Complex and Integrated Methods for the Reliability Analysis of Contactless Magnetic Bearings

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Abstract

In many fields of energy technology the proof of reliability is required for the application of magnetic bearings. The application of active magnetic bearings in turbo machines for power plants is characterized by extreme process and environmental conditions. The parameters variegate due to manufacturing tolerances and the influence of specific operation and load conditions of the control loop components of a magnetic bearing. That involves a load-dependent reliability of the bearing components. Therefore an active magnetic bearing which is under nominal conditions in terms of its function, may fail due to drifts of mechanical, electrical and magnetic parameters.

The objective of this project is the reliability analysis of active magnetic bearings considering their nonlinearities. The analysis will be carried out by means of appropriate methods which consider the specific fuzzy parameters compared to conventional approaches. The part failure probability of the several components will be determined by Monte-Carlo-Simulations. The failure probability of the whole system will be summarized by use of a fault tree analysis. Whether any components have to be integrated redundantly/diversely will be determined in the early design process.

1 Motivation

Active magnetic bearings (AMB) are an essential key technology in modern power plant concepts. Due to their advantages like lubricant-free and low-wear operation, the influence of damping and stiffness during operation and high efficiency AMBs are increasingly integrated into safety-related systems, especially in turbo machines (cooling pumps, steam turbines and compressors) of nuclear power plants.

Practical experiences gained during start-up of a cooling pump with magnetic bearings in a power plant showed, that an AMB-system in working order may fail under real power plant conditions (mainly high environmental temperatures) despite a careful execution of the design algorithm. Related to the specific case, the environmental temperatures of power electronics were higher than the design specifications. The result was a premature failure of power electronics due to a response of the thermal protection of the power amplifiers. Moreover, the axial thrust of the pump for individual operation conditions was 5–6 times higher than the value in the load specifications which was an experienced value provided by the cooperating pump manufacturer.

The qualitative and quantitative assessment of reliability is a necessary condition for the approval and use of AMB in safety-related systems. During des AMB design process it must be checked how the AMB system fulfills his system purpose in compliance with process uncertainties and nonlinearities of its components.

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Active Magnetic bearings in Power Plant Technology

An AMB considered as a mechatronic system consists of mechanical, electrical and electronic components and, if required, software. The application of magnetic bearings in turbo-machines of power plant technology is marked by high process and environmental temperatures and also by high mechanical stress caused by massive rotors. The bearing components have various failure mechanisms, whose restriction limits lead to operating point-depending reliability of the subcomponents and thus of the magnetic bearing system.

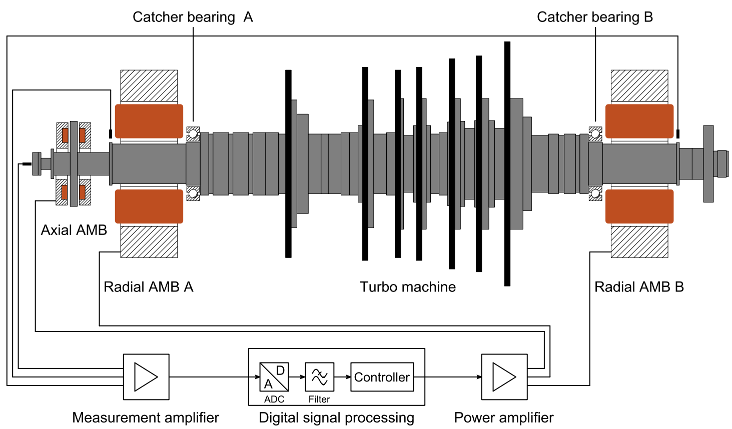

Figure 1: Machine completely supported by magnetic bearings

AMB-Design for Power Plant Machinery Based on Nominal Values

Presently, the design of active magnetic bearings is based on nominal values. Nominal value design is used to parameterize an AMB which is supposed to provide the essential lifting capacity assuming that the components behave optimal. In practice, however, the required input parameters and loads can often only be estimated. The main cause for this fact is the lack of information due to missing measuring data or the lack of knowledge about the process. Particularly in terms of turbo machinery, in power plant technology do exist corresponding uncertainties. The flowing medium – fluid or gas – can basically turn from a laminar flow into a turbulent flow with mechanical loads that are hardly or unpredictable for the machine.

The uncertainties in designing AMB, resulting from tolerances and drifts from the manufacturing process or from thermal influences are discretized with safety factors.

