Design of a Bearingless Canned Motor Pump

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Abstract: Motors of pumps used in aggressive environments have to be protected from the fluid. A common approach is to enclose both the rotor and the stator with a metallic can: a canned pump. In today's systems the rotor is held in position with slide bearings. In this paper an approach with magnetic bearings is described. The shaft of the rotor is thereby levitated magnetically with one conventional 3-phase AC bearing, a bearingless motor and a semiactive axial bearing. Positioning and field probes sense all through the metallic can; there is no direct contact between any sensor and the medium. The pump is of centrifugal design, rated 0.6 kW and delivering 60 l/min against a pressure of 16 bar. To supply the pump, conventional industrial switched power converters are used and controlled by a digital multiprocessor system. The application of the pump is planned in the pharmaceutical/chemical industry. A prototype was built to prove the principle of a bearingless canned motor pump.

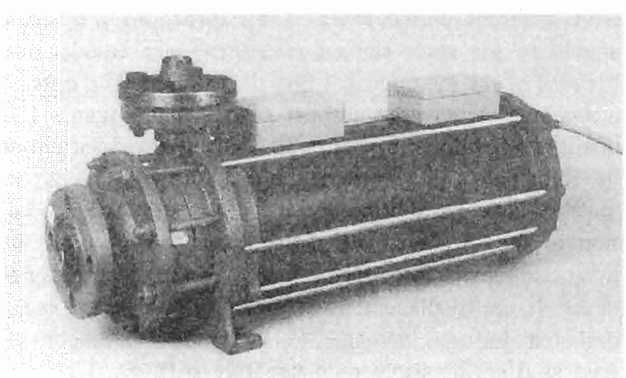

figure 1: *Bearingless Canned Pump*

1. Motivation

The chemical and pharmaceutical industry has a strong and increasing need for hermetic transportation and production systems. The objectives are to prevent pure substances, i.e. drugs or enzymes in biochemical processes, from external pyrogens and microorganisms and to protect the environment and the workers from hazardous substances. The main problems in today's self-contained production plants are the pumps, and there the shaft seals and bearings. In [1] it is documented that of all pumps employed in chemical industry, 80% are withdrawn from service because of mechanical seal failures, while the remaining 20% fail because of bearings, couplings and other associated items. Even if the reliability of seals is further improved, it must be considered that all types of seals represent a penetration of the pressure containment shell. Thus, it is expected that the use of canned motor pumps and magnetic coupling pumps will increase dramatically in the future.

Unfortunately, today's canned motor pumps require process lubricated bearings. Often, these bearings cause reliability problems because not all chemical products are adequate bearing lubricants. Furthermore, dry running of the pump damages these bearings in a short time. So the best pump would be a canned motor pump with magnetic bearings. The design of a magnetically levitated canned motor pump is e.g. described in [2]. Unfortunately such a pump is too expensive for most applications because of the high costs of magnetic bearings. The only applications which are documented are in the field of nuclear, military and space technology (see e.g. [3]).

2. Approach

Recent developments at the Laboratory for Electrical Equipment Design (EEK) of the Swiss Federal Institute of Technology (ETH) in Zurich and at several universities in Japan in the field of electrical drives and magnetic bearings have led to so called "bearingless motors" (see [4], [5], [6], [7]). With the new technology of the "bearingless electromotor" a simple solution for a magnetically levitated canned motor pump without separate magnetic mountings becomes possible. For the development of such a bearingless canned motor pump, the ETH Zurich co-operated with Sulzer Electronics, Sulzer Pumps and Lust Antriebstechnik.

