ACTIVE MAGNETIC BEARINGS AND MOTOR DRIVE TOWARDS INTEGRATION

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ABSTRACT

This paper presents the motivation for the integration of active magnetic bearings (AMBs) and motor drive and describes a specific integration approach. The latter is reached on the electronics hardware and control software side rather than on the electromechanical component (actuator) side. This allows for dealing with the often conflicting physical requirements for high power motor drive on the one side and low power AMB on the other side. The paper gives a short overview over novel technological developments mandatory for such integration and presents the resulting overall system design concept. Examples of systems realized on the basis of the chosen concept underline the suitability and technical feasibility of the approach.

INTRODUCTION

For a long time considered complex, costly and commercially ineffective, active magnetic bearings have lately proven their effectiveness, reliability and competitiveness in industry, where the number of AMB applications is rapidly growing. From today's perspective this success can mainly be attributed to the fact that AMBs show a number of important advantages over conventional bearing technologies, such as lubricant- and contamination-free operation, suitability for high speed and high performance applications and inherently built-in instrumentation facilities for system monitoring.

This development has, in parallel, also called for a high performance motor drive technology, especially in the fields of turbo machinery and energy generation. While AMB and motor drive technologies have been treated separately in the past, there is now a clear need for integration in order to achieve both technical and economical benefits.

State of the Art AMB System Setup

Today's industrial AMB applications most often feature an overall system setup as outlined in figure 1.

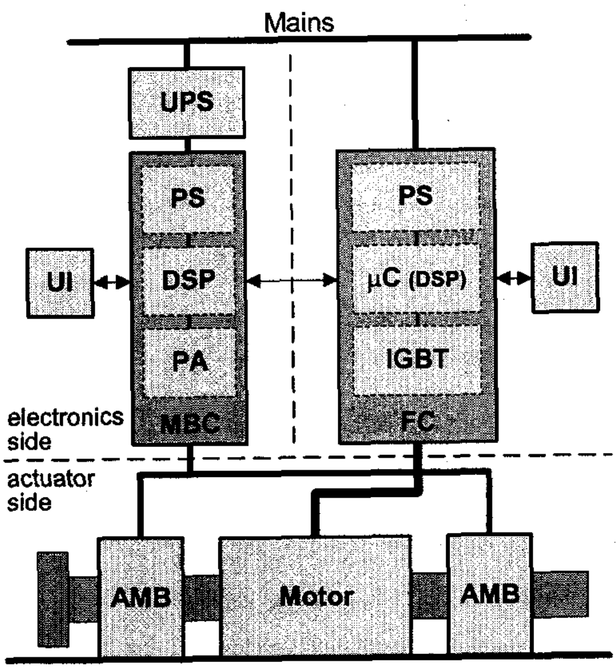

FIGURE 1: Standard AMB/motor setup

Bearings and motor are controlled by two separate units, the magnetic bearing controller (MBC) and the frequency converter (FC). Both drive units feature a micro controller (μC) or a signal processor (DSP) as central units which are able to communicate with each other (digital I/O, field bus, etc.) and with their corresponding user interfaces (UI). Furthermore, each control unit comprises the necessary power stages, the power amplifier (PA) for the AMB and the motor power switches (IGBT) respectively. The two systems are fed by two independent power supplies (PS). Finally, the power supply of the MBC is backed up by an uninterruptible power source (UPS) that guarantees stable AMB operation in case of a mains failure.

Integration Requirements

The technical and economical requirements for the integration of AMB and motor drive can be summarized as follows:

- compact and cost-effective design
- high level of reliability
- ease of operation
- reduced maintenance complexity
- high networking and system monitoring capability
- independent physical scaling of AMB and motor drive for high application flexibility
- elimination of auxiliary units such as an uninterruptible power supply (UPS), etc.

System Setup for Integrated AMB and Motor Drive

The system setup presented in figure 1 cannot be considered cost-effective due to its hardware complexity caused by the independent controllers for AMB and motor. Moreover, overall system reliability can also be degraded by the number of cables and connectors necessary to link the two separate controllers.