Main objective

Subsequently, methods and procedures on modelling and simulating the reliability of machines with magnetic bearings will be described. They are supposed to add qualitative and quantitative reliability evaluation to the design of magnetic bearings. Furthermore, the goal is to evaluate the reliability of the machine with magnetic bearings using online condition diagnosis. This procedure shall enable to detect and avoid damage escalations early and shall also allow condition-oriented maintenance of high-performance machines with magnetic bearings in the power plant.

2 Modelling and Simulating Nominal Values

Physical sub-models form the basis for reliability simulations considering component-specific non-linearities. Bearing dynamics are simulated numerically for

- rotor
- electromagnetic actuator
- electrical cable
- power amplifier
- position controller
- position sensor

by the use of model equations.

Modelling and Simulating a Electromagnetic Actuator

The impact of nonlinearities of electromagnetic actuators is considered by electrical, thermal and magnetic sub-models which are interconnected in networks in accordance with magnet geometry. Energy and power flows arising during operation are balanced under consideration of environmental and process impacts. Load-dependent self-heating of the windings and the laminated core leads to thermal stress. The electro-magnet may fail, if i.e. the insulation temperatures exceed the defined limitation.

The basic modelling process of electrical and thermal behavior is depicted by the example of an 8-pole radial bearing in UI-arrangement (Figure 2). To simplify the modelling-process, the rough

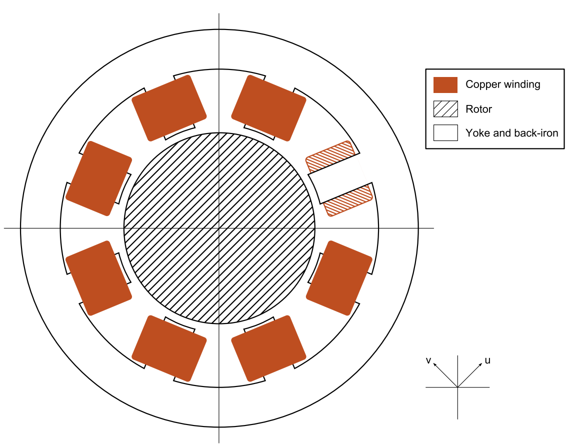

Figure 2: Radial electromagnetic actuator

structure (radial magnet) is decomposed into n- fine structures (winding, yoke) while systematic and geometric symmetries are used.

Electrical Behavior

To model the electrical behavior, a coil is considered in an idealized way as a series connection (Figure 3) of an ohmic resistor R and of inductivity L. The coil current i is calculated using the

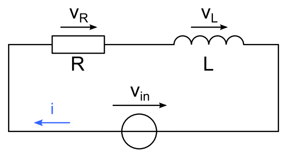

Figure 3: Coil -– electrical equivalent circuit

Kirchhoff mesh rule:

$$i = \frac{1}{L} \cdot \int_0^T (v_{in} - i \cdot R)\, dt \tag{1}$$

Inductivity L:

$$L = \frac{N^2 \cdot A_{Fe} \cdot \mu_0}{\frac{l_{Fe}}{\mu_r} + 2 \cdot s_0} \tag{2}$$

Temperature-dependent resistor R of the copper winding:

$$R = R_{20} \cdot (1 + \alpha_{Cu} \cdot \Delta T) \tag{3}$$

with

$$\Delta T = T_0 - 20\,^{\circ}\mathrm{C} \tag{4}$$

Table 1 identifies interface parameters for the sub-model of an electromagnet. Figure 4 shows a

Parameter	Meaning
v_{in}	Terminal voltage
N	Number of windings
A_{Fe}	Surface of magnetic pole
μ_0	Permeability of vacuum
μ_r	Relative permeability
l_{Fe}	Length of magnetic flux line in iron
s_0	Nominal airgap
R_{20}	Ohmic resistor of coil winding at 20 °C
α_{Cu}	Linear temperature coefficient of copper

Table 1: Coil -– electromagnetic interface parameters

family of curves of the temperature-dependent coil current in the range from 20 °C to 120 °C.

Thermal behavior

To develop the thermal model equations, thermal equivalent circuits [1] for coil winding and a yoke are derived from the electromagnetic design of the radial magnet. The equivalent circuit (Figure 5) consists of a thermal source, sink, accumulator and a thermal resistor which are interconnected in a

