A SELF-HEALING MAGNETIC BEARING

H. Ming Chen
Foster-Miller Technologies, Inc.
Albany, NY

SUMMARY

A fault tolerant magnetic bearing control scheme, which independently controls each stator pole using a proportional-integral-derivative (PID) displacement feedback, has been analytically tested. The scheme was applied to a 16-pole magnetic bearing with a load capacity of 6000 lb and a static load of 4000 lb. Transient response simulation of pole failures (such as those caused by power amplifier failure or coil short circuit) demonstrated that the rotor recovered its bearing center position in a fraction of a second after two consecutive failures of the two top load-carrying poles. The scheme does not require on-line current monitoring to determine the pole failure patterns or storage of precalculated control data to counteract pole failures.

INTRODUCTION

Conventional magnetic bearings share one common trait that impacts system reliability — if a single component fails, the entire system fails. For example, in a large turbine-generator supported by three radial magnetic bearings and one thrust magnetic bearing, a bearing system malfunction could occur due to burned-out electronic switches in one power amplifier out of thirty. Such unreliability is inherent to the method used to control the bearing. Consider the typical 8-pole bearing configuration shown in Figure 1. The conventional control method separates the poles into four pairs and uses two opposite pairs of poles (1-2 and 5-6) to control shaft motion in the vertical direction (y), and the other pair of poles (3-4 and 7-8) to control shaft motion in the horizontal direction (x). For each pair of poles, their coils are connected in series and driven by a power amplifier. If any of the four power amplifiers or coils fails, control of the associated direction or axis would usually fail due either to loss of static load-carrying capacity or when the system becomes dynamically out of tune. When one axis fails, the bearing cannot function, and the entire system must be shut down.

This paper addresses this deficiency of conventional magnetic bearing technology. Other methods have been developed to introduce redundancy into the control but all have certain limitations. Lyons, et al., [1] have designed and tested a fault-tolerant magnetic bearing system in which each radial bearing has three magnetically isolated control axes, any two of which can maintain control of the rotor position. However, with this approach, there is only one redundant control axis. Maslen, et al., [2] have taken a distributed approach that independently controls each pole-coil set by determining the coil currents for given required magnetic forces. The multi-pole force-to-current relationship needed for feedback control is not unique and requires complex computation of a matrix relationship that is stored digitally in look-up tables. For the failure of a specific coil or a combination of coils, a specific matrix exists for the application of the servo control, and on-line monitoring of the coil currents is required to identify the pattern of coil failure.

As shown in Figure 2 for an 8-pole configuration, this author also uses the same distributed approach to independently control each pole-coil set (hereinafter called "pole"), but does not use the precalculated matrix method. Instead, a special set of bias currents and PID constants are assigned to each pole. These special values are determined by an engineering design analysis of the magnetic actuator, considering possible current and flux saturation, and overload due to different pole failure patterns. This new control scheme proves to be amazingly resilient to pole failures and shows a "self-healing" characteristic [3]. Specifically, when pole failures occur, the remaining poles work in unison and adjust current individually to regain control of the rotor. There is no need to monitor the pole failure pattern or provide precalculated current control parameters.

MULTI-POLE CONTROL MODEL

The self-healing control method is applicable to magnetic cores of heteropolar or homopolar configurations with any number of poles greater than three. To keep the discussion simple, we will concentrate on those bearings with uniform or identical poles in heteropolar configurations. The cross-sectional areas of magnetic flux paths at poles, rotor, and stator are all equal as with conventional active magnetic bearings. Each pole has a single coil driven by a dedicated power amplifier. Heteropolar bearings usually do not use separate bias currents, and the current in each coil may vary from zero to the maximum amperage but never change sign. Note that the flux variation or redistribution is no longer limited locally in a quadrant of poles. The current or air gap variation of one pole not only changes the flux density of that pole and the opposite quadrants, but also affects the perpendicular quadrants. Assuming negligible core metal reluctance, the flux distribution is calculated using the model in Figure 3 with an 8-pole example and the following matrix equation [2].

$$\mathbf{R}\boldsymbol{\phi} = \mathbf{N}\mathbf{I} \tag{1}$$

where:

$\boldsymbol{\phi}$ = magnetic flux vector = $\{\phi_1, \phi_2, \ldots \phi_n\}^t$
$\mathbf{I}$ = current vector = $\{I_1, I_2, \ldots I_n\}^t$
R_i = $g_i/\mu_o A$ = air gap reluctance at i^{th} pole
g_i = air gap at i^{th} pole
A = pole area
μ_o = air permeability
n = number of poles
N = number of coils per pole

$$R = \begin{bmatrix} R_1 & -R_2 & 0 & \cdots & 0 \\ 0 & R_2 & -R_3 & \ddots & \vdots \\ \vdots & \ddots & \ddots & \ddots & 0 \\ 0 & \cdots & 0 & R_{n-1} & -R_n \\ 1 & 1 & 1 & 1 & 1 \end{bmatrix} \quad \text{and} \quad N = \begin{bmatrix} N & -N & 0 & \cdots & 0 \\ 0 & N & -N & \ddots & \vdots \\ \vdots & \ddots & \ddots & \ddots & 0 \\ 0 & \cdots & 0 & N & -N \\ 0 & 0 & \cdots & 0 & 0 \end{bmatrix}$$

The current vector, **I**, includes the bias currents and the modulating or dynamic currents from the displacement feedback control. The bias currents are set at equal amounts for all poles before the servo control starts. Once the control starts, the bias currents will be redistributed according to the bearing static load. The bias currents are set, for example, at the half value of the maximum allowable continuous current of the power amplifiers. The neighboring poles are assigned with alternate signs to avoid magnetic flux saturation at local cores. The dynamic current of each independently controlled pole is:

$$i = -C_p D - C_i \int D dt - C_d dD/dt \qquad (2)$$

where:

C_p, C_i, C_d = proportional, integral, derivative constants
D = $x\cos(\theta) + y\sin(\theta)$
x, y = displacement measurements in X, Y directions
θ = pole angle
t = time

Only two orthogonal displacement measurements are required as for conventional magnetic bearings. No sensor redundancy is assumed in the above formulation. The determination of the PID constants follows a linear system method for the magnetic bearing control [3], which is not elaborated on here. Additional filtering for phase and gain compensation to eliminate system resonance, for example, may be imposed on the dynamic current, i, if needed.

Once the flux vector, ϕ, is calculated using Equation 1, the pole force at the i^{th} pole can be calculated by:

$$F_i = p\phi_i^2 \qquad (3)$$

where p is a constant depending on the units. The magnetic bearing rotor is thus subjected to n of these pole forces, equally spaced around the circumference.

Our interest is to know how the magnetic bearing behaves during pole failures. The transient behavior was simulated using the above nonlinear formulation, including the magnetic flux saturation in cores and the current limit of the power amplifiers. The formulation has been implemented into a commercial rotordynamics program, DyRoBeS, as a special bearing [4, 5]. Using this program, a rotor-bearing system including one or more self-healing magnetic bearings can be analyzed for its transient response by assigning pole failures in a time sequence.

TRANSIENT RESPONSE SIMULATION OF POLE FAILURES

The self-healing control method was simulated using a large-size magnetic bearing. Shown in Figure 4, this bearing has 16 poles, runs at 3600 rpm, supports a 4000-lb rotor weight, and has a load capacity of 6000 lb. Other important bearing parameters include:

Axial Length	L = 5.5 in.
Journal OD	JD = 18.95 in.
Saturation Flux	B = 90,000 Maxwell/in.^{2}
Air Gap	g = 0.030 in.
Coil Turns	N = 65
Pole Area	A = 15 in.^{2}

The proposed test rotor weighs about 8500 lb and is supported by two bearings: one rolling element bearing and a self-healing magnetic bearing, with a bearing span of 6 ft. The mathematical model for this rotor from DyRoBeS is presented in Figure 5. The lower half of the model is drawn with the rotor stiffness diameters and the top half with the mass diameters. The self-healing magnetic bearing is at the condensed model station no. 4. The following pole failure time sequence was assumed:

At time = 0.35 sec, the top pole #5 fails.
At time = 0.60 sec, another top pole #4 also fails.
At time = 0.85 sec, the horizontal pole #1 also fails.

To present a clear picture of transient response, only gravity force was considered. No unbalance or other excitations were included. Figures 6 and 7 present the transient displacements at the bearings due to the pole failures. Figure 6 shows the displacements for the ball bearing, which has a static rotor load of 4500 lb and an assigned stiffness of 1 x 10^6 lb/in. The x (horizontal) and y (vertical) time traces are very flat and uneventful, because the bearing is relatively stiff. In the Y-direction, there is an average of 0.0045 in. of deflection as expected. Figure 7 presents the behavior of the self-healing magnetic bearing due to the pole failures. As the rotor position approaches steady-state position, the top pole #5 fails at 0.35 sec. The rotor drops vertically about 0.0055 in. and recovers its position in less than 0.25 sec. At 0.60 sec, when another top pole (#4) fails, the self-healing magnetic bearing loses more load-carrying capacity, and the rotor dips further down to 0.010 in. However, it also recovers its levitated position in 0.25 sec. Since #4 is an inclined pole, its failure also slightly affects the horizontal position of the rotor. The horizontal pole #1, which fails at 0.85 sec, affects both directions only slightly, because no horizontal static force exists. Figure 7 shows that the self-healing bearing can apparently correct for the pole failures in a fraction of a second and continue to function.