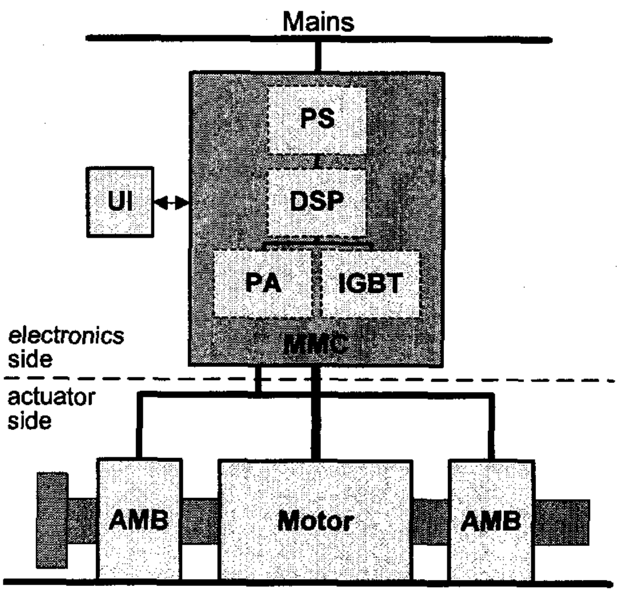

FIGURE 2: Integrated AMB/motor drive setup

In figure 2 an alternative concept is presented which promises a technically and economically more effective system. Here, the magnetic bearing and motor controllers are merged into one control unit (MMC) featuring one single DSP carrying out both AMB and motor drive control functions. Moreover, surplus power supplies, user interfaces and, most important, the uninterruptible power supply are eliminated. The UPS, in particular, is replaced by a purely software-based feature of the motor control: the generator-mode which covers the entire functionality of the former UPS without any need for additional hardware. Due to this important reduction of hardware complexity (number of components, amount of cabling) not only costs are reduced but also system reliability is increased.

It is important to stress the fact that such system integration - from the author's point of view - does not simply involve a common packaging (one controller box instead of two) of AMB and motor drive electronics without further advantage. True system integration must lead to a complete "marriage" of the hitherto separated systems in terms of common DC bus, common control software running on one single DSP, common system monitoring and supervision, common user interface, etc.

Finally, it must be noted that "off the shelf" frequency converters, as requested by many AMB applications, are presently hard to find on the market, with the respective consequences on the cost side. This is mainly due to the fact the most available high power FCs operate at relatively low frequencies, whereas AMBs are typically used for high speed applications. This fact leads to the assessment that today's AMB manufacturers are better off developing their own and - naturally integrated - motor frequency converters.

New Technological Developments

For state of the art AMB systems, digital control technology has proven to be the only suitable way to achieve the required system flexibility and reliability. This fact turns out to hold for the motor drive as well.

Here, the latest developments in microprocessor and especially in digital signal processor (DSP) technology have paved the way for such integration, since these single chip devices not only feature the needed computation power but, newly, also the peripherals and micro controller capabilities necessary for field oriented PWM motor drive control. These new DSP capabilities are:

- various independent hardware timers and corresponding interrupt levels
- PWM drivers
- fast on-chip A/D converters
- sufficient on-chip memory (RAM and ROM)
- field bus interface

Apart from the advanced DSP technology, the latest achievements in power electronics allow for electronic circuit designs integrating both AMB drivers and high power switches for motor control in a very compact way. Typically, such designs combine the highly compact and thermally optimal SMD technology for AMB control with the latest IGBT technology for high performance motor drive control, thus, leading to a substantially raised level of power density and reliability [1].

CONCEPTUAL SYSTEM DESIGN

The AMB and motor drive integration concept dealt with in this paper is based on a development experience dating back to as early as 1994, when first suitable micro controllers became available [2]. Since then many improvements in terms of performance, efficiency and cost have been made.

It must be mentioned here that, unlike other on-going integration approaches such as the "self-bearing motor" technology [3][4], the present approach does not involve any integration on the actuator side, i.e. the magnetic bearing and the motor drive actuators remain physically separate and individually scalable components (see figure 2). This decision is motivated by the experience that actuator side integration can lead to performance trade-offs that cannot be tolerated in case of high performance applications with contradictory requirements for AMB and motor drive. Moreover, this approach guarantees a minimal design risk on the machine side.

