresis loss, windage, frictional loss to population size 1000 are
14.177W, 4368.47W, 90.2797W, 309.73W, 62.059W respectively.

Optimum values of variable vectors for population size 100 and run 1

Variables:	l_g	B	f	t
Values:	0.002587m	0.05190T	57.87rev/sec	0.001128m

Optimum values of variable vectors for population size 1000 and run 47

Variables:	l_g	B	f	t
Values:	0.0015m	0.0376T	50rev/sec	0.001m

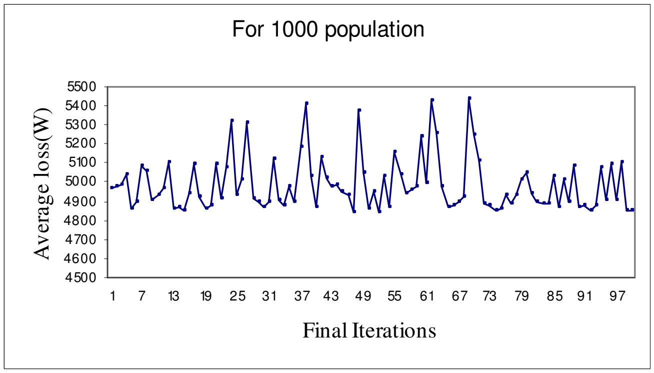

Figure 4. Average loss for final population

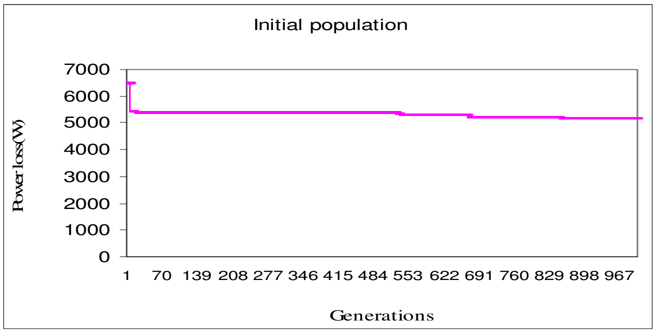

Figure 5. Total power loss showing best fitness for initial population 100.

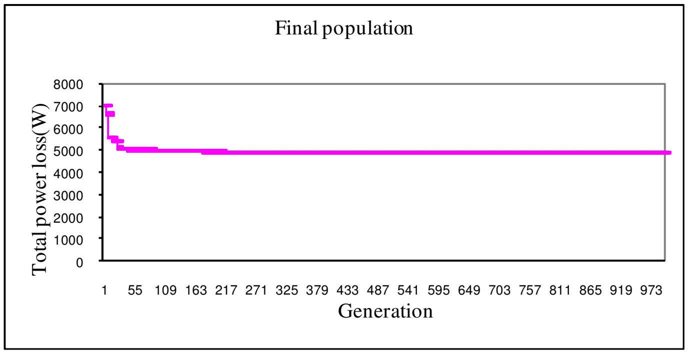

Figure 6. Total power loss showing best fitness for final population 1000.

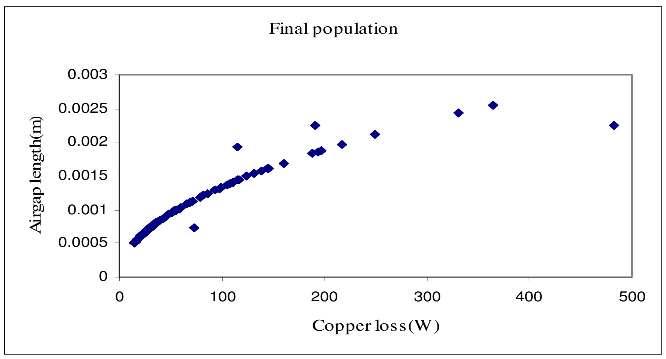

Figure 7. Effect of air gap on copper loss.