Figures 8 and 9 present the transient coil currents. As shown in Figure 8, as the top poles fail, the remaining top poles, noticeably #3 and #6, pick up more current to support the 4000-lb static load, which becomes a consideration for the design of power amplifiers for the self-healing bearing. Slight current saturation of the #3 and #6 coils occur when the #5 and #4 poles both fail. For the bottom poles, Figure 9 clearly shows that #11, #12, #13, #14 and #15 poles may all be eliminated without much impact on the dynamics for this application.

CONCLUSION

Power amplifier and coil failures can be catastrophic for rotor systems using magnetic bearings. A magnetic bearing control scheme that copes with this type of failure has been described, including a nonlinear formulation of the magnetic bearing dynamics based on this scheme and the transient simulation of rotor responses when the failures occur. The scheme independently controls each magnetic bearing pole without requiring on-line monitoring of failures or use of any precalculated, stored control data. When pole failures occur, the remaining poles work in unison and adjust current individually to regain control of the rotor, demonstrating the characteristics of a self-healing magnetic bearing.

REFERENCES

1. Lyons, J. P., et al.: "Design and Control of a Fault-Tolerant Active Magnetic Bearing System for Aircraft Engines." *Proceedings of 4th ISMB*, Zurich, Switzerland, pp. 449-454, August 23-26, 1994.

2. Maslen, E. H., et al,: "A Fault Tolerant Magnetic Bearing System." *Proceedings of MAG'97*, Alexandria, Virginia, pp. 231-240, August 21-22, 1997.

3. Chen, H. M.: "Self-Healing Magnetic Bearings." *Proceedings of 53rd Meeting of the Society for Machinery Failure Prevention Technology*, Virginia Beach, Virginia, April 19-22, 1999.

4. Eigen Technologies: "*DyRoBeS(c) User's Manual - Version 5.0.*" Eigen Technologies, Inc., Kentucky, 1999.

5. Chen, W. J.: "A Note on Computational Rotor Dynamics." *ASME Journal of Vibration and Acoustics*, Vol. 120, pp. 228-233, January 1998.

