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Research paper

A review on active magnetic bearing system limitations, risks of failure and control technologies

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Abstract

This paper provides a review on active magnetic bearing (AMB) system limitations, risks of failure and control technologies. Details regarding the operation of an AMB system and background on bearings and sensors are provided. The following benefits for AMBs was identified and are discussed: 1) high reliability, 2) clean environment, 3) high speed applications, 4) position and vibration control, 5) equipment design, development and testing, 6) machine diagnostics, 7) elimination of oil supply, 8) low power consumption and long life, 9) low weight and 10) capability to operate under extreme conditions. The paper further discussed the limitations of AMBs under the following headings: 1) larger bearings, 2) higher complexity and cost, 3) requires electrical power and 4) windage losses. System faults can be broadly classified as either internal or external to the magnetic bearing control system. This classification then relates to the way in which the faults can be dealt with following occurrence. The measures for reducing risks of failure include the following: 1) quality control and standards, 2) systematic check of the design, 3) software development system, and 4) redundancy. Possible future AMB control technologies are likely to be driven by 1) higher operating speeds, 2) lower power loss, 3) greater use of the available clearance, 4) generalised actuation, sensing and control and 5) control of the unbalance response, which are all discussed in this paper. The paper ends with a conclusion on the review of AMB system limitations, risks of failure and control technologies.

Keywords: *Active Magnetic Bearing Systems; Limitations; Risks of Failure; Control Technologies; Electrical Machines.*

1. Introduction

This paper provides a review on active magnetic bearing (AMB) system limitations, risks of failure and control technologies. An overview of the operation and benefits of AMB systems are discussed. Faults on AMB systems are classified into internal and external faults, with a detailed explanation on each of these classifications provided. The limitations of AMB systems and measures for reducing risks of failure are also discussed.

An AMB is a mechatronic system and contains information processing components, software and feedback loops [1]. AMBs have become established in bearing technology over the past few years. Radial loads or thrust loads are acquired by utilising a magnetic field to support the shaft rather than a mechanical force as in fluid film or rolling element bearings [2].

An AMB system constitutes four basic components [3]: 1) magnetic actuator, 2) electronic control, 3) power amplifier and 4) rotor displacement sensor. In many ways, magnetic bearing components resemble electric motors with the basic magnetic actuator being constructed of soft ferromagnetic material which is electromagnetically activated by a coil of wire [4]. An AMB typically consists of three or more electromagnets, each of which exerts an attractive force on the ferromagnetic rotor, levitating it without contact.

In particular, AMBs need extensive improvements in reliability for wide and safe field application. This requirement can be met by improving the individual reliability of each component or by introducing an intelligent system capable of fault detection and diagnosis [5].

Magnetic bearings are non-containing, which means they have negligible friction loss, no wear, and higher reliability. Magnetic bearings enable previously unachievable surface speeds to be attained. Lubrication is eliminated, meaning that these bearings can be incorporated into processes that are sensitive to contamination, such as the vacuum chambers in which many semiconductor manufacturing processes take place [4].

Magnetic bearings are inherently unstable and require active control to ensure proper levitation. Compared to conventional bearings, magnetic bearings have relatively low stiffness.

Magnetic bearings are more expensive and bulkier than conventional bearings, mainly due to the size of the magnets needed [6]. Stiffness, damping and force characteristics of the bearing can be adapted to actual machine operating conditions by adaptive control strategies, easily implemented into the feedback control device [7].

The condition monitoring system is normally not an integral part of conventional systems, such as motors and turbomachinery, but AMB systems are ideally suited for diagnosis and correction, since the bearing system is already equipped with sensors and actuators, which provide the exact displacement and current values during machine operation [8].

The sensor signals (which are usually used for control purposes) can be analyzed to obtain information on the system's operating condition. Furthermore the bearing magnets can be used to apply test signals to the system, the response which can again be analyzed, yielding detailed information about the system that allows for identification of complete system dynamics and detection of changes in system behaviour [9].

The growth in the area of industrial applications of AMB systems caused an increase in the demand of highly reliable systems at any operating conditions. AMBs are currently applied to high-speed rotating machinery, like turbo pumps [10], flywheels for energy storage [11] and turbo compressors [12].

2. First practical magnetic bearing

This section provides an overview of the first practical magnetic bearing. Beams [13] developed the first practical magnetic suspension for high speed rotating devices. These devices include high speed rotating mirrors, ultracentrifuges and high speed centrifugal field rotors.
Beams further employed magnetic suspension as a means to carry out extensive experiments on physical properties in areas of isotope separation, biophysics, materials science and gravitational physics. He typically thought of ways to modify and improve experimental equipment. The improved equipment then provided much better experimental results [14].