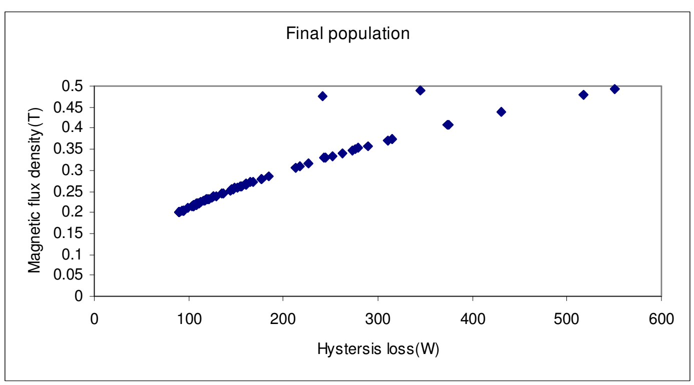

Figure 8. Effect of magnetic flux density on hystersis loss

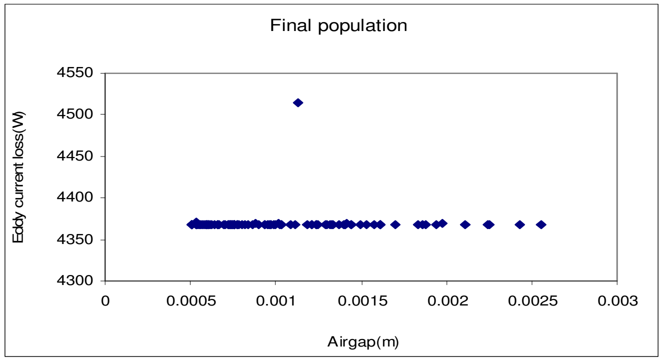

Figure 9. Effect of magnetic flux density on eddy current loss

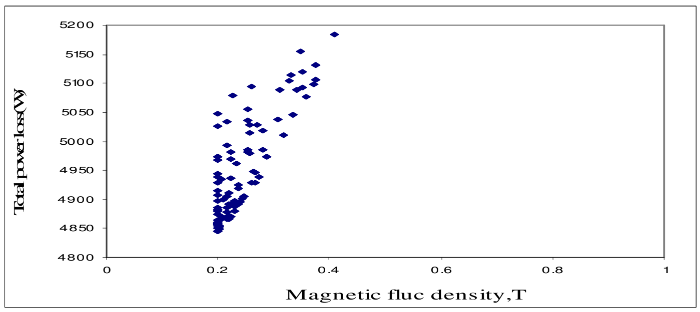

Figure 10. Effect of magnetic flux density on total loss at final population.

