A SOPHISTICATED ACTIVE MAGNETIC BEARING SYSTEM WITH SUPREME RELIABILITY

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ABSTRACT
Within this work a new active magnetic bearing (AMB)-system offering supreme reliability is presented. It provides bearing capacity even in case of a defect within any sub-assembly over the whole operating time.
Each AMB consists of completely decoupled electromagnet (EM)-channels configured in hot redundancy, comprising a singular EM, controlled and driven by a decentralized hot-swap controller amplifier module (HCA) and one displacement sensor. Each HCA is responsible for controlling the position of the structure towards its dedicated EM and comprises a digital controller, a switching amplifier, local power supplies, and a local error detection unit.
All functional EM-channels contribute to support the structure. On occurrence of an error within a certain EM-channel this error is detected by the local error detection unit and the defective EM-channel automatically shuts down. The adjacent redundant EM-channels take over the bearing functionality and the defective sub-assembly can be replaced during system operation (hot-swap) without degrading system performance.
This paper gives detailed information on the AMB functionality and the HCA design.

INTRODUCTION

Despite many advantages compared to conventional roller or journal bearings some drawbacks compared with conventional bearings limit the widespread application of active magnetic bearings (AMB).

One of the major drawbacks of AMB, besides a lower specific load capacity, is the higher risk of a breakdown compared to conventional bearings caused by a rather large number of sub-assemblies needed (controller, power amplifiers, magnetic actuator, sensors, signal conditioning electronics, power supply, interconnections, etc.). In a worst case scenario, the failure of one single component of an AMB may cause the complete loss of the bearing load capacity.

The danger of an unpredictable machine break down caused by an AMB-failure is one of the major reasons that AMB-technology is not sufficiently accepted so far by industry for many practical applications. One field of application includes all systems, where AMB failures directly affect human life as e.g. in aircraft industry. By eliminating turbine bearing lubrication a further step to an all electric aircraft could be realized.

Other fields of applications are industrial processes, where AMB failures result in large financial losses. Typical examples are petrol, textile and paper industry which require extremely high reliability for their plants. Even a short shutdown may cause high costs because of loss of production and expensive start up procedures of the plant, including synchronization along the whole production line.

Therefore, a broad industrial acceptance of AMB-technology is very strongly associated with high operational reliability and safety.

Concepts for increasing the reliability of AMB-systems, known from literature, are based on a more or less multiple redundancy of AMB sub-assemblies.