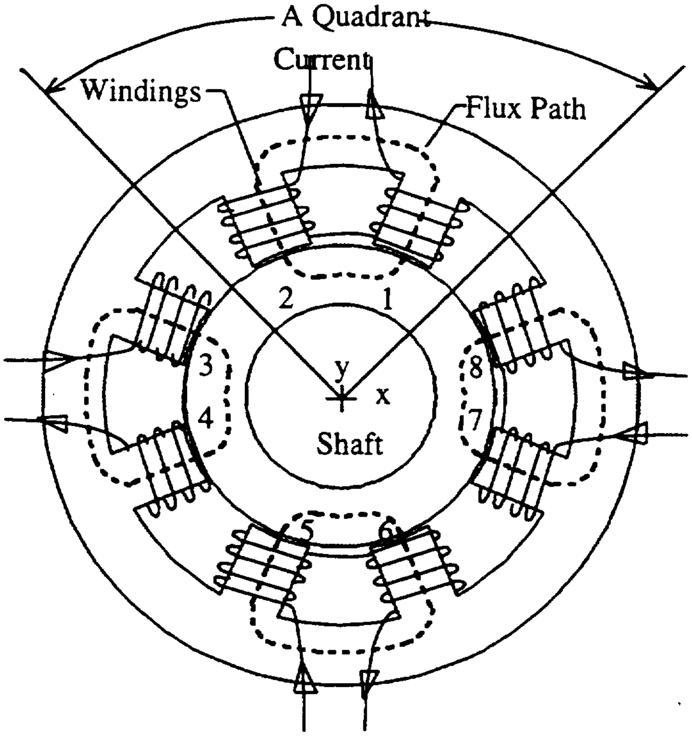

Figure 1. Conventional magnetic bearing coil arrangement

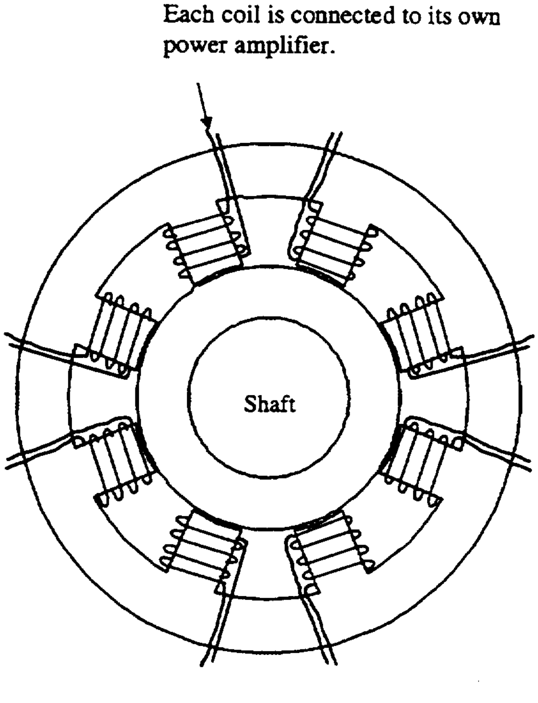

Figure 2. Self-healing magnetic bearing coil arrangement

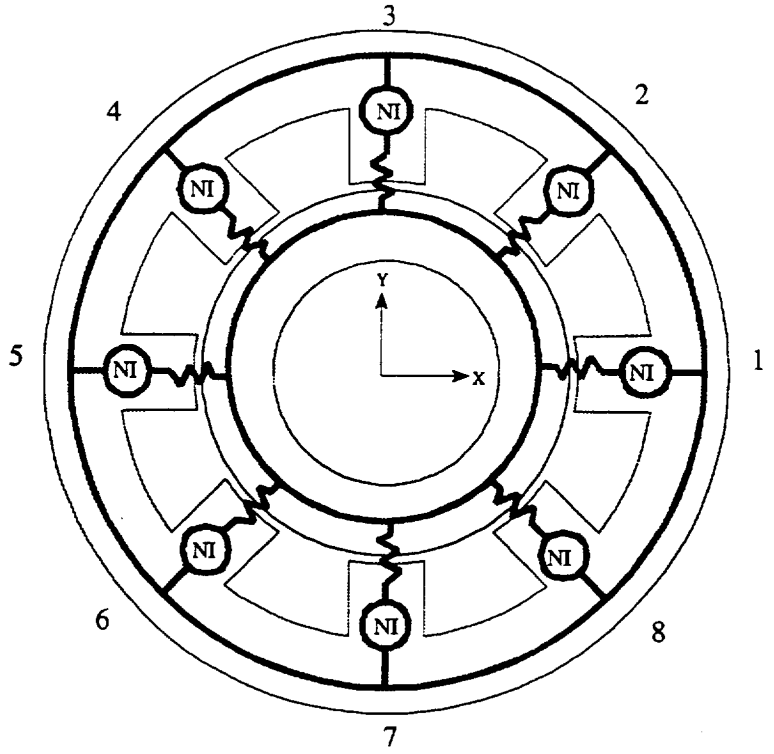

Figure 3. Self-healing magnetic bearing mathematical model