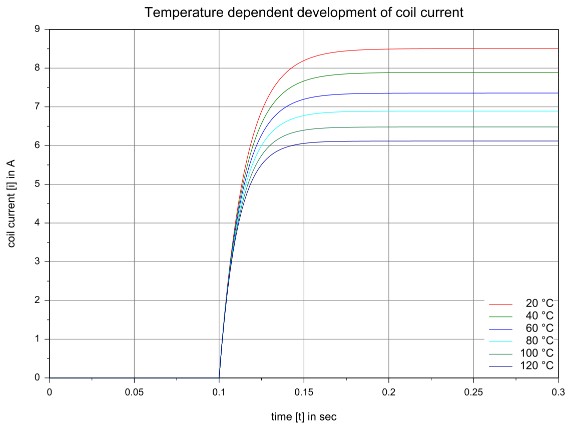

Figure 4: Temperature-dependent course of the coil current

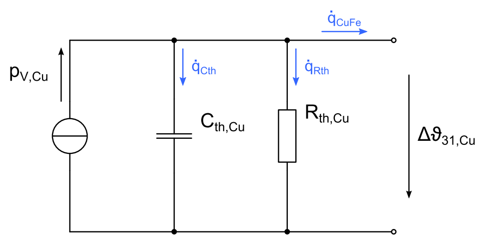

Figure 5: Thermal equivalent circuit of a copper winding

network.

Thermal capacity:

$$C_{th,Cu} = m_{Cu} \cdot c_{Cu} \tag{5}$$

Generally, the heat flow results in:

$$\dot{q} = \frac{\Delta\vartheta_{31}}{R_{th}} \tag{6}$$

By the aid of Kirchhoff's laws the following capacity balance is developed for the copper winding:

$$p_{V,Cu} = \dot{q}_{Cth} + \dot{q}_{Rth} + \dot{q}_{CuFe} \tag{7}$$

The numerical simulation of the differential equation of 1st order results in a functional overtemperature $\Delta\vartheta_{31}$ course of the copper winding. Under consideration of process and environmental temperatures T_A in the range of the electromagnetic actuator an absolute temperature T_0 is obtained.

$$T_0 = \Delta\vartheta_{31} + T_A \tag{8}$$

The considerations for the copper winding are assigned to the yoke analogously. Table 2 summarizes the parameters of the thermal interfaces. Copper winding and yoke form a parallel circuit regarding

Parameter	Meaning
m	Mass of copper, iron
c	Specific thermal capacity
R_{th}	Thermal resistor
$\Delta\vartheta_{31}$	Overtemperature of a body
T_A	Ambient temperature of process, environment

Table 2: Coil -– Thermal interface parameters

the resulting heat flow $\dot{q}$. Heat is transferred between them. The potential difference, i.e. the difference between the overtemperatures $\Delta\vartheta_{31}$ determines the direction of the heat transfer.

The parallel circuit of 8 electromagnets (Figure 6), consisting of a yoke and a copper winding forms the thermal equivalent circuit of radial bearing magnets. $k^2 - k$ heat flows between the k poles

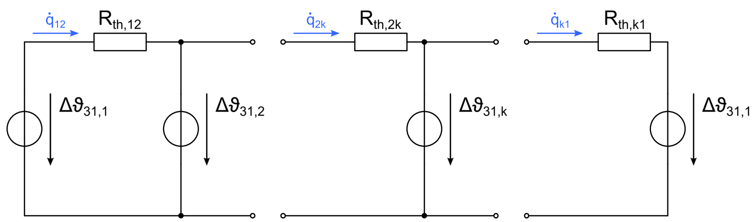

Figure 6: Thermal equivalent circuit of the yoke rear

over the yoke rear from high-temperature areas (sources) to low-temperature areas (sinks).

For the partial heat flows $\dot{q}_{12}$ and $\dot{q}_{21}$ is defined:

$$\dot{q}_{12} = \frac{\Delta\vartheta_{31,1} - \Delta\vartheta_{31,2}}{R_{th,12}} \tag{9}$$

$$\dot{q}_{21} = \frac{\Delta\vartheta_{31,2} - \Delta\vartheta_{31,1}}{R_{th,21}} \tag{10}$$

Determination of the heat flow balance $\underline{\dot{q}}$ in the yoke with:

$$\underline{\dot{q}} = \left(\underline{\vartheta}^T - \underline{\vartheta}\right) \cdot \underline{G}_{th}^T - \left(\underline{\vartheta} - \underline{\vartheta}^T\right) \cdot \underline{G}_{th} \tag{11}$$

Figure 7 shows an example of the temperature courses for two copper windings. Over winding 1 a power loss was implemented to the system. Through the heat conduction of the yoke the heat flux flows to winding 2, whose temperature rises. It shows PT2-behavior.

Conclusion

The utilization of symmetries allowed the development of sub-models for the simulation of the electrical and thermal behavior of an electromagnetic actuator. The connection in appropriate and coupled networks the capacity and energy flows can be balanced. The load and temperature dependent power losses in the copper windings are considered.