3. Bearingless Motor

The expression "bearingless motor" was first used in [4]. In this context bearingless does not mean the lack of bearing forces, which are necessary in any case to stabilise the rotor, but the absence of actual bearings. In principle the bearingless motor is based on the contactless magnetic bearing of the rotor. In contrast to conventional magnetic levitated drives, the bearing forces in the bearingless motor are not built up in separate magnetic bearings placed to the left and right of the motor block, but in the motor itself. The conception of a bearingless motor is shown in figure 2. In a conventionally borne electrical machine (figure 1a), the active motor part generates only the torque. The rotor is supported by two radial bearings on either side of the active motor part. In a bearingless motor, the active motor part generates not only the torque but also the radial magnetic bearing force which is needed to suspend the rotor. Two motor parts or one motor and a conventional magnetic bearing are needed for the active control of five degrees of freedom.

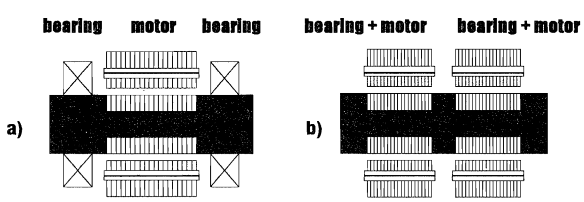

figure 2: *a) conventionally borne motor*
b) bearingless motor

The idea of combining the magnetic bearing function and the torque generation in an electricmotor is not new. Most of the proposed solutions combine a high pole machine to generate the torque (at least eight poles) with a conventional active magnetic radial bearing.
In these solutions, the flux density under a bearing pole is modulated by the torque building machine flux. There is only a slight disturbance of the magnetic bearing force by the torque generation as long as the flux modulation is small compared with the bearing flux. In the stationary case, if the torque building machine flux is constant, the controller for the magnetic bearing will compensate this influence. In order to show the way to the new approach, it is apposite to examine the magnetic forces in a conventional electrical machine.

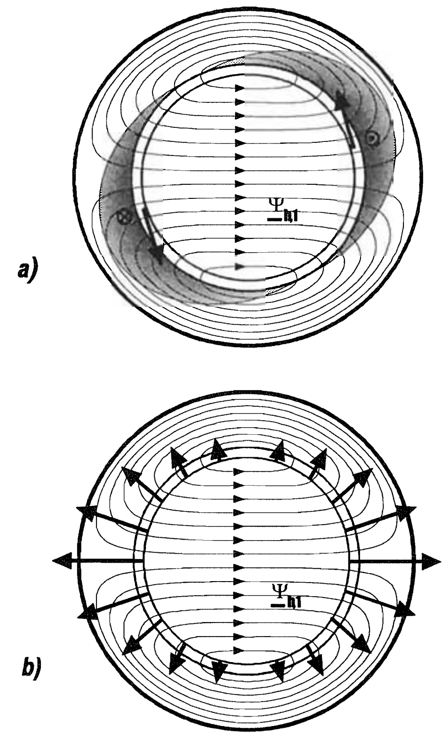

figure 3: *a) Lorentz forces*
b) Maxwell forces in a convential AC Motor

Two different magnetic forces are known: the Lorentz force and the Maxwell force (reluctance force). The Lorentz force acts on a conductor with a current flow which is in a magnetic field. The formation of the torque in a polyphase motor is based on it. In the machine there are also Maxwell forces, i.e. forces which are produced in magnetic circuits at the boundary layers of materials with different permeability. Their directions are right-angled to the rotor surface and their sum equals zero because of the symmetrical flux distribution. The case of a machine where the number of pole pairs equals 1 is qualitatively shown in figure 3b. Only a displacement of the rotor out of the centre of the machine gives an asymmetrical flux distribution and a radial force in the direction of the displacement. This effect is known as the magnetic tensile force in the theory of the electrical machine. If the displacement of the rotor grows, the magnetic tensile force increases. So this effect can be considered as a spring force with negative stiffness. Now the question arises, how to transform the negative into a positive stiffness.
With the superposition of a steering flux (with the pole pairs $p_2 = p_1 \pm 1$) to the motor flux (with the pole pairs

p_1), radial magnetic forces can be built up in the AC machine. These forces can be controlled by the current in a special steering winding (with the pole pairs $p_2 = p_1 \pm 1$) and are suited for the contactless bearing of the rotor.

