VECTOR CONTROL OF THE BEARINGLESS MOTOR

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ABSTRACT

In an a.c. motor lateral magnetic forces can be generated with a control winding in addition to the torque. These forces are suitable for the contactless bearing of the rotor. The feasibility of this principle was successfully demonstrated on the example of the synchronous motor [1] and the asynchronous motor [2]. The main problem in the closed loop control lies in the coupling of the torque and the radial forces through the motor flux. In this paper a method will be presented, which is based on the flux vector control, to decouple the two variables. Even in the transient case the torque and the radial forces can be precisely controlled with this method. With a superposed control over the lateral open loop force control, the position of the rotor can be stabilized.

THE IDEA OF THE BEARINGLESS MOTOR

The expression "Bearingless Motor" was first used in [1]. In this context bearingless does not mean the lack of bearing forces, which are necessary in any case to stabilize the rotor, but the missing of significant bearings. On 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, which are placed on the left and right side of the motor block, but in the motor itself. The conception of a bearingless motor is shown in figure 1. In a conventionally borne electrical machine (figure 1a), the active motor part generates only the torque. The rotor is borne 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 for the suspension of the rotor. Two motor parts are needed for the active control of five degrees of freedom. For all further considerations only one active motor part is regarded.

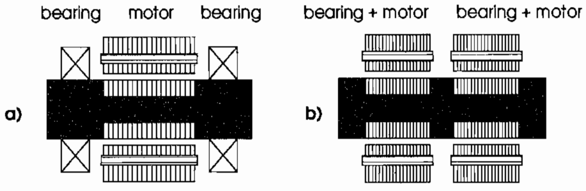

FIGURE 1: a) conventionally borne motor
b) bearingless motor

The idea of combining the magnetic bearing function and the torque generation in an electromotor 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. A bearingless synchronous motor which works after this principle was already published in [3]. Bearingless stepper motors or in general Reluctance motors are often proposed. A stepper motor with a magnetically floating rotor is described in [4]. In [5] an induction motor with integrated magnetic bearing, based on similar principles, is presented.
In all 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 to 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 anyway. The disadvantages of this principle are the poor torque generation for a given motor size and small vibration forces which are caused by the modulation of the bearing flux density.

The high frequency of the torque generating current which is necessary for high rotor speeds because of the high number of pole pairs is further problem.
In [1] and in [2] another way to the bearingless motor is proposed, which works around the above mentioned problems. In order to show the way to the new approach, it is sensible to have a glance at the magnetic forces in a conventional electrical machine.

MAGNETIC FORCES IN THE A.C. MACHINE

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. This effect is qualitatively shown in figure 2a for the simplest case of a two pole machine with sinusoidal current and flux distribution. The tangential Lorentz-Forces act on the rotor in couples and generate by this the torque. In the machine there are also Maxwell-Forces, that means 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 2b. Only a displacement of the rotor out of the center of the machine gives an asymmetrical flux distribution and a radial force which points in the direction of the displacement. This effect is known as the magnetic tensile force in the theory of the electrical machine [6]. 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 to a positive stiffness. On principle this could be achieved by controlling the magnetic drag force. To aim this goal, the force must be controllable in direction and amplitude.

GENERATING CONTROLLABLE RADIAL MAGNETIC FORCES IN THE A.C. MACHINE

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 a.c. machine. This 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. The idea of a radial magnetic bearing in an a.c. motor which uses such a steering winding for the control of the magnetic tensile forces was already published in [7]. However, the proposed control scheme would work only under limited (steady state) conditions.