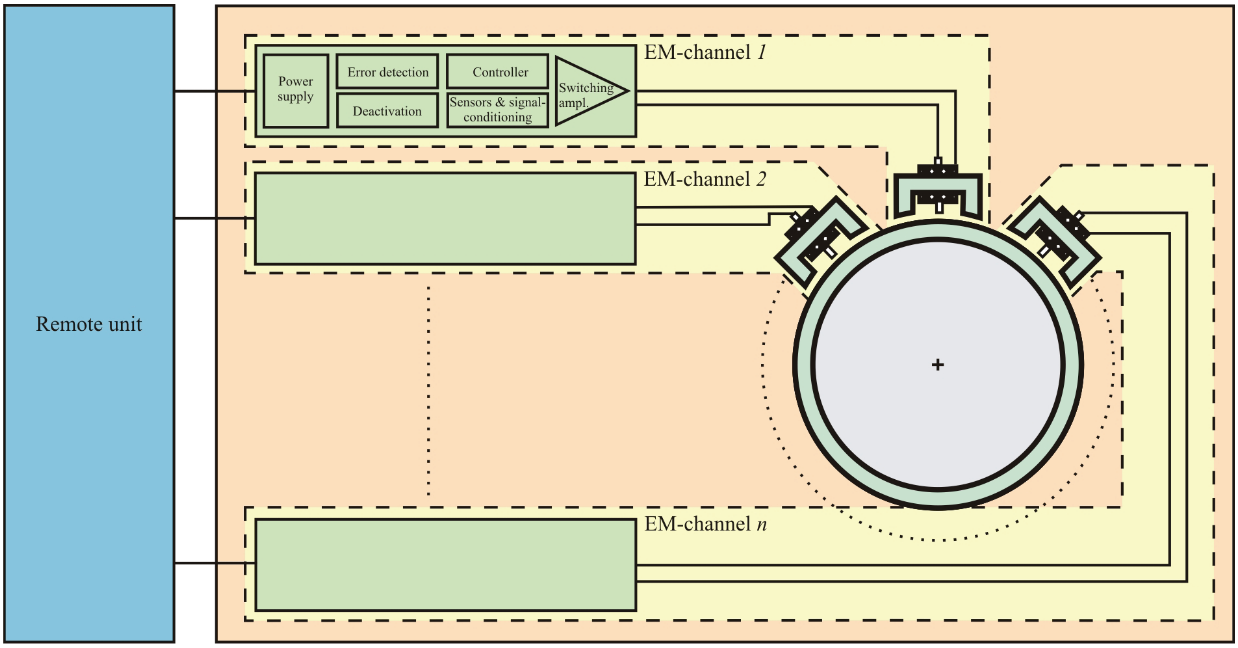

FIGURE 1: Block diagram of an active magnetic bearing system with supreme reliability.

Concepts with centralized control as in [1] to [6], use redundancy of certain sub-assemblies (sensors, analog-digital converter (ADC), controller, digital-analog converter (DAC), amplifiers), which are coupled into signal flow when fully operational.

In [7] and similar in [8] it is confirmed, that failure detection switchover schemes are crucial, and the increase in the number of components actually counteracts overall reliability. Furthermore, in [9] it is stated that in terms of reliability, a full multivariable controller could have the effect that a breakdown in a single unit, no matter how minor to the system, could have a plant-wide consequence.

Also failure detection based on majority decisions only results in wrong decisions, if more than half of the sub-assemblies show wrong results. So, even a single failure in one of the components listed below could nevertheless cause a total loss of bearing functionality[1]:

- Global voters, detecting which components are functional and therefore should be coupled into signal flow or start a reconfiguration process on occurrence of an error,
- coupling elements, which couple functioning modules into the signal flow or decouple faulty modules from the signal flow,
- communication links, including checksum generation circuits and bit error cancellation circuits,
- synchronization electronics (global system-clock, control buses, etc.).

[1] See [10] for an in depth literature analysis.

Problems of decentralized control concepts presented e.g. in [11] include centralized position measurement and the lack of an error detection, so a single failure within sensors, cabling, connectors or electronics could nevertheless yield a total loss of bearing functionality.

SYSTEM OVERVIEW

The principle configuration of the new AMB concept, offering supreme reliability of the whole AMB-system over the whole operating time and the perpetuation of bearing capacity, even in case of a defect within any sub-assembly, is shown in Figure 1.

Each AMB consists of completely decoupled electromagnet (EM)-channels configured in hot redundancy, comprising a singular EM, controlled and driven by a decentralized hot-swap controller amplifier module (HCA) and one displacement sensor (eddy current sensor).

Each HCA is responsible for controlling the position of the structure towards its dedicated EM and comprises a digital controller, a switching amplifier, local power supplies, and a local error detection unit.

All functional EM-channels contribute to support the structure. If the air gap of an EM increases, the current through this EM is increased, so that the structure recovers reference position.

On occurrence of an error within a certain EM-channel the local error detection unit detects that error, and the defective EM-channel automatically shuts down. The adjacent redundant EM-channels take over the bearing functionality without the need for a re-assignment of module functionalities, control parameters or signal re-routing.

An uninterrupted operation of all functional EM-channels is assured by a complete decoupling and by waiving any communication between the EM-channels. The intended supreme reliability throughout the whole operating time is assured by the possibility to replace the HCA, cabling, etc. during operation of the system (hot-swap) without degrading system performance.

The necessary communication with a remote unit is reduced to a minimum. Start up and soft shut down of the AMB as well as bearing data visualization (rotor position, applied force, etc.), which can be used for machine diagnosis (see [12], e.g.), is transmitted by two galvanically isolated serial communication links per HCA, validated by a secure protocol. This guarantees full bearing functionality even in case of HCA faults or failures within the remote unit.

The new concept is a logical next step from the AMB-system presented in [13] comprising a reliable switching amplifier (RSA) [14] – [17] with hot-swap amplifier half-bridges and a local voter to a complete hot-swap AMB-assembly for supreme reliability. Depending on the desired reliability and requirements on achievable force and physical dimensions the number of EM-channels can be chosen optimally.

In order to make sure, that in case of a failure the functional EM-channels are capable of supplying the specified bearing capacity, a certain over-dimensioning of the magnetic actuator is required. However, large machines with high force requirements typically comprise magnetic actuators with a large number of poles, which leads to a reduced proportional over-dimensioning. A further advantage during normal operation is the reduced electrical and thermal stress on the AMB-components, which further increases operational reliability of the system.