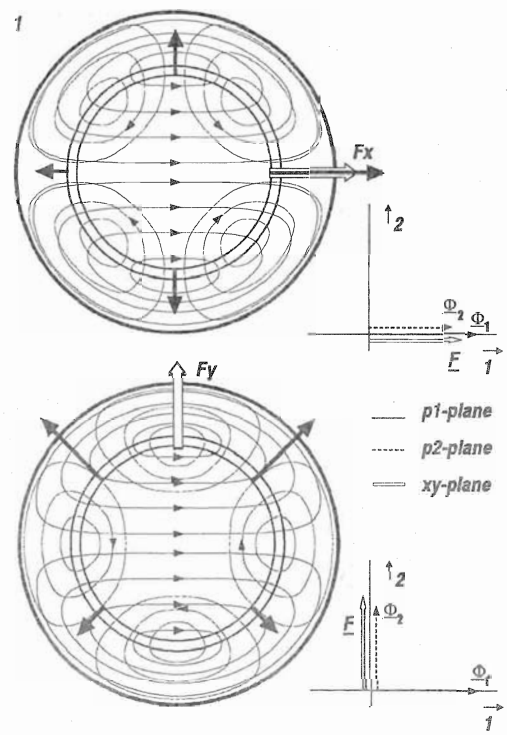

figure 4: Generation of controllable Maxwell forces by superposition of a four pole steering flux over a two pole machine flux

The plausibility of this idea can easily be demonstrated graphically. Figure 4 shows the easiest case of a two pole motor flux ($p_1 = 1$) and a four pole steering flux ($p_2 = 2$). The steering flux (dashed lines) weakens the motor flux (plain lines) in some regions and strengthens it on the opposite side. It is obvious that the resulting radial force always points in the direction of the steering flux vector of the p_2-pole pair electrical system (p_2-plane), relative to the motor flux vector in the p_1-plane. This can be described in a simple equation for the vector components of the radial force.

$$F_x = +\frac{\pi p_1 p_2 L_2}{4 l r \mu_0 w_1 w_2}\left(i_{S2d}^{(p_2)} \cdot \Psi_{1d}^{(p_1)} + i_{S2q}^{(p_2)} \cdot \Psi_{1q}^{(p_1)}\right)$$

$$F_y = \pm\frac{\pi p_1 p_2 L_2}{4 l r \mu_0 w_1 w_2}\left(i_{S2q}^{(p_2)} \cdot \Psi_{1d}^{(p_1)} - i_{S2d}^{(p_2)} \cdot \Psi_{1q}^{(p_1)}\right)$$

To decouple the radial force from the torque vector, control is used.

4. Prototype

4.1 Overview

To prove the feasibility of a bearingless canned pump, a whole system with signal electronics, power electronics and the pump itself had to be built up. With regard to a future industrial employment , the single parts were build up as far as possible out of standard units. The bearingless motor and the special design of the AC bearing allow using conventional switched power converters, which are less expensive than magnetic bearing converters. Figure 5 gives an overview of the control system together with the pump. The chapters below describe the separate parts in detail.