Thus, the designed complex physical electromagnet model forms the basis for reliability simulation. On the one hand temperature values resulting from the simulation of thermal behavior in temperature-dependent coil parameters are considered. Moreover, in line with reliability analyses,

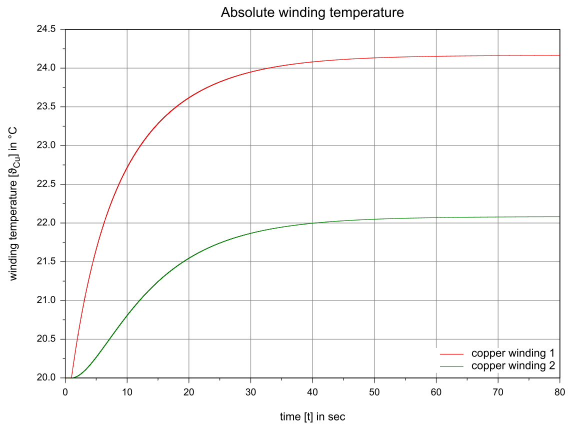

Figure 7: Absolute winding temperature

the winding and yoke temperatures are analyzed as restriction values (limiting value is specified by the class of insulation). The input vectors of complex sub-models are parameterized within the framework of probabilistic simulations (Chapter 3) via specific interfaces.

Similar considerations and methods are carried out for all other subcomponents of a magnet bearing control circuit (sensor, controller, power amplifier, rotor, power supply, electrical cables).

3 Probabilistic Simulations

Due to the described partial lack of information physical models can be parameterized only incompletely. Contrary to nominal value simulation (Chapter 2) working with certain values, mathematical models are used in line with probabilistic simulations to neutralize the lack of information.

Consideration of Uncertainties in Input Vectors

To the parameters are allocated equally or normally distributed random values or values following the rules of fuzzy logic. The probabilistic uncertainty of a physical parameter [2] can be described by its expected value

$$\bar{x} = \frac{1}{N}\sum_{i=1}^{N} x_i, \tag{12}$$

its variance

$$\sigma^2 = \frac{1}{N-1}\sum_{i=1}^{N}(x_i - \bar{x})^2 \tag{13}$$

and by its empiric standard deviation σ. Table 3 shows as an example the consideration of technical parameter values with uncertainty compared to nominal value depiction: The parameterization of interface parameters with fuzzy values i.e. the scattering in input vectors leads to scattered system responses.

Parameter	$\bar{x}$	σ
T_A	40 °C	±10 °C
l_{Fe}	100,0 mm	±0,2 mm

Table 3: Technical parameters with uncertainty

Monte-Carlo-Simulation

The system responses are determined with *Monte-Carlo*-Simulation which generates a control sample n_{sample} having the extent of the corresponding parameter or a combination of several parameters. The state space of the dynamic AMB-system is sampled. The *system state* is defined as a time-dependent combination of all variables in the system structure.

In *Monte-Carlo*-Simulation the following phases have to be passed:

- determination of specific parameter values by application of mathematical models (preprocessor)
- value allocation to the input vector of the discrete sub-models (parameterization)
- calling up the physical complex model (simulation)
- receipt of the system response
- statistic evaluation within the framework of reliability analysis, if necessary (postprocessor)

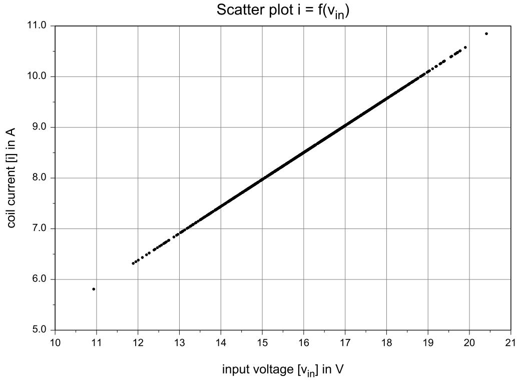

Figure 8: Scatter plot $i = f(v_{in})$

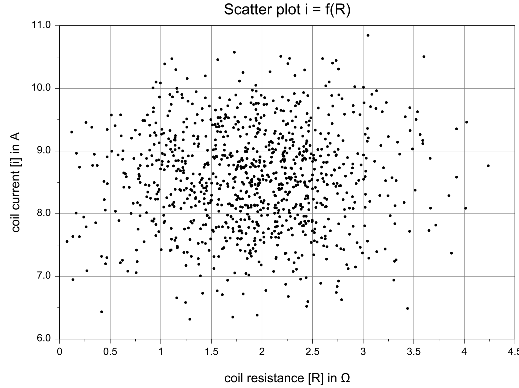

Figure 9: Scatter plot $i = f(R)$

As one essential result of the *Monte-Carlo*-Simulation the exemplary scatter plots in Figure 8 and Figure 9 show the correlation between different parameters after sampling the state space. Implementing actions concerning stabilizing the ohmic coil resistance are not necessary. In contrast, the coil voltage has to be stabilized very well because of influencing of the magnetic force. The demand for a reliable magnetic bearing could be, for example, a redundant design of the position controller and/or redundant/diverse power supply. In addition, the fault tree analysis provides further results.