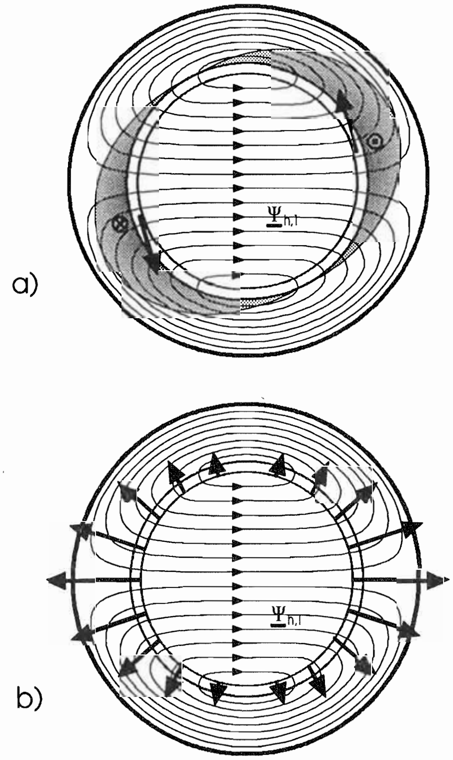

FIGURE 2: a) Lorentz-Forces and b) Maxwell-Forces in a conventional ac-motor

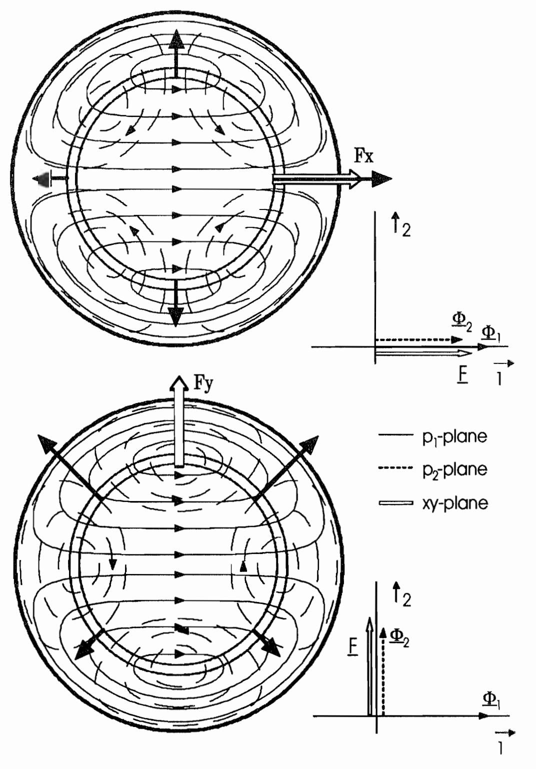

FIGURE 3: Generation of controllable Maxwell-Forces by superposition of a four pole steering-flux over a two pole machine-flux

With a closer look to the controllable magnetic tensile forces and a vector-description of them, a much better control approach can be found. It's not possible to present the mathematical derivation of the force vector formula on this pages. But its plausibility can easily be demonstrated graphically. Figure 3 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 visible 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.

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

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

The smaller, but also existing radial Lorentz-Force (compare [1] and [2]) is not considered in these equations.

DECOUPLING THE RADIAL FORCE FROM THE TORQUE BY VECTOR CONTROL

If the equations above are transformed in a rotating coordinate system which rotates synchronous to the motor flux-vector (called flux reference frame), the coupling components vanish. The vector equation becomes very simple and can be written in the following form:

$$\underline{F} = \frac{\pi p_1 p_2 L_2}{4 l r \mu_0 w_1 w_2} \cdot \Psi_1 \cdot \underline{i}_{S2}^{(F,p_2)}$$

Together with the equations for the magnetic tensile force [WiKe/67]

$$F_x = 0.3 \cdot \frac{\pi \cdot r \cdot l \cdot \hat{B}_{10}^{\,2}}{\mu_0} \cdot \frac{s}{l_{10}} ,$$

and the well known mechanical equations of the system, the radial bearing part of the bearingless a.c. motor is described completely. Figure 4 shows the idealised model of such a bearing system. To simplify the model, only lateral Maxwell-Forces are considered. The Lorentz-Forces are neglected because their influence is small. A complete description of the system can be found in [8]. The block diagram of the radial bearing function is the same for the bearingless synchronous motor and the induction motor.