3. Operation of an AMB

This section provides an overview of the operation of an AMB. AMBs operate on the principle that ferromagnetic particles are attracted by an electromagnet [15]. This property of the rotor makes it ideal for a rotor to be supported by an electromagnet in the stator of a motor. The purpose of the electromagnet is to apply a force on the rotor to maintain a constant air gap between the rotor and the stator [16].
As the air gap between these two parts decreases, the attractive force increases, therefore, electromagnets are inherently unstable. A control system is needed to regulate the current and provide stability of the forces and position of the rotor [5].
The control process begins by measurement of the rotor position by means of a position sensor. The signal from this device is received by control electronics, which compares it to the desired position during machine start-up. Any differences between these two signals result in calculation of the force necessary to pull the rotor back to the desired position [7].
The position error is translated into two commands to the power amplifiers connected to the magnetic bearing stator. The current is increased in the one power amplifier, causing an increase in magnetic flux, an increase in the forces between the rotating and stationary components, and finally, movement of the rotor toward the stator along the axis of control. While the current in the one power amplifier increases, the current in the other power amplifier decreases with the inverse effect [17].
Since the natural tendency of the stator is to attract the rotor until it makes contact, some control action is required to modulate the magnetic field and maintain the rotor in the desired position. The most common type of control involves the feedback of shaft position. This information is then used by the control system to modulate the magnetic field through power amplifiers, so that the desired rotor position is maintained even under changing shaft load conditions [18].
An AMB system constitutes of magnetic actuators, position sensors, power amplifiers and a control system. The bearing actuators and sensors are located in the machine, while the control system and amplifiers are generally located remotely [19].

4. Background on bearings and sensors

To provide support in more than one direction, magnetic poles are oriented about the periphery of a radial bearing [20]. Radial bearing construction is very similar to that of an electric motor, involving the use of stacked steel laminations, around which power coils are wound. Stacked laminations are also used in the rotor to minimize eddy current losses, which are a small source of drag in a magnetic bearing and cause localized heating on the rotor [21].
The sensors are also oriented about the periphery of the stator, usually inside a ring or individual tubes mounted adjacent to the actuator poles. Position sensors are used, that measure the distance of the air gap between the sensor and the rotor laminations. Two measurements are taken for each radial axis and the rotor center position is calculated by means of a bridge circuit [22].
A typical rotating machine will experience forces in both the radial and axial directions. Typically, a 5-axis orientation of bearings is used, incorporating 2 radial bearings of 2 axes each, and 1 thrust bearing [23].
Thrust bearings provide a magnetic flux path in the axial direction, between 2 stators oriented on either side of a thrust rotor (or disc) [15]. This is then mounted on the rotating shaft and an axial sensor measures the position of the shaft [6].

5. Benefits of active magnetic bearings

The following section provides some benefits of AMB systems.

5.1. High reliability

With magnetic bearings there is no contact between the rotating and stationary parts, meaning there is no wear. In most cases failure modes are limited to control electronics, power electronics, and electrical windings. These components have design lives far greater than that of conventional bearings [24].
Magnetic bearings are fitted with protective retainer (backup) bearings and have built-in overload protection. Magnetic bearings can signal process control equipment to stop the machine instantaneously in the case of excessive load [25].
Magnetic bearings provide high reliability and long service intervals in time critical applications for semiconductor manufacturing, vacuum pumps, and natural gas pipeline compression equipment [26].
Users are aware that, beyond function, the aspects of safety and related areas become increasingly important. Safety is more than a mere technical issue. It contains a strong component of psychological interpretation, and expectations as to safety are running very high. Reliability on the other hand appears to be more amenable to engineering calculations and to economic considerations [27].
Mathematical tools for assessing reliability of classical technical systems, and performance numbers for comparing them, such as mean time between failures, are readily available. The reliability analysis of given technical structures and systems, consisting of a more or less large number of classical components, is rather well developed [28].

5.2. Clean environments

In a magnetic bearing system, particle generation due to wear and the need for lubrication are eliminated. There is therefore no chance of contaminating a clean process with oil, grease or solid particles [29].
Magnetic bearings offer a dry, clean and economic solution for semiconductor fabrication equipment, vacuum pumps, gas and air compressors, and various other turbo machines that require submersion in process fluid, even under pressure [30].