4 Reliability Analysis

The resulting values of probabilistic simulation are analyzed statistically in line with reliability analysis.

Reliability according to Standard DIN 40041

According to the reliability definition of standard DIN 40041 [3], the gained data series is used to assess the functionality degree of subcomponents and of the overall system under consideration of the fundamental operating and controlling scenario.

Therefore, the reliability-relevant restriction limits, like coil current i, magnetic force F_m or winding and yoke temperature ϑ are determined from the system response. Parallel to that, specific parameter restriction limits must be determined using data specifications, standards and instructions. In this context should be pointed for example to the maximum temperature of winding and metal insulation. For insulation class F it is 155 °C. Another important restriction limit for the electromagnetic actuator is the maximum permitted coil current. Both limitation values are reliability-relevant values in terms of overtemperature protection and overcurrent protection. Magnet force helps to evaluate the efficiency of AMB regarding mechanical stress.

After selecting the restriction variables the corresponding data series are investigated for violation of their limit values. The number of violation events within one control sample is counted. If for a specific violation event is defined

$$n_{error} > 0, \tag{14}$$

then a partial failure probability with regard to the restriction value can be determined

$$P_A = \frac{n_{error}}{n_{sample}} \tag{15}$$

under consideration of the control sample amount.

With

$$R_A = 1 - P_A \tag{16}$$

the corresponding probability of survival is determined. In fault trees by means of Boolean algebra, the partial failure probabilities of the control loop components are summarized (Chapter 5) to a failure probability of the AMB-overall system.

5 Fault Tree Analysis

In fault trees, the results of reliability analysis, partial failure probability or partial probability of survival are summarized to failure probabilities or probability of survival of the overall system. The requirement for fault tree application (sufficiently precise knowledge of the system structure) is fulfilled for AMB. This deductive method according to standard DIN 25424 [4] summarizes all fault paths starting with the fault event (AMB Failure) up to the triggering primary events.

For the conjunction (AND) of two partial failure probabilities P_1 and P_2 the failure probability results in:

$$P_A = P_1 \cdot P_2 \tag{17}$$

For a disjunctive combination (OR) of two partial failure probabilities is defined:

$$P_A = 1 - (1 - P_1) \cdot (1 - P_2) \tag{18}$$

Electromagnetic Actuator

Related to the electromagnetic actuator, two failure mechanisms are currently described which may occur during operation. Its efficiency is reduced or missing if

- magnetic force is outside of the required working point in the force-current-path characteristic field, depending from air gap and coil current or
- temperature of the electromagnet rises above 155 °C (Insulation class F).

While temperature is a variable limited to only one side, the magnetic force is a variable limited to both sides. If the temperature of the electromagnet rises above the accepted temperature limit, the electrical insulation system would be destroyed. The result is a winding, wrapping or iron short circuit.

Correspondingly to the force at the rotor, a magnetic force must be impressed in that way that it remains in a stable (quasi-stationary) state. This force adapts itself over the coil current and the air gap between the rotor and the stator according to the force-current-path characteristic field. If the actual magnetic force is higher or lower than the mechanical force to be compensated at the rotor, the rotor would destabilize. Figure 10 concludes the verbal description of the failure mechanisms logically in a fault tree. If at least one primary event happens, then the current efficiency of the