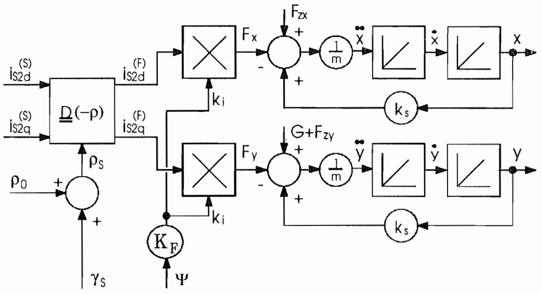

FIGURE 4: Structure of the bearing function

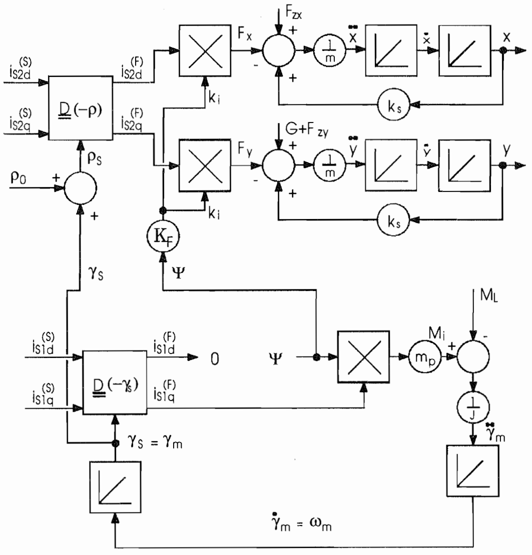

FIGURE 5: Structure of the bearingless synchronous motor

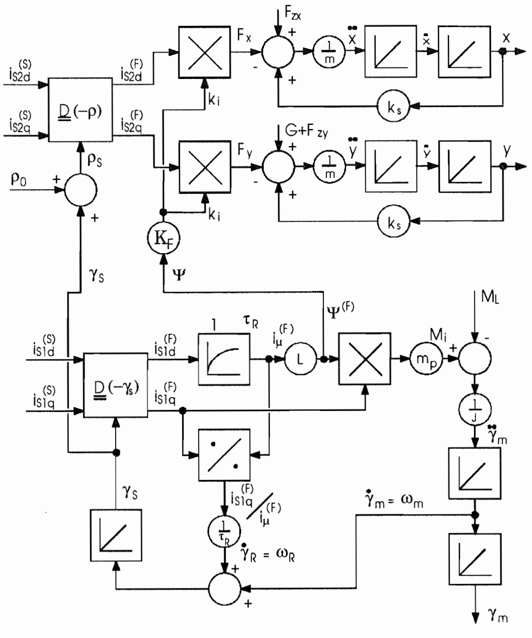

FIGURE 6: Structure of the bearingless induction motor

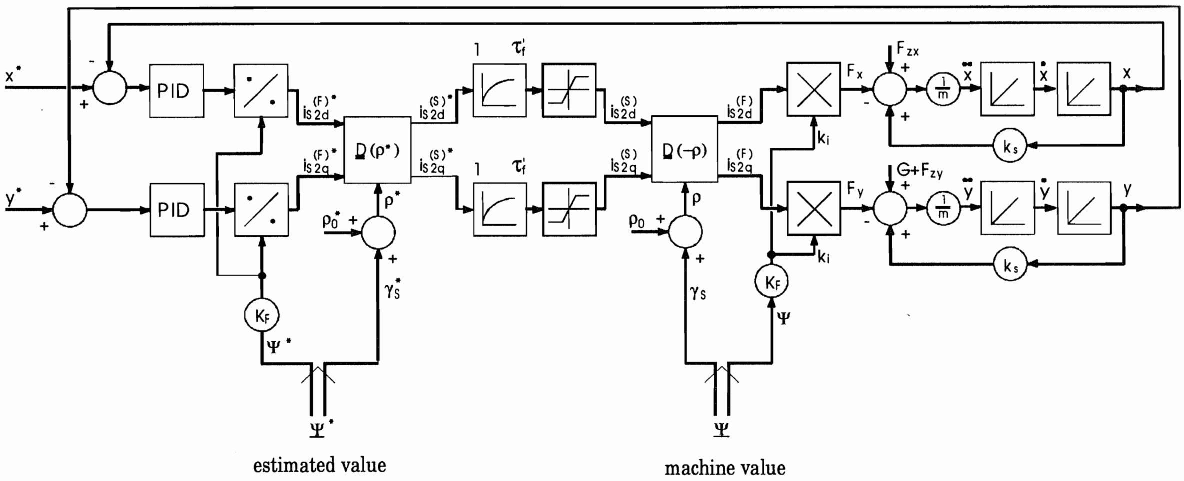

FIGURE 7: Position control for two axes

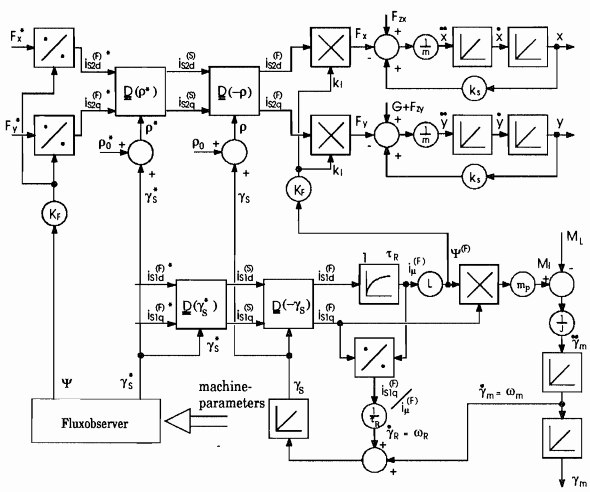

FIGURE 8: Decoupling of the lateral force and the torque

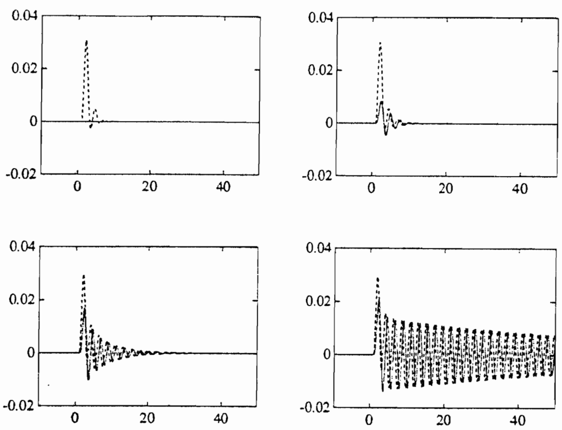

FIGURE 9: Behaviour of the position controller for the y-axes (plain line) and the x-axes (dashed line) on a disturbance in y-axes for a flux angle error of 0, 10, 20 and 25 degrees.

Figure 5 shows the simplified block diagram of the complete bearingless synchronous motor (for the turning and bearing function) and figure 6 the one of the bearingless induction motor. As the block diagrams and the above equations shows, the bearing and the torque system are coupled through the flux vector (magnitude and angle). If it is possible to exactly appoint the flux vector, the torque and the bearing forces can be completely decoupled. This is done by dividing the steering-force-vector components F_x^* and F_y^* through the magnitude of the machine flux and transforming the stator current vector from the flux linked reference frame to the stator linked reference frame (vector rotation by the flux-angle γ_S). With the decoupling shown in figure 8, the lateral force can be controlled in both components.