Concept Overview

As mentioned above system integration involves a complete merge of components starting from the common power source and ending with a common user interface and control development environment which offers synergies for both AMB and motor drive control design. The following sub-sections address the individual steps necessary to achieve the complete system integration.

Power Source and Power Management. The integration of the power source involves different hardware design concepts which depend on the individual levels of power consumption of both AMB and motor.

Basically, three different types of power supply schemes can be distinguished:

- high power motor, low power AMB
- high power motor and AMB
- low power motor and AMB

The basic difference between the three power supply types is the DC bus voltage level. Applications requiring a relatively high motor power will typically feature different DC bus voltage levels for AMB and motor. Systems requiring low motor power or high dynamic AMB performance, however, will typically have identical DC bus voltages for both motor and AMB (see figure 3).

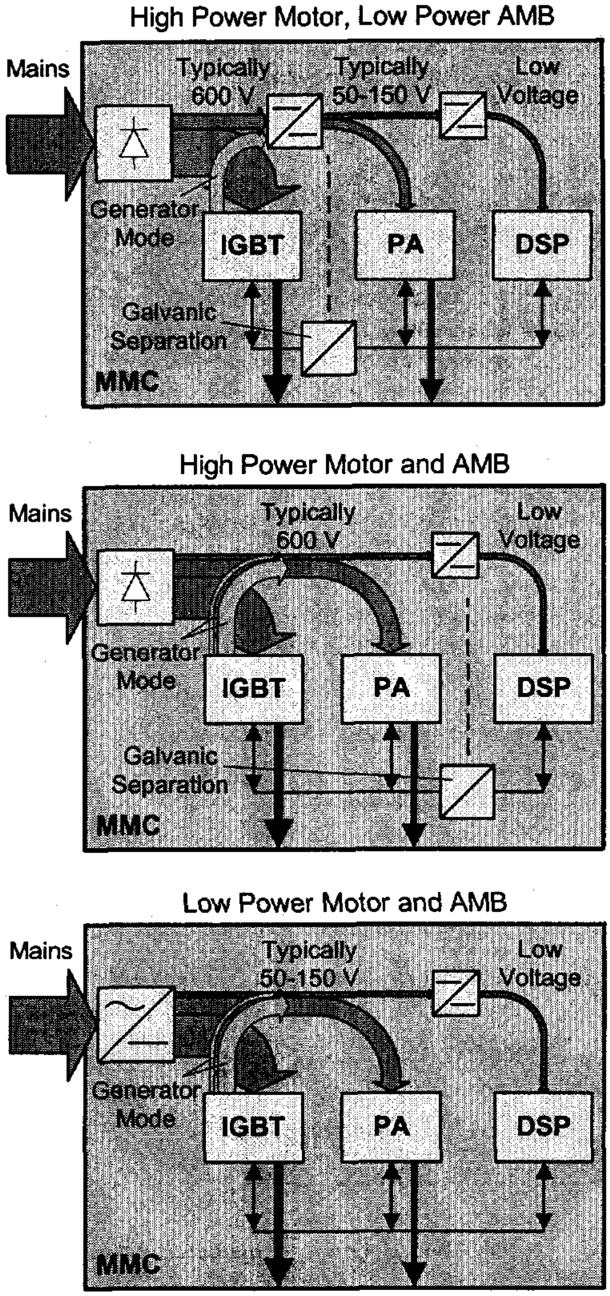

FIGURE 3: Power demand and power supply schemes

It is to be noted that, independently of the supply scheme to be chosen for a specific application, automatic generator mode is a built-in feature which allows to recover energy from the rotating machine in order to supply the AMB power amplifier and the controlling DSP in case of a mains failure. In generator mode, only as much energy is recovered as needed, hence, rotor deceleration can be minimized. It is important to state again that the generator mode feature does not require any additional hardware.

Finally, it must be recalled that the power demand of motor and AMB are fundamentally different by the fact that the major part of the motor demand is active power, whereas the AMB predominantly needs reactive power. It is understood that this difference is also reflected in the architecture of the corresponding power supply parts.