5.3. High speed applications

The fact that a rotor spins in space without contact with the stator means drag on the rotor is minimal. That opens up the opportunity for the bearing to run at exceptionally high speeds, where the only limitation becomes the yield strength of the rotor material [29]. Please note windage losses under limitations of magnetic bearings (section 6.4).

5.4. Position and vibration control

Magnetic bearings use advanced control algorithms to influence the motion of the shaft and therefore have inherent capability to precisely control the position of the shaft within microns and to virtually eliminate vibrations [31].

5.5. Equipment design, development and testing

A magnetic bearing system can be used as an exciter, where the bearing force is modulated for deliberately exciting vibrations. The excitation force is applied to the rotor without contact and can be measured precisely. This makes magnetic bearings a valuable tool in equipment design, development and testing as well as in rotor dynamic research [32].
5.6. Machine Diagnostics
In order to function, a magnetic bearing must determine rotor position, rotor vibration and bearing load. This information is processed into an electronic database which provides an output to the end users, such that there is a constant knowledge of the operating state of the machine. This allows the user to detect incipient faults, plan maintenance and optimise performance [29].

5.7. Elimination of oil supply

Magnetic bearings do not require oil lubrication so they are well suited to applications such as canned pumps, turbo-molecular vacuum pumps, turbo-expanders and centrifuges where oil cannot be employed [2].

5.8. Low power consumption and long life

There is no contact between the rotor and stator, this means no wear. Where fluid film bearings have high friction losses due to the oil shearing effects, magnetic bearing losses are due to low level air drag, eddy currents and hysteresis [31]. Also the losses associated with oil pumps, filters and piping are much greater than the power associated with controls and power amplifiers. Overall, magnetic bearings normally have an order of magnitude lower power consumption than oil film bearings [2].

5.9. Low weight

A recent study of aircraft gas turbine engines indicates that the elimination of oil supply and associated components with magnetic bearings could reduce the engine weight by approximately 25 % [2].

5.10. Extreme conditions

The following section provides some extreme conditions of AMB systems.

5.10.1. Temperature

The magnetic bearing system is capable of operating through an extremely wide temperature range. Magnetic bearings can operate as low as -256 °C and as high as 220 °C, thus allowing operation where traditional bearings will not function [11].

5.10.2. Corrosive fluids

Magnetic bearings can operate in corrosive environments by means of canning both the stationary and rotating parts [33].

5.10.3. Pressure

Magnetic bearings are virtually insensitive to pressure. They can be submerged in process fluid under pressure without the need for seals, as is the case with conventional bearings. Magnetic bearings can also operate in vacuum where their operation is even more efficient due to lack of windage [2].

6. Limitations of active magnetic bearings

6.1. Larger bearings

Magnetic bearings have a specific load capacity (maximum load per unit of area of application) lower than most conventional bearing systems which results in bearings that are physically larger than other similarly specified bearings. Magnetic bearings therefore have a lower load capacity [2], [34].

6.2. Higher complexity and cost

The higher complexity of magnetic bearings often means the initial purchase price is higher than competing technologies. However, magnetic bearings' life cycle cost can often be less than traditional bearings. This is particularly true where the alternatives are exotic bearings [2], [20].

6.3. Requires electrical power

Magnetic bearings require power to drive the control systems, sensors and electromagnets [26].

6.4. Windage losses

At high rotating speed, windage (friction between moving parts and air) becomes a problem. For inline electric motors the circumferential speed needs to be limited not due to the material strength but due to high windage losses at the motor surface. These windage losses increase linearly with pressure [35].
Modern flywheel uninterruptible power supplies has a useful power delivery for 10 to 50 seconds, a maximum surface speed of 122 m/s and windage losses over 1 kW for systems not operating in a vacuum [36].

7. Faults on active magnetic bearings

System faults can be broadly classified as either internal or external to the magnetic bearing control system. This classification then relates to the way in which the faults can be dealt with following occurrence.

7.1. External faults

Faults that are external to the magnetic bearing/control system do not generally require any reconfiguration of the control system itself although some adjustment or adaptation of the control algorithm may improve operation. Consideration of abnormal, or fault related, system disturbances in the controller design will also improve robustness to certain aberrations from normal operating conditions [37].
Faults are considered to be external when either the fault manifests itself as, or the effect of the fault can be replicated by, some external vibration (disturbance) acting on the system. These disturbances will always have a transient component and possibly a steady state component. Typical faults that can be classified in this way include the following:

7.1.1. Rotor impact

A direct impact of the rotor with a foreign body could occur in a number of applications. For example, a pump or turbine fluid/air intake could be contaminated with solid matter. This type of fault would result in impulsive force acting directly on the rotor, the magnitude of which would depend on velocity, mass and material hardness [25].