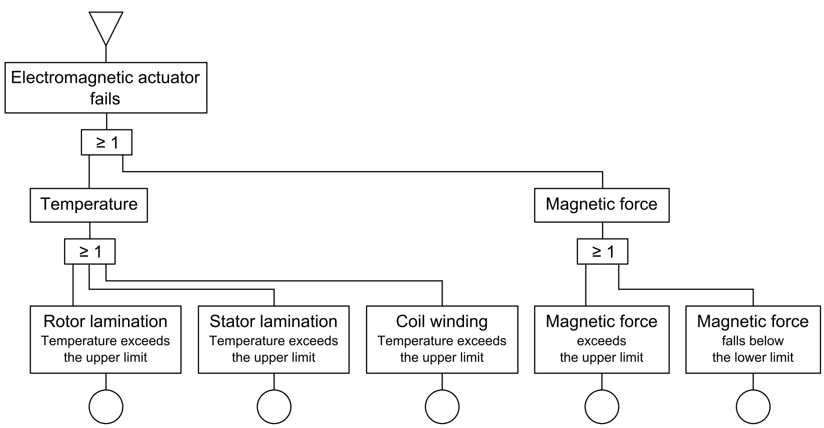

Figure 10: Fault tree of an electromagnetic actuator

electromagnet does not meet the efficiency requirements. The subcomponent fails.

Electrical Cable

For the electrical cable only one safety-relevant failure mechanism is described which leads to a failure of the magnetic bearing system during operation. Due to a comparably high current load of the electrical cable between power amplifier and bearing coil, the cable can heat up strongly depending on environmental temperatures. Installation situations often lead to reduced heat removal by natural convection along the cable jacket. Figure 11 depicts the verbal description of the failure mechanism in a partial fault tree.

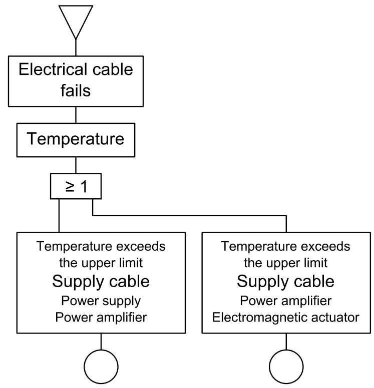

Figure 11: Fault tree of an electrical cable

Power Amplifier

The failure probability for the electromagnetic actuator and the electrical cable can be calculated by means of physical models. The reason is the relatively simple and thus well resolvable design of the subcomponents. These are robust electromagnetic components whose efficiency is determined only by thermal (temperature) and electrical load (current).

At the power amplifier (PA), however, this approach cannot be applied exclusively. It consists of two component groups for which two different approaches for failure probabilities evaluation must be selected. On the one hand, the dynamic behavior of the power semiconductor devices can be modelled sufficiently exact by means of physical models. On the other the PA contains other electronic components which are mainly for controlling and actuating the power semiconductor device. Seamlessly integrated components or component groups are here applied (e.g. MOSFET-driver). These are electronic circuits of whose inner structure information is lacking. Therefore, approaches for calculating the reliability as a function of component quantity, type of component, etc. must be selected. However, these have not been investigated in line with this project yet. In the partial fault tree of the power amplifier the failure of the electronic circuit is an *undeveloped event*.

For power amplifiers are currently described three failure mechanisms, which may occur during operation. Its efficiency is reduced or missing if

- an overcurrent is detecting,
- junction temperatures within the power semiconductor device rise over 125 °C
- control electronics/power supply fails or
- environmental temperature exceeds a temperature limit

An output stage (controllable current source) may on the one hand provide a short-term peak current and on the other hand a continuous nominal current. Contrary to unipolar output stages bipolar DC-DC converters may provide currents with negative algebraic sign. An overcurrent is detected, if the absolute value of instantaneous current is higher than the current limit value. Another failure mechanism describes how the power transistor or power diode is shorted out. Thermal overload destroys the junction within the semiconductors irreversibly. The system function of the semiconductor is not provided anymore. The power amplifier fails also, if peripheral electronics, e.g. MOSFET-output stages and power supply (switch power supply) on the board fail.

Figure 12 summarizes the verbal description of failure mechanisms logically in a fault tree. If at