DSP System Architecture. As pointed out earlier, the present AMB and motor drive integration concept relies on the fact that a digital AMB control is already available and that the chosen DSP already offers all the surplus features needed for the additional motor control, i.e. for achieving a fully 6 DOF controlled system. This approach optimally takes advantage of a proven software architecture and creates substantial synergies, namely also by the available Matlab® based user interface which offers vast possibilities for control design and real-time monitoring of relevant physical quantities. That is to say that not only AMB but also motor quantities can be tracked and monitored on-line (e.g. phase currents, PWM output signals, voltage and power levels, etc.), which turns out to be of high importance for motor control optimization.

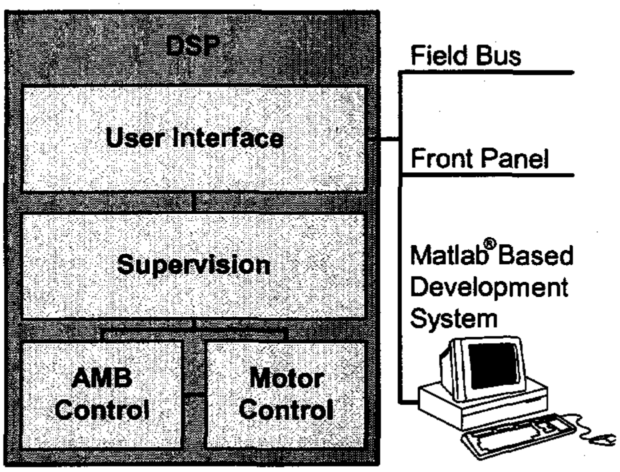

FIGURE 4: DSP system architecture

In figure 4, a schematic overview of the DSP system is given. The individual blocks comprise the following principal state-of-the-art software components:

AMB Control

- linear and non-linear control core
- unbalance force rejection control (UFRC)
- application specific control options
- digital and analog I/O
- automatic sensor calibration (no potentiometers)

Motor Control

- linear and non-linear field oriented control core
- resolver-less operation (no hall sensors needed for commutation)
- high frequency PWM output (typ. 20-40 kHz)
- sinusoidal phase current waveform for low harmonics and high efficiency
- freely adjustable rotor speed
- automatic generator mode
- field weakening control
- brake chopper control

Supervision and User Interface

- self check and fault diagnosis at startup
- continuous supervision of all relevant AMB and motor states
- configurable field bus interface (e.g. CAN bus)
- Matlab® based development system with built-in real-time signal access

Hardware Architecture. Compact and low-cost design, reliable operation and simple maintenance are the prevailing requirements that influence the hardware architecture of an integrated AMB/motor drive control unit. Particular attention must also be paid for the layout of the cooling system which essentially affects overall system reliability.

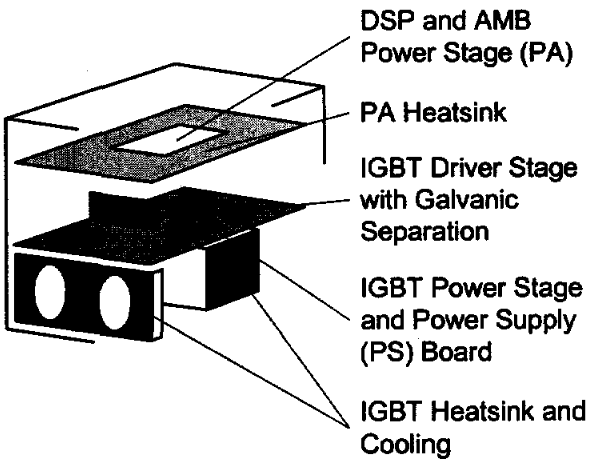

FIGURE 5: MMC hardware architecture overview

In figure 5, a schematic architectural overview of an existing and field-experienced integrated magnetic bearing and motor control unit is given. Technical data for this unit is listed in the next section.

APPLICATION EXAMPLES

The magnetic bearing and motor drive integration concept presented in this contribution has been realized in a number of various industrial applications with different requirements. Some of these units are already field-experienced, others are currently undergoing extensive testing.

To date, only brushless DC motor drives have been realized. The motor control software and hardware concept, however, allows for driving both asynchronous and synchronous motor types with minor changes.