7.1.2. Rotor mass loss (load unbalance)

This type of fault is well documented for high-speed turbines where loss of compressor or turbine blades, though uncommon, can occur. Typically, sudden loss of a blade occurs due to a fracture at the blade root. This can be modelled by a step change in amplitude of the synchronous forces acting on the rotor [38].

7.1.3. Motion of system base (foundation looseness)

Motion of the system base, on which the bearings are mounted, can occur in various applications and environments [24]. In transport applications, motion of the vehicle will be transmitted to internally mounted machines. Base motion may also arise from external vibration sources (e.g. other machines), seismic events and accidental impacts or explosions [39].

7.1.4. Rotor deformation

Deformation of the rotor while in operation could occur for a number of reasons. For example, a plastic deformation of the rotor or ancillary component may occur due to excessive loading/wear. Another possibility is thermal deformation, for example, due to rotor rub. This effect can be modelled by synchronous forces acting directly on the rotor, but for control purposes should not be treated the same as unbalance [40].

7.1.5. Sudden changes in loading (Overhung rotor)

A change in the steady state load could occur due to some fault conditions. For example, in compressor or pump applications, a sudden change in fluid pressures due to an external fault or error will result in a step-change in the axial rotor loading. Rotor mass loss events will also cause a step change in mean loading due to a change in the total weight of the rotor [41].

7.1.6. Rotor rub

Contact of the rotor with stationary components causes vibration both of the rotor and the surrounding ancillaries. This may occur for a variety of reasons e.g. rotor deformation, unbalance changes or component damage. It will generally be characterised by directly forced rotor vibration, mainly at the synchronous frequency, although sub-harmonics and higher frequencies will also be present. Rotor rub can significantly alter the closed loop dynamics of the system and if so, treatment as an external fault may be inappropriate [42].

7.1.7. Bent rotor

In the case of a bent rotor, the excitation is proportional to the magnitude of the bow along the rotor [43]. A bent rotor gives rise to synchronous excitation, as with mass unbalance, and the relative phase between the bend and the unbalance causes different changes of phase angle through resonance than would be seen in the pure unbalance case, as described in [44], [45].

7.1.8. Misalignment

Misalignment occurs when there are geometry changes due to assembly procedures. Misalignment is typically caused by the following conditions [46]:

- Inaccurate assembly of components, such as motors, pumps, etc.
- Relative position of components shifting after assembly
- Distortion due to forces exerted by piping
- Distortion of flexible supports due to torque
- Temperature induced growth of machine structure
- Coupling face not perpendicular to the shaft axis
- Soft foot, where the machine shifts when hold down bolts are torqued.

If the machine speed is varied, the vibration due to imbalance will vary as the square of the speed. If the speed is doubled, the imbalance component will rise by a factor of four, while misalignment-induced vibration will not change in level [47].

7.1.9. Rotor faults

Mechanical faults in the system could be catastrophic if the system cannot retain adequate control. Possible faults of this nature include fatigue, cracking, deformation of the rotor or detachment of part of the rotor. Also, problems not directly attributable to the rotor can occur, such as external rubbing, ancillary parts becoming loose or unexpected impacts or loading. Mechanical abnormalities in the rotor can be considered as a variation in system parameters. As such, there is a realistic chance that these types of faults can be included in robustness specifications during the controller design stage [48].

7.2. Internal faults

7.2.1. Power amplifier failure or malfunction

To power each magnet coil, a solid state amplifier is commonly used. Although, these units are inherently reliable, their dynamic performance depends on a number of variables (e.g. ambient temperature and power demand). The amplifiers are usually configured for either voltage or current control. When amplifiers and magnet poles are configured in opposing pairs, loss of a single amplifier and pole will result in an attractive force from the remaining opposite pole. Unless this can be turned off quickly the rotor will collide with the backup bearings [3].

Actuator faults in AMB systems may have a number of causes. Problems may arise in any point in the series connection of amplifier, wiring, and coil. Connectors or cables may fail, amplifiers and fuses may burn. For experimental purposes actuator faults can be restricted to open circuit failures that can be tolerated by the system, i.e. failures of a lower sensor coil such that the current suddenly goes to zero [48].