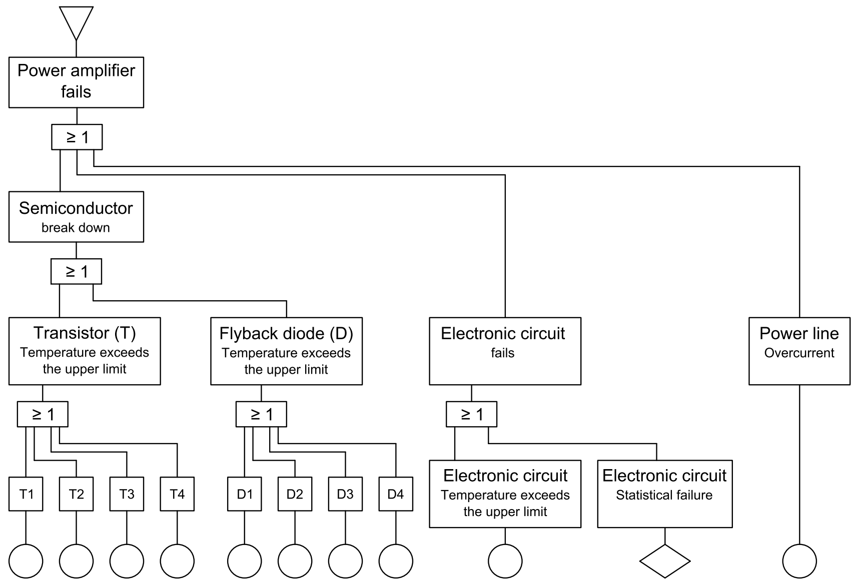

Figure 12: Fault tree of a power amplifier

least one primary event happens, the current efficiency of the amplifier will not meet the efficiency requirements. The subcomponent fails.

Position controller

The magnetic bearing component *position control* (digital controller) is a mechatronic system consisting of an electronic circuit (digital signal control, voltage supply, hardware interfaces) and software (if necessary operating system, user source code). The user source code implements the necessary structure for position control of the rotor (filter, control, general control). Currently, four failure mechanisms are described which lead to reduced efficiency of the subcomponent. Thus, the system fails if

- environmental temperature exceeds temperature limit,
- electronics fail,
- error in program processing due to faulty software (run time error, logical/semantic errors) leads to a freeze or a crash of the program or
- faulty/non-optimal sets of parameters destabilize the control.

The applied process computers including all essential hardware interfaces are seamlessly integrated components. Their partial reliability is not a function of the working point. If, however, an acceptable temperature limit is exceeded, the efficiency will be reduced.

Another failure mechanism describes the partial reliability regarding program execution on the microprocessor. Logical errors within the software (e.g. switching of parameter sets) lead to unpredictable behavior of the digital control. Moreover, numerous hardware interfaces (memory, analog-to-digital converter, digital-to-analog-converter, RS-485) require compliance with essential latency times. Mainly in connection with memory access, the violation of this restriction leads to a program crash. This failure mechanism, also, is not a function in the working point of active magnetic bearings.

Typically, PID-controllers are used in position control loops. They compensate the time constant of the extended control path which consists of power amplifier, bearing coil and rotor. The advantage of the linear controller is that it can easily be parameterized for a working point and by evaluation of the frequency response of the open position control loop. The disadvantage is that an active magnetic bearing is a nonlinear extended control path. However, to make the application of this controller possible, the control path at the working point must be set linear. As known from experience, the determined set of parameters is optimal for rotor deflection with about $\pm 5\,\%$ around its specified position.

Parameter drifts reduce the stability of the position control loop in the extended control path. The destabilization of the control loop is failure-relevant. It may cause a rotor touch down into the catcher bearings. The basis for stability evaluation is the frequency response (amplitude and phase response) of the open control loop. The phase response is used to check, whether the phase margin is positive at the gain crossover frequency (amplitude response). If the condition is breached, the closed control loop gets instable. Oscillations do appear because of positive feedback. Furthermore, the gain crossover frequency is used to evaluate the efficiency of the controller in terms of disturbance frequencies.

Figure 13 shows the failure mechanisms logically connected in the corresponding partial fault tree.

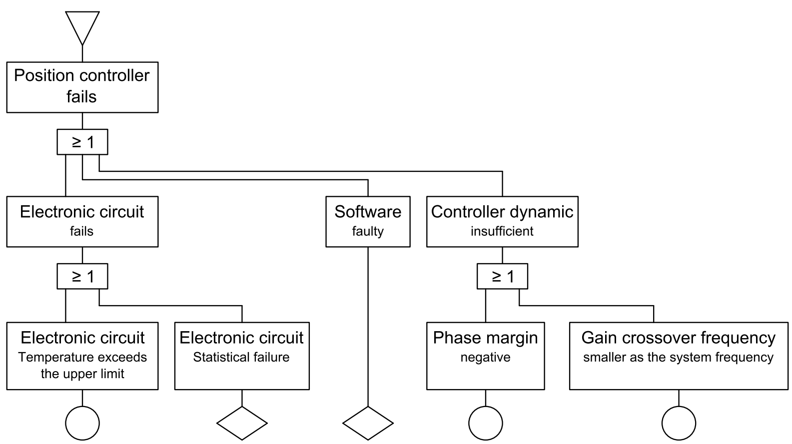

Figure 13: Fault tree of the position controller

Position sensor

Position sensors are seamlessly integrated components consisting of a sensor head and an associated conditioning unit. Partial reliability is assessed workingpoint-independent but under consideration of a temperature limit. Thus, two failure mechanisms are described for the position sensor, which may appear during operation. Its efficiency is reduced or absent if

- the environmental temperature exceeds a temperature limit at the place of observation or
- electronics fail.