In table 1 an overview of the systems realized to date is given[1]. It is important to stress the fact that all systems feature similar reactive AMB power but most different motor power levels. Moreover, the installed AMB power is only a fraction of the installed motor power (0.42%–10.5%), which is also reflected by the size relation of the corresponding actuators. Both properties are common to many AMB systems and underline the suitability of the chosen approach versus combining bearing and motor function in the same actuator. In this way full flexibility for independent scaling of the individual electromechanical components is maintained.

TABLE 1: Realized AMB/motor drive control units

	MMC 2A	MMC 15	MMC 100
motor power [kW]	2	15	100
reactive factor [cos φ]	0.8	0.82	0.8
reactive AMB power per channel [VA]	210	150	420
DC bus voltage motor [V]	140	600	600
DC bus voltage AMB [V]	140	100	140
rotational speed range [rpm]	1,000 - 80,000	1,000 - 80,000	1,000 - 80,000

1. MMC100 currently in prototype phase

Control Unit MMC2A

This unit has been tailored to a specific application with the guideline of reaching maximum possible compactness. It consists of 2 separate boards, the DSP board and the power board for both AMB and motor. The unit is capable of driving brushless DC motors up to a power of 2 kW providing sinusoidal motor phase currents without output voltage sine filter. Due to the relatively low DC bus voltage, FET power switches are more advantageous than IGBTs.

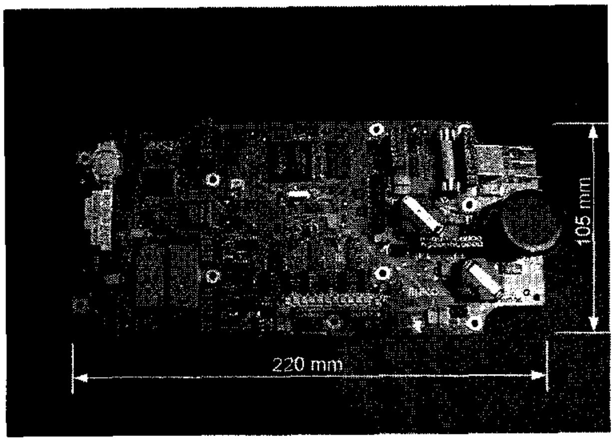

FIGURE 6: DSP board of the MMC2A control unit

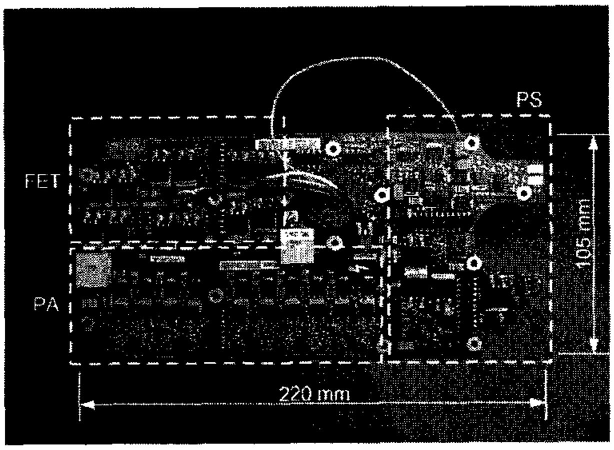

FIGURE 7: Power board of the MMC2A control unit

Control Unit MMC15

In contrast to the MMC2A, the MMC15 is a general purpose AMB/motor control unit for a wide field of applications. It provides a similar AMB power stage as the MMC2A. However, its motor power is considerably higher which also asks for a higher motor DC bus voltage level (see figure 3). In figure 8, a picture of a

MMC15 rack is shown which underlines the achieved high level of overall unit compactness.

FIGURE 8: *MMC15 AMB/motor control unit*

Control Unit MMC100

Currently this AMB/motor control unit is in its prototype phase. Test results and final design specifications can, therefore, not yet be presented.

SUMMARY AND OUTLOOK

AMB and motor drive integration is a technical and economical must for future magnetic bearing applications. Such integration is capable of closing the present gap that has formed due to the different backgrounds and diverting paths that these two technologies have followed throughout the history of their development. Moreover, it is a most convincing solution for those high performance applications where suitable "off the shelf" frequency converters are presently either hard to find on the market or not cost-effective enough for high volume production.

This contribution has presented the motivation and a possible concept for such an integration approach. Successful industrial implementations on the basis of the chosen concept have been shown.

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