A conventional closed loop control system for magnetic bearings can be superposed over the lateral force vector control. Because of the design of controllers for magnetic bearing systems has been investigated intensively (e.g. compare [9], [10], [11]) it will not be discussed in this paper. Crucial is the question what happens with the controller when a fault in the determination of the flux vector occurs. Figure 7 shows the simplest case of a PID-controller to control each axis separately. It is visible that an error in the estimation of the flux angle gives a coupling of both bearing axis. A disturbance in X-direction gives a disturbance in Y-direction and vice versa. The controller for the magnetic bearing system must deal with this effect beside normal disturbances. The quality of the control is reduced drastically if a flux angle error occurs. The simulations in figure 9 and experiments show, that a flux angle error of more than about 10 degrees already impairs the quality of the control. With an error of 20 degrees a control of the rotor position is hardly impossible.

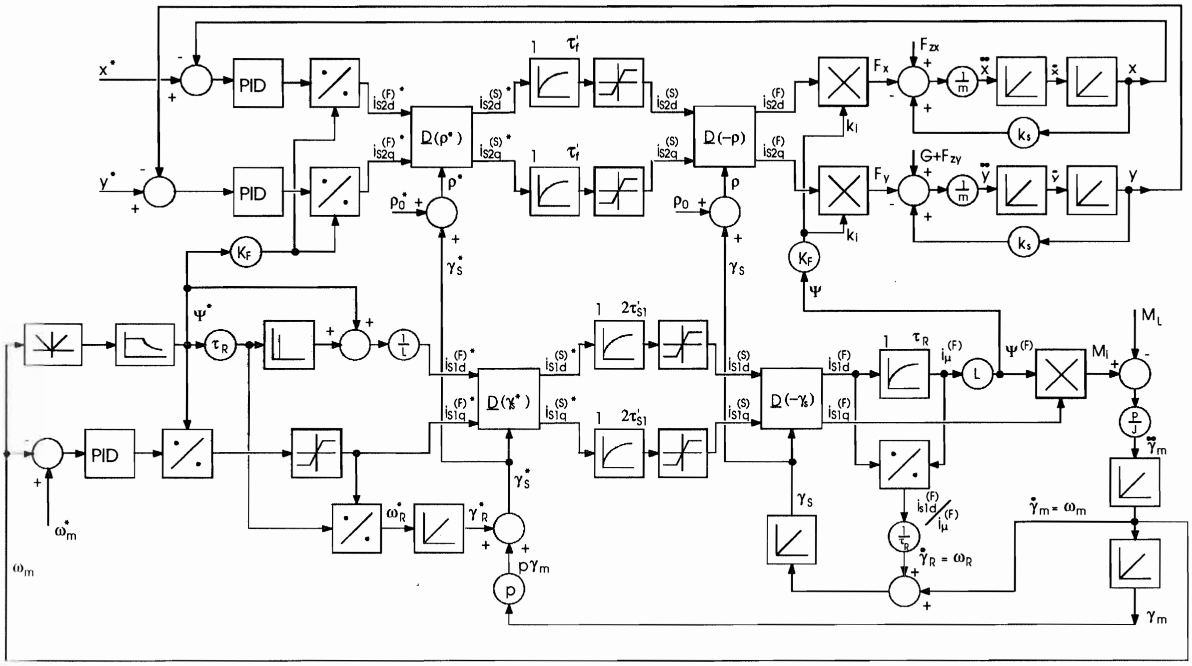

FIGURE 10: Control block diagram of the prototype system

An exact and fast determination of the flux has a major meaning for the quality of the position control. In the synchronous motor, the flux vector is linked with the rotor. So it is only necessary to measure the mechanical rotor-angle ω_m to get the flux-angle γ_s. However in the case of the induction motor, the flux vector turns with an additional slip frequency. In contrast to the synchronous motor, in the induction motor the torque and the motor-flux are both controlled by the stator-current. So the estimation of the flux-angle is much more difficult than at the synchronous motor. Fortunately flux-oriented control techniques for the induction motor are already well known since the flux-oriented control gives also big advantages in the control of the machine torque. There is a great number of publications about this theme. For example [12] gives a good overview over different vector control schemes for the a.c. motor. So it is not necessary to discuss the problem of the flux-estimation in these pages. It is more important to specify the requirements for the use in the presented application. For good results the estimation error for the flux angle must be less than about 10 degrees over the full operation area, which is not a big problem in the case of the synchronous motor but in the case of induction motor. None of the basic schemes for the flux estimation in induction motors can fulfil this specification itself. Only a combination of two estimation models, for example the stator voltage model and the current will do it. A very simple but efficient control scheme is shown in figure 10. It is a Model Reference Adaptive Control (MRAC) which is based on the current model in the rotor-flux frame and uses the voltage model for the adaption of the parameter τ_R., which is highly dependant on the operation state.