By choosing the number of redundant EM-channels this new concept is an economic solution for applications with reduced requirements on the reliability and safety, as well.

In Table 1 a comparison between the best AMB-concepts for high reliability presented in literature and the new AMB-system with supreme reliability is shown. With an increasing number of EM-channels, the load capacity of the new system reaches that of best AMB-concepts for high reliability presented in literature, whereas their centralization allows more complex and therefore better control algorithms. However, component faults might result in a complete system breakdown, whereas the new AMB-concept with supreme reliability will continue operation.

HOT SWAP CONTROLLER AMPLIFIER MODULE (HCA)

In Figure 2 a block diagram of an HCA is shown. The design avoids any single point of failure and basically consists of the previously mentioned functional blocks:

1. Controller and error detection (CED).
2. Switching amplifier (drives the dedicated EM).
3. Power supply.

Controller and error detection (CED)

The controller and error detection comprises two totally independent working digital signal controller boards (DSB). Each DSB has its own independent power supply and is galvanically isolated from the second DSB as well as the power circuitry (high power supply and switching amplifier). A DSB comprises a digital signal controller (DSC) – a digital signal processor with additional components and interfaces included on a chip (such as ADC, pulse-width modulators (PWM), RS232 and high speed serial interfaces as well as timers and counters, etc.).

TABLE 1: Comparison between the best AMB-concepts for high reliability presented in literature and the AMB with supreme reliability.

	Best AMB-concepts for high reliability presented in literature		AMB with supreme reliability	
	normal operation	component fault	normal operation	component fault
Load capacity	best	best – malfunction*	high**	high
Control performance	best	best – malfunction*	high – medium	high – medium
Controller complexity	high		medium	
Electronics complexity	very high		high	
Initial costs	very high		high***	
Reliability / safety	high – malfunction*		best	

* depending on type of fault ** with increasing number of EMs up to MRAMB *** can be optimized economically