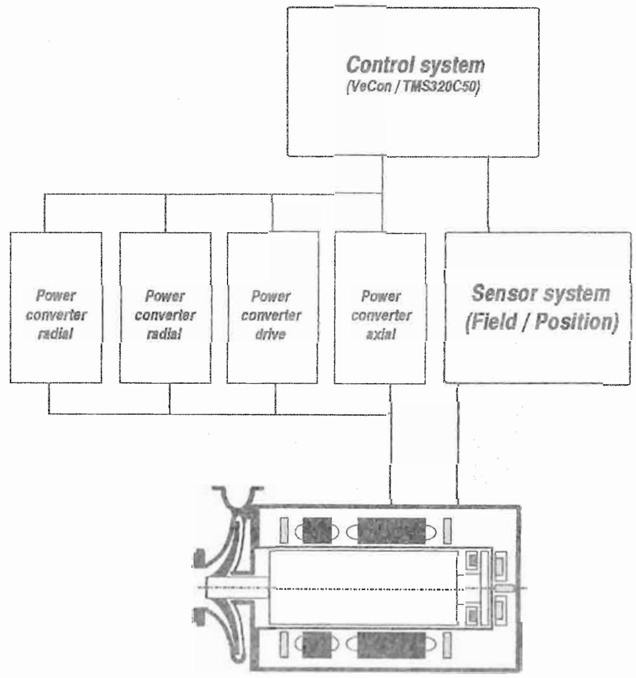

figure 5: *System overview*

4.2 Pumping System

The pump head is taken from a standard canned pump. The conventional motor unit with the slide bearing system was replaced by the new magnetic bearing/motor unit. The pump is of double-staged centrifugal design with a multiple volute casing. Centrifugal pumps with multiple volute casings generate low radial forces, which reduces the force requirement of the radial bearings. To power the pump, about 0.5...0.6 kW is needed to deliver up to 3.5 m^3/h against a pressure of 16 bar.
Figure 6 shows the constructional principle of the pump with the motor/bearing unit. The main stream of the pumped liquid goes directly from the inlet of the pump

over the two stages to the outlet. A small quantity of the pumped liquid is circulated through the motor/bearing unit as well. The pumped liquid itself is used as a coolant for the motor. To maintain the circulation around the rotor, the discharge pressure of the pump itself is used.
The material used for the can must be resistant to corrosive attack from the pumped liquid, consequently the chosen material is Hastelloy C22. In the chemical industry Hastelloy is a commonly used material, very resistant to corrosion. The can must be as thin as possible (0.6 mm); its thickness is a direct criterion for the induced eddy current losses and hence for the generation of heat in the can [8]. Canned pumps normally have various monitoring systems to avoid damage to the slide bearings, which may be caused by steamy liquids, dry run of the pump or too many on-off cycles. If a bearing failure occurs, the whole hermetic system has to be opened.
The bearingless canned pump should have no problems like those mentioned above, because there are no bearings in the medium. Sensors and bearings are all on the outside of the hermetic system and are exchangeable without the need to open the system.

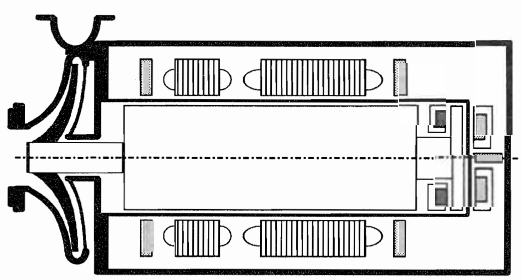

figure 6: *Cross Section of Bearingless Canned Pump*

4.3 Bearing/Drive System

The bearingless canned pump has two radial and one axial bearing. The front radial bearing is a conventional 3-phase AC bearing. It is designed to be supplied by a standard 3-phase power converter. The maximum radial force is about 180 N. The total „air gap" between rotor and stator is 1 mm. The can has a thickness of 0.6 mm, the geometric air gap is 0.4 mm. The low force requirement makes it possible to have a very short bearing. The force can thus act close to the impeller, which is the main radial load on the shaft. Therefore the shaft is better stabilised and the radial force requirements for the bearingless motor are not so big.
The second radial bearing is of bearingless motor type. The motor employed is asynchronous with a squirrel-cage rotor. It is designed for a speed of 3000 rpm. Higher speed for this pump is pontless because of the increasing hydraulic losses.
The axial load in the pump is high. It is mainly caused by the different pressure on the suction side of the pump impeller. The axial forces can be up to 200 N in the direction of the impeller. The axial bearing is designed half passively, half actively: an active axial bearing is at the end of the tube and acts against the axial main load. The passive permanent magnet part is in the tube. The special combination enables the necessary forces to be assured with only one coil.
Annother approach for a canned pump is shown in [9]. There impeller and the motor are one unit. Therefore only one radial bearing is needed.