Test Results

For the test of the proposed vector control,a bearingless induction motor and the necessary control electronics was constructed (figure 11). It is built with parts of a conventional 3-kW norm induction motor. The measurements at the prototype machine show a good immunity to interference over the whole speed range (figure 12).

NOMENCLATURE

Symbols

$\underline{\underline{D}}(\alpha)$	rotation matrix
F_x, F_y	force in x- and y-direction
F_{zx}, F_{zy}	disturbance force in x- and y-direction
i	current
i_s	stator current
J	rotor moment of inertia
k_i	force-current coefficient
k_s	force-displacement coefficient
l	active length of the machine
l_{lo}	length of the air gap
L	inductance
L_1	inductance of the winding with p_1-pole pairs
L_2	inductance of the winding with p_2-pole pairs

m_p	number of phases
M	torque
M_L	load torque
M_i	inner torque of the machine
p	number of pole pairs
r	rotor radius
$\underline{s}$	displacement vector
w_1	number of windings for p_1-winding
w_2	number of windings for p_1-winding
γ_m	mechanical rotor-angle
γ_S	flux-angle
μ_o	magnetic constant
τ_R	rotor-time-constant
Ψ	flux linkage
ω_m	mechanical angular speed
ω_R	angular rotor frequency (slip frequency)
ω_S	angular stator frequency (angular speed of the flux-oriented reference frame)

Subscripts

1	p_1-pole pairs system
2	p_2-pole pairs system
d,q	direct and quadrature components of a vector

reference frames

F	flux-oriented reference frame
S	stator-oriented reference frame

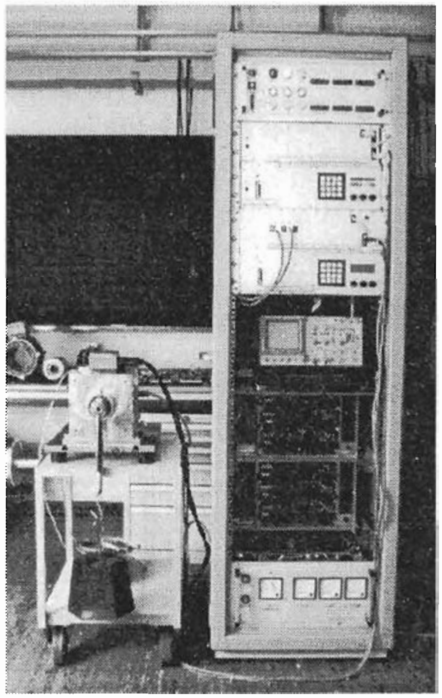

FIGURE 11: Prototype machine with control electronics

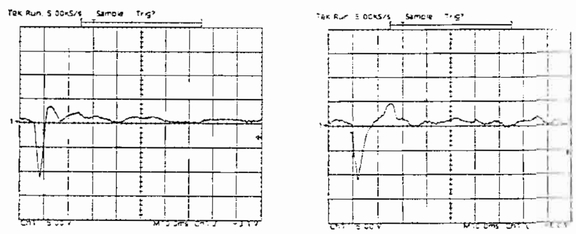

FIGURE 12: Behaviour of the position controller for a vertical disturbance at 0 rpm (right) and 4500 rpm (left). Scale factors: 50 µm/div.and 10 ms/div.

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