Figure 14 depicts the failure mechanisms logically connected in the corresponding partial fault tree.

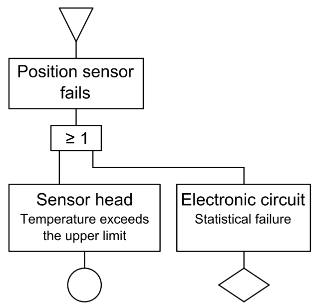

Figure 14: Fault tree of a position sensor

Power Supply

Data of the power plant or network operator are used for quantitative reliability assessment of the power supply including distribution network. Figure 15 shows the failure mechanism — low voltage or voltage breakdown -– in a partial fault tree.

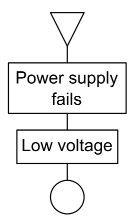

Figure 15: Fault tree of power supply

Fault Tree

Experiences show that we basically speak of AMB-failure if at least one magnetic bearing control loop of the machine fails. The series arrangement of control loop subcomponents results only in disjunctive connections of the subcomponents within the fault tree (Figure 16), if no redundancies/-diversities are intended.

Figure 16 shows the fault tree for a machine with complete magnetic bearings. Corresponding to the magnetic bearing topology the partial fault trees Figure 10 to Figure 15 are summarized to an overall fault tree.

Conclusion

Function prototypes (electromagnet, cable, power amplifier, ...) are designed for subcomponents, which summarize the entirety of their specific failure mechanisms and their partial failure probabilities under application of Boolean algebra. For the planned topology of control and power circuits function prototypes are connected logically which result in topology-specific fault trees.

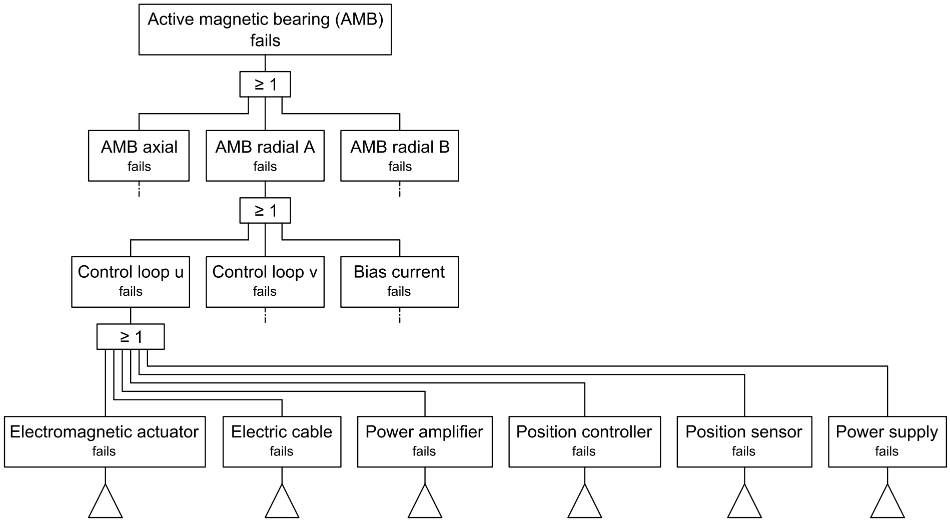

Figure 16: Section of the AMB fault tree

6 Summary

By means of the methods presented, subcomponents of active magnetic bearings are modelled under consideration of their specific nonlinearities. For each subcomponent, the input vector is specified, failure mechanisms are defined and restriction limits are derived. The methodology intends to parameterize the input vectors of discrete sub-models in line with Monte-Carlo-Simulation with uncertain values and to simulate the overall system. The scattering in the input vector causes the scattering of technical parameters in the system response. The gained system response consisting of data series of restriction variables is analyzed for reliability. Moreover will be checked how often the determined limit values of physical parameters were violated. This will be a measure for partial failure probability under consideration of the control sample amount. By the use of Boolean algebra and with the help of fault trees partial failure probabilities are summarized to a failure probability of AMB.

The approach presented allows the future evaluation of reliability for a selected magnetic bearing topology during the design process. Uncertainties in technical parameters which can be traced back to a fundamental lack of information are considered during the design process. By means of the results, statements on essential redundancies are derived. The interfaces of physical models can be supplied with measuring values. The algorithms implemented into a magnetic bearing diagnostic system allow the evaluation of system reliability within the framework of online condition diagnosis.

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