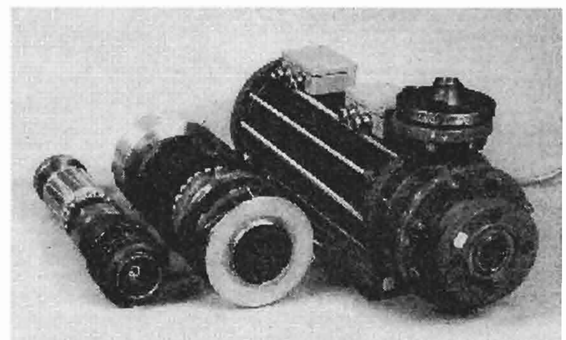

figure 7: *Rotor and stator of the canned pump*

4.4 Power Electronics

The power electronic part of pump system consists of three conventional switched 3-phase power converters and one special magnetic bearing converter. The conventional units are normal drive converters and are used on the one hand for the motor and on the other hand for the two radial bearings. The axial bearing is supplied by a magnetic bearing converter. The power converters are controlled by two signal processors; one for the drive system (VeCon) and one for the whole bearing system (TMS320C50-80MHz). The processors directly control the switches of the converters.
The DC links (540 V) of the power stages are all connected to make use of the kinetic energy of the motor for the bearings during a power loss; if this case is detected the system runs down , the motor behaves as a generator and maintains the bearings and the control unit until the pump stops.

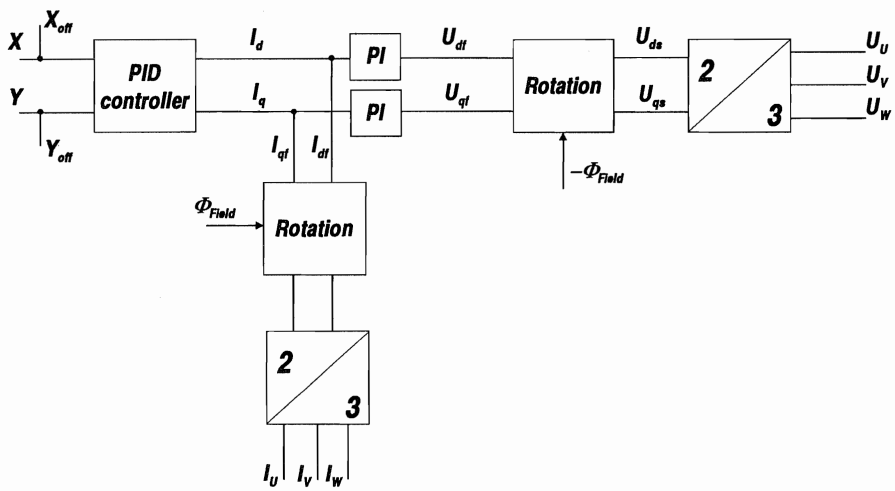

figure 9: *Position controller for the bearingless motor with embedded current controller*

The drive converter is a 4 kW/9 A type, for the bearings a 2.2 kW / 5.5 A type is used. The converters are oversized for this special application, but the system is also usable for larger bearingless drives or pumps.

figure 8: *Control unit*

4.5 Sensors

To guarantee a safe function of a bearingless system, it is necessary to have precise positioning sensors with high reliability and low drift. In addition , the flux in the motor must be measured as well. In a canned pump the probes must not be in contact with the medium, therefore they have to be placed outside the canned system. The can in the described pump is of metal, which leads to further problems for the choice of the sensor system.

