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Effects of Operational Losses in Active Magnetic Bearing Designs.

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ABSTRACT
This paper studies the effects of different forms of operational losses that are associated with active magnetic bearing designs.Active magnetic bearings are generally considered as having much lower frictional losses as compared to fluid and roller bearings, however AMBs are considered as more complex mechatronic systems, associated with various potential power loss mechanisms during it cycle of operation. Minimizing of losses consist of various measures and depends largely on the requirements of the application,among all these losses, aerodynamic losses are classified as been the more dominant in modern high speed applications and turbomachinery especially in expanders and compressors where its working gases are considered to be under very high pressures and temperaturesVarious forms of losses such as hysteresis, eddy current, iron, aerodynamic have been discussed. The methods of reducing these losses in order reduce energy losses with the ultimate goal of improving bearing efficiency haveall been discussed in this paper.
Keywords: Active magnetic bearing,Eddy current losses, Electrical resistance, Hysteresis losses,Magnetic flux density, Rotor.

I. INTRODUCTION

Active magnetic bearings are generally considered to have much lower frictional losses as compared to fluid bearings and roller bearings [1]. However, since AMBs are considered more complex mechatronic systems, which consist of many potential power loss mechanisms. As such, minimizing of losses consist of various measures and depends largely on the requirements of its application. In turbomachinery, minimizing the overall losses with the aim to increase the efficiency is most important. In vacuum applications such as turbomolecular pumps, the focus of minimizing its frictional losses in its rotor is to avoid heating of the system since the process of cooling would be very effective. The diagrammatical layout of the flow of energy process which is necessary to cover the losses from it sources such as the drive-electronics and the AMB-electronics up to the power loss mechanisms.

In contact-free rotors there exists no mechanical friction in the magnetic bearings but frictional losses such as windage and aerodynamic losses continue to be present on these rotors and its magnetic fields which intend introduces a new form of mechanism losses such as iron losses [2]. Braking torque which results from iron loss usually occurs in journals, ferromagnetic bearing bushes of the rotor. These frictional losses which heats up the rotor during its operation will have to be compensated by the drive power of the motor.

In practice large portion of iron losses usually results from the eddy currents which are induced in the non-laminated target of the axial bearings when compensating for dynamic loads.

II. ROTOR LOSSES

2.1 Aerodynamic Loss

Aerodynamic losses are seen to be more dominant in modern high speed applications and machinery more especially in expanders and compressors where it gases are under very high pressure which obviously are not in vacuum applications.

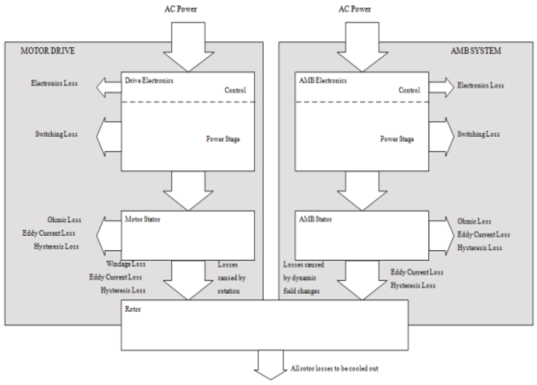

Figure. 1. Flow of energy losses in a motor driven AMB system.

The more dominant aspect of these losses are usually caused independently of the bearings which are within the motors, sealings etc. Often than not the thrust bearing disc with its high circumferential speed is the most critical bearing part in terms of the windage losses.

As convectional aerodynamic losses basically are proportional to the cubic metre of circumferential speed.

2.1.2 Iron Loss (Magnetic Loss)

Magnetic losses which exist on rotors are usually caused by variation of magnetic flux density B in the iron parts. In high speed applications eddy currentlosses are the most important ones that occurs in the system. Changes of flux density are the causes of induced eddy currents in the iron. These eddy currents generate losses through electrical resistance in the iron, the flux density and its polarities varies when the iron of the rotating rotor moves along the poles of the bearing magnets with opposite polarity.

Eddy current losses are basically proportional to the square of the frequency of the variation and is therefore proportional to the square its rotor speed and proportional to the square of the amplitude of the flux density. Eddy current losses can be reduced when the electrical resistance of the iron and by lamination of the iron are increased. Since magnetic field distribution around the rotor is rather far from being sinusoidal, its Fourier series representation includes many harmonics of the rotational angle. Higher order harmonics are made to expelled from the laminations due to the skin effect. A comprehensive analysis of the rotating losses can be found in [3].