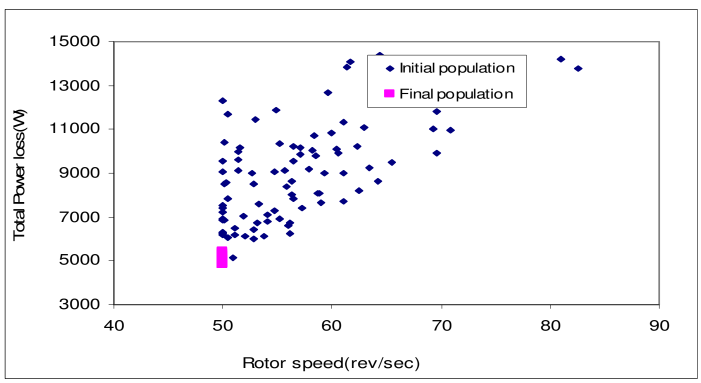

Figure 11. Effect of rotor speed on total loss

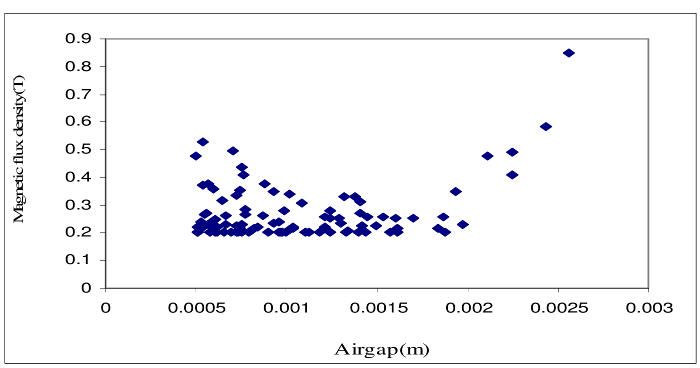

Figure 12. Effect of air gap on magnetic flux density at final population

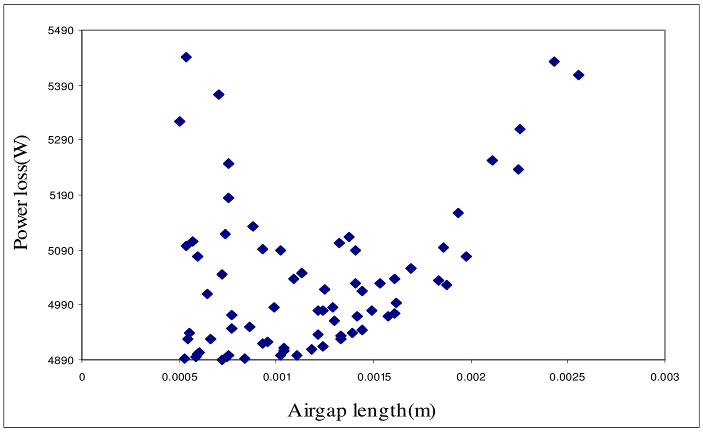

Figure 13. Effect of air gap on total power loss at final population

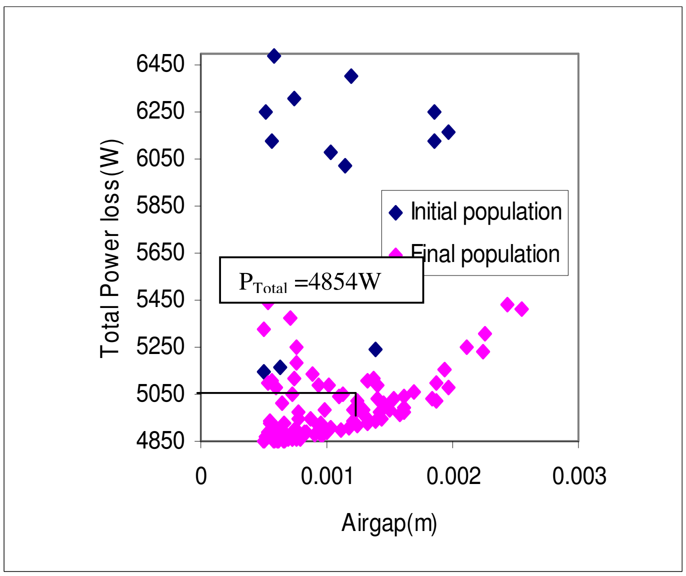

Figure 14. Effect of air gap on total loss for combined initial and final population

VI. CONCLUSION

All types of losses are considered for finding optimum power loss in eight pole radial magnetic bearing. Most power loss affecting parameters are studied and these are fixed as constraints with bounds. Each loss is simplified in terms of loss affecting variables and objective function is defined as sum of loss variables. Single objective genetic algorithm Optimization tool is used to compute the objective function. Simulation results are obtained for initial population 100 and final population 1000 with 100 runs. Total power loss obtained in each run is plotted as shown in figure 4. Further as shown in figure 5 and 6 the best fitness curve for total loss with 1000 generation is plotted at initial and final population for run 01 and 47 respectively. Selection of these runs based on curve satisfies convergent criteria. Whereas from graphs 7 and 9 we concludes, copper loss increases with increase in air gap ,magnetic flux density plays important role in hysteresis loss which increases proportionally whereas eddy current loss unaffected . From figure 10 to 13 at final population we obtained effect of each variable on total power loss, graphs are convex in nature which satisfies optimum value of each variable. From graph 14, it was found that total power loss initially decreases to 4854W with increase in air gap unto 0.0015m.But further increase in air gap, total power loss increases. Hence optimum value of total power loss is chosen as 4854 W.

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Biography:

Santosh Shelke was born on 2 June 1977 in India. He has completed his Mechanical Engineering and post graduation in Design Engineering in Pune University, Maharastra, India in the years 1999 and 2005 respectively . He is doing PhD Under Guidance of Dr.R.Venkatachalam at National Institute of technology, Warangal, Andhra Pradesh, India on "Optimization of losses in radial magnetic bearing" Author has completed one research project on "Solar energy optimization" sponsored by Pune university with grant Rs one Lakh. Author has total 12 years teaching experience and presently working as Assistant professor at Sir Visvesvaraya Institute of Technology, Nasik, India.

Rapur Venkatachalam was born on 28 April 1953 at Visakhapatnam, India. He obtained Bachelor's degree in Mechanical Engineering from Andhra University College of Engineering, Visakhapatnam in 1975. Later he did his M.Tech and Ph.D. in Mechanical Engineering at the Indian Institute of Technology, Kanpur, India, in the years 1977 and 1981, respectively. He is currently working as a Professor of Mechanical Engineering at the National Institute of Technology, Warangal, India. His reach interests include space dynamics, controls, machine design, kinematics, vibrations, optimization methods, theory of elasticity.