Without correction, such a failure can be modelled as a decrease in bearing stiffness combined with the disability to exert downward forces onto the rotor, as a consequence of the changes in the actuator. The system may become unstable in one channel (axis). As the case with uncorrected sensor faults, unstable behaviour with violent crashes of the rotor against the retainer (backup) bearings is the consequence [21].

7.2.2. Transducer malfunctions (sensor failure)

The malfunction of a transducer could produce a variety of erroneous signals. However, a short circuit or an open circuit is likely to produce a dc signal. Other than an electrical fault, physical damage or deterioration is a likely cause of sensor malfunction. For example, damage to the shaft at the measurement surface will affect proximity detectors [49].

Without correction, failure of a sensor leads to the controller being provided with incorrect position information. As a consequence, the controller sets up inappropriate reference currents, which inevitably entails a destabilization of the system. Violent crashes of the rotor against the retainer (backup) bearings are the consequence [6]. The electronics may fail or the signals may be disturbed, most often by excessive noise from electromagnetic sources, which are mistaken as sensor signals.

7.2.3. Loss of I/O board channel

The complete loss of a channel on the computer input/output board would produce an undefined control input or output signal. A possible cause of this type of fault would be a circuit break or short in the connection cable [50].

7.2.4. Bearing magnet coil failures

The failure of a magnet coil usually occurs due to a breakdown in winding insulation, resulting in a short circuit. Depending on where the short occurs, there will be a reduction in the number of effective coil windings [51].

7.2.5. Computer software errors (controller failure)

Real-time control software can be susceptible to latent programming errors that may arise unexpectedly and may be difficult to pre-detect. These types of errors will result, at best, in unpredictable behaviour or, at worst, in program termination. The key to avoiding this type of situation is well structured programming and thorough program testing. Code can be written with a certain degree of built in tolerance to run-time errors [52].
However, a complete program execution failure would require a redundant microprocessor to take over control [53]. The alternative is to rapidly restart the processor, which would require reloading of the control program, initialising and restarting. It is doubtful whether this could be achieved in the necessary time-scale [54].
Examples of software failures are a system breakdown, run-time exceptions, i.e. address errors and bus time-out, or incompatible program versions. The software area is least covered by systematic approaches to improve its reliability [25].

7.2.6. Computer hardware failures

A failure of microprocessor hardware is relatively uncommon, but would probably have similar consequences to a program termination. Again the only alternative for dealing with this type of problem would be if back-up hardware were available to take over the control operation [55].

8. Measures for reducing risks of failure

The following section provides measures for reducing risks of failure.

8.1. Quality control and standards

An overall approach for systematically introducing quality aspects into the design, production and operation of products and systems, are standardized procedures as described in the ISO 9000 series [56]. A company or an establishment following the procedures of ISO 9000 can be recognized as a certified institution with a defined quality level. In addition the ISO 14839 provides information and standards on mechanical vibration of rotating machinery equipped with active magnetic bearings [3].

8.2. Systematic check of the design

A classical method to ensure best practice of the state of the art is to use the FMECA approach for checking the design, i.e., to do a Failure Modes, Effects, and Criticality Analysis. In this approach a group of experts with different background, from design, production, test, repair, and potential users, are evaluating the design or the product [23].
They have to identify potential failure modes, determine the effects and consequences of such failures and their criticality, and suggest modifications of the design to improve it. There are various standards and specifications on how to proceed in detail, depending on the application areas (see for example the military standard procedures MIL-STD-1629A [56]). FMECA is an integral part of any QS 9000 compliant quality system [57].

8.3. Software development system

In a mechatronic system, software is an integral part of the system and has to be developed and implemented. The software has to be logically correct, and the operating system should take care of the syntax. In addition to that, the correct time sequence of the computational tasks is most essential in real time applications [58].
For industrial AMB applications most often proprietary software is running on single chip digital signal processors (DSP) giving an efficient and economical solution, which is dedicated to specific tasks with well-defined constraints. For experimental application the tasks usually are much more diverse, sometimes complex and require a versatile solution [46].
For complex tasks it may not be sufficient to just use a high-speed computer with high sampling frequency and assume that this is adequate for real time operation. It might be better to use a real time operating system (RTOS) from the onset in order to develop and finally operate the software. Such RTOS are available in various versions, such as dSPACE®, RTLinux®, XO/2® and VxWorks® [59].