2.1.2 Copper Loss

Copper losses are caused by control current which are by the resistance of the coils which are dominant in bearing magnet designs. Thermal balance that exist between copper losses and cooling capacity are the most important design criterion of the bearings, copper losses can be influenced in itsdesign process by balancing the amount of volumes for the copper and the iron within the total available which are volume for the bearing. Copper losses can be reduced by using a larger section of the copper wires which leadings to more volume of the copper.

2.1.4 Iron Loss

Iron losses description in fig. 1 are usual valid also for the losses in the bearing magnets. Variation of the flux density in the bearing magnets are caused by variation of the control current, and on one hand it is caused by the variations of flux to the bearing force and on the other hand variations ripple are caused by the pulse width modulation (PWM) of the power amplifiers.

2.1.5 Losses in Power Amplifier

Power amplifier supplies to the bearing magnet basically reactive power and secondary power to cover the copper losses and the magnetic losses present in the stator as well as copper losses in the cables. The losses that occurs in the control electronics and the power supply are usually deem negligible as compared to losses in the power stage. Basically power amplifiers are of two forms, Analog amplifier and switched amplifier because switched power amplifiers are by far more efficient than analog amplifiers, analog amplifiers are used for special applications in the area where noise is very crucial.

In switched amplifiers design switching losses are considered very dominant. Switching losses are proportional to the switching frequency and depends on the design of the electronic switches and its properties for a specific switching transistors.

Switching frequency is considered not to be lower than 20 kHz to avoid noise in the audible frequency range. High switching frequency reduces the ripple on the control current and as a result reduces the iron losses in the bearing magnets

2.1.6 Iron Losses in the Rotor

Iron lossesP_{fe}depends largely on the following factors: rotor speed, the material used for the bearing bushes as well as the distribution of flux density B over the circumference of the bushes. The braking torque caused which are cause by iron losses consists of constant components of hysteresis loss and a component of the eddy-current losses which increases with respect to rotational speed.

2.1.7 Hysteresis Losses

Hysteresis losses are usually caused by hysteresis in the process of magnetization of ferromagnetic material. Hysteresis losses are proportional to the rotor speed and are therefore not as critical during high speed applications as compared to eddy current losses. They are also dependents on the flux density B and are proportional to $B^{1.6}$. A detailed assessment of the hysteresis losses have been discussed in detailed in [4].

Iron losses are normally influenced by the design of the magnetic bearings, through homopolar vs. heteropolar design the lamination of iron, the volume of the iron, the use of iron with little hysteresis-loop of the *B-H*diagram and its high Ohmic resistance, etc.

During remagnetization, iron in the B-H-diagram are made to travels along a hysteresis loop at each loop the energy in the system diminishes by$Wh = V_{fe}A_{BH}$. A_{BH} represents the area of the hysteresis loop, V_{fe} the volume of the iron. Hysteresis losses are proportional to the frequency of remagnetization f_r. The area of the hysteresis loop usually depends on the material of the magnet used and the amplitude B_m of the flux density. For iron and flux densities between 0.2 and 1.5 Tesla, the relationship

$$P_h = k_h f_r B_m^{1.6} V_{fe} \quad (1)$$

2.1.8 Eddy-Current Losses

Eddy currents are generated when flux density within the iron core changes A solid magnetic core which acts like a short circuit winding are made to generates large eddy currents [5]. Eddy-current losses can be reduced by dividing the iron core insulated sheets into particles sintered cores.

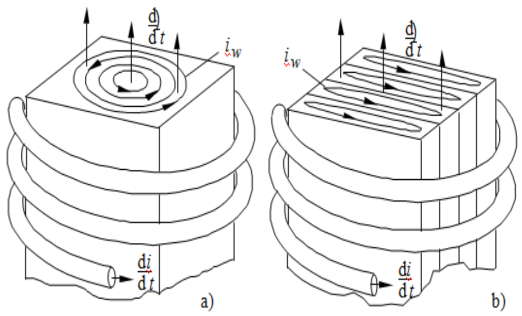

Figure. 2 reducing the eddy current losses by dividing the iron core into sheets

The smaller these divisions are, the smaller the eddy-current losses becomes, if the flux in the sheets is sinusoidal and distributed evenly then

$$P_e = \frac{1}{6\rho}\pi^2 e^2 f_r^2 B_m^2 V_{fe} \quad (2)$$

Here, ρ represents the specific electric resistance of the iron, e thickness of the sheets, f_r as remagnetization frequency, and B_m as the maximum flux density or the amplitude of the flux density respectively.