The positioning probes commonly used with magnetic bearings are of inductive or eddy-current type. These detect the distance of a metallic sensor ring. If there is a metallic can between the ring and the sensor, the signals have a high attenuation. The choice of the sensor type was a major problem for the design of the pump. Three sensing principles were tested: eddy-current, inductive and Hall distance probes. Optical and capacitive measuring is impossible, because of the can. The sensors of the frontal 3-phase AC bearing are placed in the centre of the bearing stator to reduce the influence of the angular displacement of the shaft. The bearingless motor has its sensors behind the motor near the axial bearing: the sensors cannot be placed in the motor itself. There the above-mentioned influence must be compensated by the software.

For exact positioning in the bearing and for the function of the vector control of the motor, the flux must be known as well. Vector-controlled drives normally use a resolver or an optical encoder to estimate the flux in the machine. The employment of these sensors is unsuited in a canned pump. The flux in this pump is directly measured by Hall probes. To achieve immunity to radial rotor displacements it is measured differentially. Altogether four sensors are needed with this method.

4.6 Control

The heart of the control system for the canned pump is formed by two fast signal processors. The whole control is made digitally. The inputs are the signals of the current measurements from the switched power converters, the signals of the 5 positioning probes, and those from the flux sensors. The output directly controls the switches of the power stages with PWM signals.

The signal processors are embedded in two PCBs with AD converters for the inputs and PWM converters for the output. An 80 MHz signal processor is responsible for the whole bearing control, another special drive processor (VeCon) controls the motor itself.
The 3-phase AC bearing and the axial bearing are controlled by a PID position controller with an embedded current controller.
The motor is vector controlled with flux-frame referenced current controllers. The controller of the bearing in the motor is shown in figure 9. As proposed in [6] the current controllers act in the rotating field system. The outputs are rotated into the stator system after the PI controllers. The advantage to the system with the current controllers in the non-rotating stator system is that the bandwidth of the controller can be reduced.

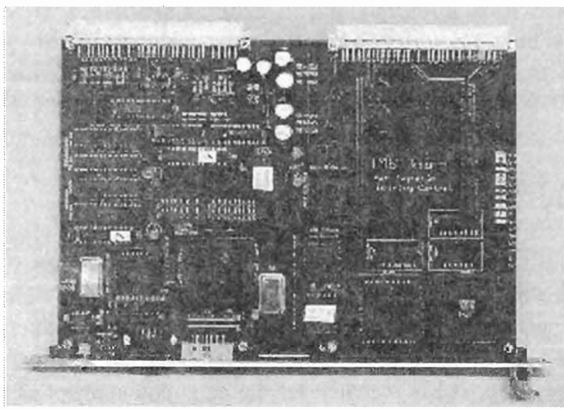

figure 10: *Signal processor hardware (TMS)*

A digital system allows a very flexible management of the controllers and filters. At the moment there is a project at our institute involving a fast one signal processor system for bearing and drive. With the new unit it is possible to reduce the space and complexity of the controlling system for the pump and in general of the magnetic bearing controllers.

5. State of the Project

The principle of the bearingless canned motor was successfully demonstrated with an 1.5 kW induction motor. The motor windings are powered by commercial 3-phase frequency converters from LUST Antriebstechnik. The digital controller hardware is based on the VeCon chip set and on a TMS 320C50 DSP from Texas Instruments. The main problems with the realisation of the bearingless canned motor were related to eddy-current losses in the metallic can. This caused not only problems for the bearing and drive function but also for the position sensors.

6. Outlook

In a further step the bearingless canned motor will be coupled with a two-stage centrifugal pump. With this pump, a maximum flow rate of 120 l/min and a maximum pump head of 25 cm should be reached with water. After the pumping tests, it is planned to start the development of a big industrial pump. Since the bearingless motor requires the same fabrication technology as today's canned motors and needs only simple 3-phase frequency converters as power sources, it will be available at a moderate price.

7. Acknowledgement

The project was supported by the Laboratory for Electrical Engineering Design (EEK) of the Swiss Federal Institute of Technology (ETH) in Zurich and the companies Sulzer Electronics AG., Winterthur (Switzerland) and Lust Antriebstechnik GmbH, Lahnau Germany.

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