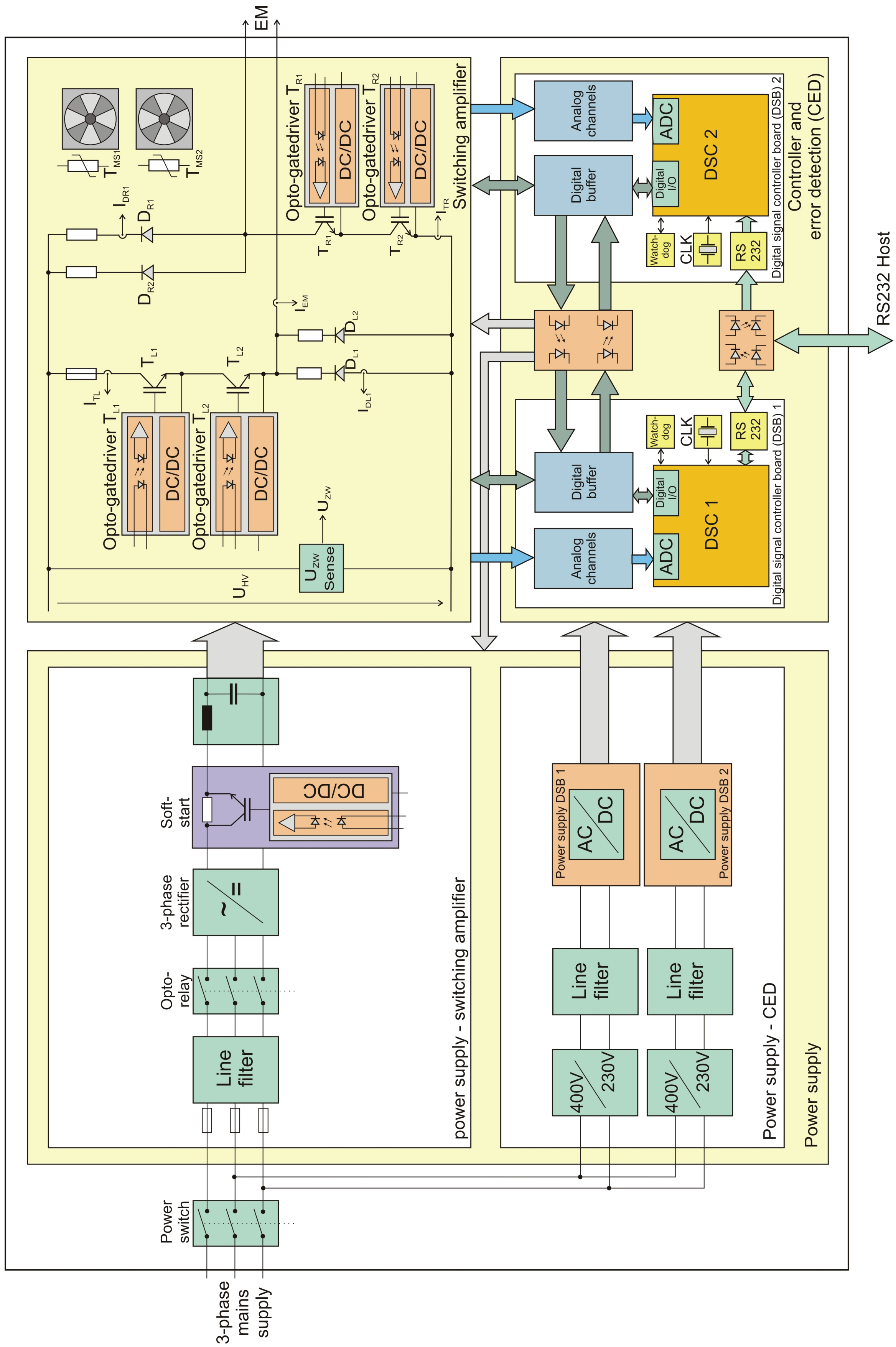

FIGURE 2: HCA block diagram

Previously mentioned galvanically isolated communication with a remote unit is carried out via the RS232 interface of DSC1. For detection of communication errors, DSC2 listens to the bus and reads both, sent data from DSC1 and from the remote unit. Wrong data sent by DSC1 is followed by a deactivation of the communication by DSC2, which signalizes the remote unit a faulty HCA.

Additionally, a high speed serial communication interface with galvanic isolation via optocouplers between the two DSC is implemented. This is required for data, system status and control parameter exchange between the DSC. For highest reliability, hard- and software of the DCB should differ from each other (hardware and code diversity), ideally designed by different design groups.

The functionality of DSC1 includes:

- PID position controller with underlying proportional current controller and noise shaper[2],
- control of the switching amplifier,
- self-sensing,
- error detection of DSC2,
- deactivation of EM-channel.

The functionality of DSC2 includes:

- Error detection of:
  - switching amplifier,
  - high power supply,
  - DSC1,
  - communication with the remote unit,
- deactivation of EM-channel.

Switching amplifier

Since for AMB (not for hybrid magnetic bearings) only one current direction is sufficient, a two quadrant switching amplifier circuit is used. Unlike the standard circuit with one active switching element (transistor) and one passive switching element (free-wheeling diode) per half-bridge side, two switching transistors in series and two free-wheeling diodes in parallel are implemented. This special circuit topology allows a complete functional test of all components during system operation as well as a safe deactivation of the amplifier even in case of a component error, e.g. short circuit or high impedance state within a power semiconductor. Additionally, using a special PWM scheme for transistor control a reduction of the effective switching frequency for each transistor is gained, resulting in reduced heating of the transistors and therefore a higher mean time to failure (MTTF).

Control of the switching amplifier is done via optogatedrivers – drivers with optocouplers and outputs with high current drive capability. The gate-driver´s secondary sides are supplied by DC/DC-converters.

All current sensors (for EM-current, transistor- and free-wheeling diode currents) are closed loop hall effect sensors using the flux-compensation principle. Voltages are measured galvanically isolated via isolation amplifiers.

Power Supply

The power supply is divided into a high power supply for the switching amplifier and galvanically isolated low power supplies for the two DSB.

DC link voltage for the switching amplifier is generated via direct full-wave rectification of the three-phase mains supply. Beneath a smoothing inductor for reduction of inrush current from the mains during regular operation, a soft-start circuit for limiting the inrush current from the mains during start-up and a series-parallel arrangement of electrolytic capacitors is implemented.

All voltages for the DSB are generated via transformers (400VAC to 230VAC conversion), followed by line filtering and AC/DC-converters.

AMB FUNCTIONALITY

System start-up

1. Switch on of all HCA via local power switches.
2. Both DSC of each HCA start up and perform a first self- and cross-check.
3. After a positive first test a soft-start of the high power supply is initiated.
4. Check of all switching amplifier voltages.
5. After a positive voltage test: waiting for “levitation”-command from the remote unit.
6. Soft-start of the switching amplifier with slow increase of EM-current to the value given by the digital controller.
7. AMB is fully functional.