2.1.9 Aerodynamic Losses

To aerodynamic losses reduction of the pressure in the system is most effective way to do. This requires seals between the high pressure part that is the impeller housing and machine housing namely the motor and bearings. Obviously, the labyrinth seals also result in aerodynamic losses. Optimizing the surface of stator and the rotor within the air gap is also very effective since theinfluence of the surface texture and roughness are usually not well known to obtain optimization needs experimental testing. The thrust disk has a maximum diameter of the rotor and its size needs to be minimized. The thrust disk usually acts as a primitive compressor. It may be worthy to make sure that the air are made to flow through the air gaps in the thrust disc, thereby reducing the pressure as well as improving the cooling process.

III. REDUCTION OF LOSSES

Hysteresis losses can be reduced to its barest point by employing optimized (costly) iron. Eddy current on the other hand can be reduced using smaller sheet thickness of lamination except for the axial bearings, where the target is practically impossible to laminate.

Iron losses can be reduced by dynamic handling of the bias current. A reduction of the bias current results to lower force dynamics. Therefore, the bias current is kept low for standard operating conditions and are increased only for specific operation conditions that is during the run up and run down as well as crossing critical speeds where high dynamics forces are needed.

In the bearing magnets design copper losses can be reduced by employing permanent magnets to generate a bias flux instead off a bias current. The electrical power losses which are associated with generating these bias field are eliminated but the design of the bearing is more complicated and often very costly.

In switched amplifiers, switching losses usually dominant and therefore minimizing of the switching frequency is usually helpful but lower switching frequency normally increases the control current ripple especially in areas of applications that needs high dynamic forces, a trade-off between switching losses and current ripple in the power amplifier has to be found. The filtering of control current to improve the electromagnetic compatibility (EMC) is often very necessary. In this instance the filters have to be optimized for minimum loss. The use of power transistors which consist of topologies and low on resistance with small switching losses further go along way to reduce these losses.

In lowering the current density and therefore the copper losses, the cross section of the wires in the cable may be increased. This increases the cost of the cable and therefore eventually leads to a trade-off between losses and cost of the cables.

IV. COMPRESSORS

Due to the presences of high pressure, windage losses are more dominant in compressors designs. The most critical component is the thrust bearing disc with relatively high diameter and surface speed. Compressors are often used inharsh environment in which AMB electronics are placed in a protected control room. In such a situation a remarkable part of the losses can occur within the long cables. These losses can be reduced if the AMB electronics are placed closer to the compressor in the housing which is similar to as been placed in a harsh environment condition

V. VACUUM APPLICATIONS

Magnetic bearings are perfectly suitable for vacuum operation because they do not need lubrication. In most vacuum applications, minimization of the rotor losses is more important than minimization of the overall losses. This isduely because the rotor is cooled almost solely by radiation which is relatively ineffective. The management of rotor temperature requires a more careful attention to losses that occurs in the rotor volume.

However, the most probably common commercial vacuum application of AMBs are turbomolecular pumps, the orientation of these pumps is usually dictated by the equipment to which they are applied and to which they are commonly are not oriented with the rotor vertical. Consequently, the advantages of usinghomopolar bearings in turbomolecular pumps are lesser as compared to flywheels and most commercial implementations of turbomolecular pumps have heteropolar bearings.

VI. CONCLUSION

Compressors are often used inharsh environment in which AMB electronics are placed in a protected control room. In such a situation a remarkable part of the losses can occur within the long cables. These losses can be reduced if the AMB electronics is placed closer to the compressor housing.AMBs are considered more complex mechatronic systems, which consist of many potential power loss mechanisms.

The more dominant aspect of these losses are usually caused independently by the bearings which are within the motor, sealings etc. Often than not the thrust bearing disc with its high circumferential speed is the most critical bearing part in terms of the windage losses

Improving the performance of the bearing system may be more important than the minimization of the losses ratherthan allowing higher losses and improving the performance of the bearing as the reduction of the size of the bearing may improve the rotor dynamics of the bearings.

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