8.4. Redundancy

One way of improving reliability is to use redundant components and redundant information. There are two different kinds of redundancy. If the failure of a single component cannot be corrected and is critical for the system's safety, the function of this component should be guaranteed by redundant hardware. Two or more of these same components have to be arranged in parallel, in order to replace any failed component [30].
Appropriate failure detection and switchover schemes are crucial, and the increase in the number of components actually counteracts the overall reliability to some extent. If the function of a component is at least partially performed by another component as well, then the functional relation between these components can be used as an analytical redundancy to replace the failed component partially, or to reduce the extent and cost of a hardware redundancy [60].
If the rotor is driven by a motor drive, switching the motor from its drive mode to generator mode can supply sufficient electrical power to the system again, until the rotor can coast down safely in its retainer bearings [18].
Diagnostics and identification tools are being used for fault detection of various kinds of fault-tolerant control systems. A general introduction is given in [52] and [61]. In magnetic bearings, faults on redundant sensors and actuators and other redundant machine components have been detected and corrected, see [21], [25] and [58].

9. Future AMB control technologies

Future AMB control technologies are likely to be driven by [18]: 1) higher operating speeds, 2) lower power loss, 3) greater use of available clearance, 4) generalised actuation, sensing and control and 5) control of unbalance response.

9.1. Higher operating speeds

Magnetic bearings already permit higher operating speeds than conventional bearings. However, the demand for even greater speed is strong, e.g., for energy storage flywheel systems for electric vehicles. Higher rotational speed implies a greater rotor gyroscopic effect which results in the plant being linear parameter-varying (LPV) [62].

9.2. Lower power loss

Lower power loss is especially important for high-speed applications, since rotation of the rotor in a supporting magnetic field can cause significant losses which result in reduced machine efficiency and excessive rotor heating [36].
A common approach to improve the force slew rate is to introduce a bias current (or flux ø). With a bias, the actuator may also be accurately modelled as linear. The disadvantage of operation with

a bias is the associated ohmic loss in the coil, rotating hysteresis loss, alternating hysteresis loss, and eddy current loss [63].
For high speed rotating machinery, the eddy current loss is dominant; herein we refer to it as the rotating loss. This rotating loss may result in excessive rotor heating. Moreover, it results in decreased machine efficiency. Thus, operation without bias is appealing in applications where efficiency is critical, for example energy storage flywheels [63].

9.3. Greater use of available air gap

Most industrial magnetic bearing systems use a large air gap during operation. A larger air gap (e.g. 1 mm) results in greater actuator linearity near the centered position and thus simplifies control design and tuning. However to reduce bearing size, weight and power consumption, it is desirable to use a smaller air gap during operation. For some applications, such as precision positioning platforms the required motion may be large and a reduction of the bearing size may not be possible [64].

9.4. Generalised actuation, sensing and control

For every axis of motion there has been a devoted sensor, actuator and control system, each performing a single operation. Recently there has been a shift away from this approach. For example, magnetic actuators are used to inductively sense position as well as apply forces [21].
Motor and bearing functions are achieved with a single actuator. Direct digital control of amplifier switching is used to eliminate the separate amplifier servo-control loop, thus combining the amplifier and rotor controllers. The advantages of these generalised actuation, sensing and control methods are reduced cost and increased design flexibility [65].

9.5. Control of unbalanced response

Control of unbalanced response has been an area of intense research over the last few years, which requires substantial laboratory and industrial experience to provide a good outcome. Herzog et al. [10] propose a generalized notch filter to be used in a redundant multivariable feedback loop to reduce the response of the control system to rotor imbalance so as to avoid actuator saturation. More details on control and an energy management system are provided by [66].

10. Conclusion

This paper provided a review on AMB system limitations, risks of failure and control technologies. Magnetic bearings have structured themselves in bearing technology over the past few years. Industries, small companies and even the everyday man can benefit from the advantages of magnetic bearings.
High reliability, clean environments, high speed applications together with advantages in position and vibration control are only a few of the advantages of magnetic bearings. Like any other bearing, magnetic bearings also have limitations. Larger bearings, higher complexity and higher cost are a few of the limitations of magnetic bearings. The quality and performance of an AMB system can be greatly improved by implementing the steps outlined in the measures for reducing risks of failure.
Faults on AMB systems were classified into internal and external faults, with internal faults focussing on faults occurring within the hardware and software of the AMB system and external faults focussing on faults caused by some external vibration (disturbance) force acting on the system. These faults can be detected, corrected and identified by using fault detection techniques and intelligent control systems. More details on electrical machines are provided by [67].

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