Generally a negative test results in deactivation of the EM-channel via the HCA.

Error detection

The complete EM-channel is checked including all functional blocks of the HCA during operation:

- DSC (hard- and software),
- signal conditioning electronics,
- switching amplifier,
- watchdog circuit,
- power supplies,
- interconnections,
- EM, etc.

For error detection significant signals of each functional block have to be checked, such that a correct functionality of the EM-channel can be guaranteed. On detection of an error the HCA disconnects from the EM, informs the remote unit about the supposed source of error, sets a failure flag in a nonvolatile memory and shuts down the EM-channel. The failure memory prevents an activation of a defective EM-channel.

Since the error detection functionality is divided into

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[2] A noise shaper is implemented to improve output signal quality of the switching amplifier in conjunction with a special pulse-width-modulation scheme. Simulation results in [18] show a significant reduction of noise and higher harmonics.

two physically separated devices (DSB1 and DSB2) using a cross-check between these devices allows a complete functional test of the EM-channel.
For detection of displacement sensor/cabling/connector faults self-sensing is used.
The error detection of the switching amplifier is based on the approved method as used for the local voter of the RSA [15]. Transistor and diode currents are compared with reference signals calculated based on the actual EM-current and the switching states of the power semiconductors.
As the power for the switching amplifier current sensors is supplied by DSB1 and the check is performed by DSC2 and the power for the EM-current sensor is supplied by DSB2 and the check is performed by DSC1 the comparison of the results allows to detect errors within the signal conditioning electronics, ADC, etc. of the DSB, as well.
High power supply functionality is checked by measuring DC link voltage with DSB1 and comparison with capacitor voltages measured with DSB2.
The DSB power supplies are checked by the cross-check between the DSB.
Depending on the error type the EM-channel is switched off after one or several occurrences of the error, which will ensure a high robustness against e.g. electromagnetic disturbances and therefore incorrect detection of errors.

Sequence of events in case of errors within an EM-channel

1. Recognition of the error within the EM-channel via local HCA error detection.
2. Deactivation sequence of the defective EM-channel.
3. Supported structure begins to change its position and velocity due to the reduced number of active EM-channels.
4. Recognition of position and velocity-change of the levitated structure by all functional EM-channels via their local distance sensors[3].
5. Reaction by the digital controllers within each EM-channel to correct the position of the levitated structure.
6. Hot-swap of the defective sub-assemblies of the defective EM-channel.
7. Soft start of the new EM-channel/HCA.
8. Operation with supreme reliability is restored.

[3] Simulation results in [19] show that after one EM-channel out of six fails, even during application of heavy disturbance forces a maximum rotor deviation at the AMB-position of about 40µm can be observed, which is completely compensated within 10ms.

EM-channel deactivation

Within all functional blocks independent deactivation means for the EM-channel are implemented:

- High power supply:
  - Manual HCA power switch,
  - mains fuses,
  - opto-relay,
  - soft-start-transistor (if only a very small current can be drawn from the mains supply in the off-state, resulting in DC link voltage of the switching amplifier near zero volt).
- CED power supply:
  - Watchdog switches off the DSB on occurrence of an error.
- Switching amplifier:
  - Switching transistors (tested during operation).
- DSB:
  - Deactivation of the switching amplifier possible by both DSB.

The different principles of operation have been chosen to ensure a safe decoupling even in case of severe EM-channel faults.

CONCLUSIONS AND OUTLOOK

This work describes an active magnetic bearing (AMB)-system offering supreme reliability over the whole operation time and the perpetuation of the bearing capacity even in case of a defect within any sub-assembly.
Within this paper advantages and drawbacks of reliable systems presented in literature were investigated and compared to the new AMB-system with supreme reliability. A hot swap controller amplifier module (HCA) is described and details on the system functionality during startup, errors within an EM-channel, deactivation of sub-assemblies and the hot-swap are given.
To analyze the behaviour of this new active magnetic bearing-system at normal working conditions, when disturbance forces occur, during EM-channel failures and during the hot-swap of an HCA, an AMB rotor test-rig is currently under construction. It comprises a rotor driven by an electric motor. One rotor side is supported by an AMB with supreme reliability, the other side by a conventional bearing.

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