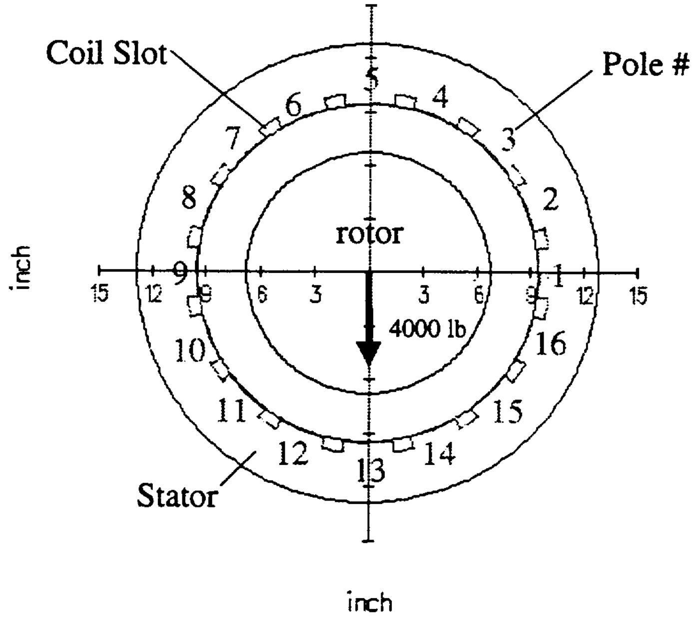

Figure 4. A 16-pole self-healing magnetic bearing

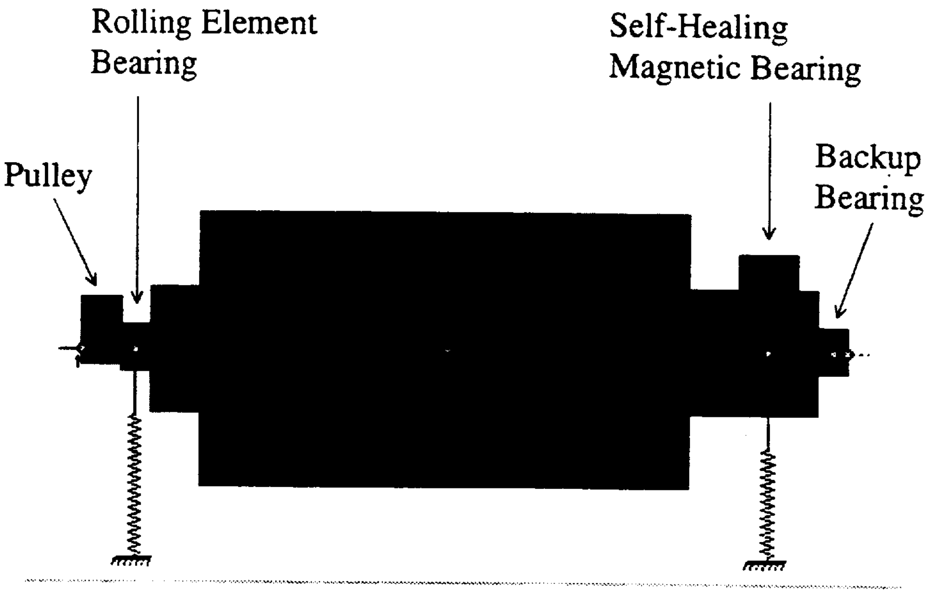

Figure 5. Test rotor mathematical model

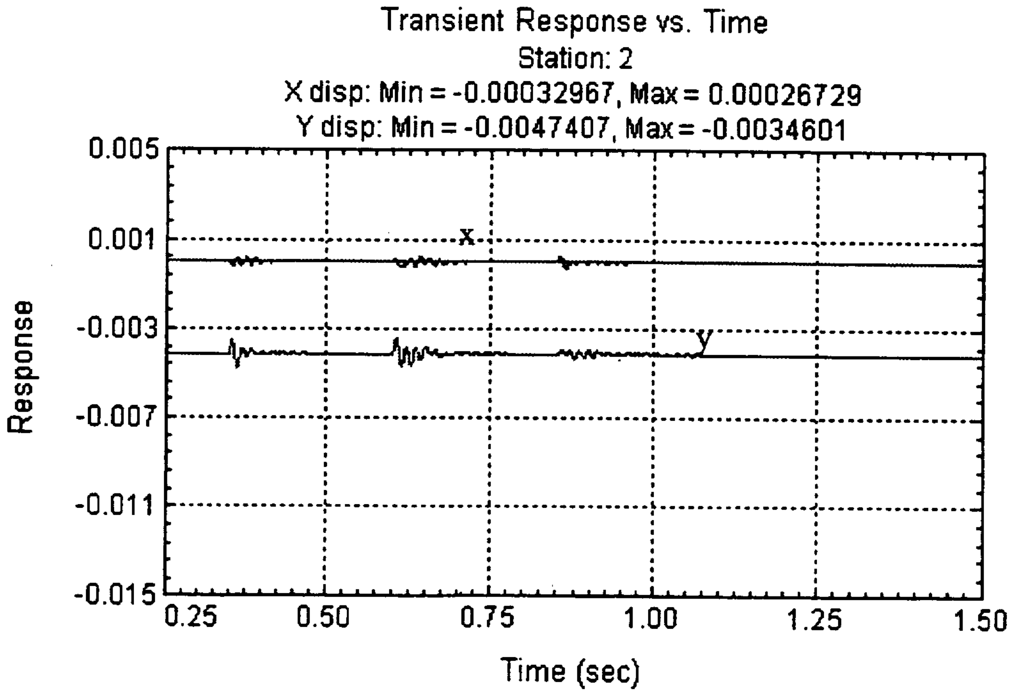

Figure 6. Simulated transient response at rolling element bearing due to pole failures

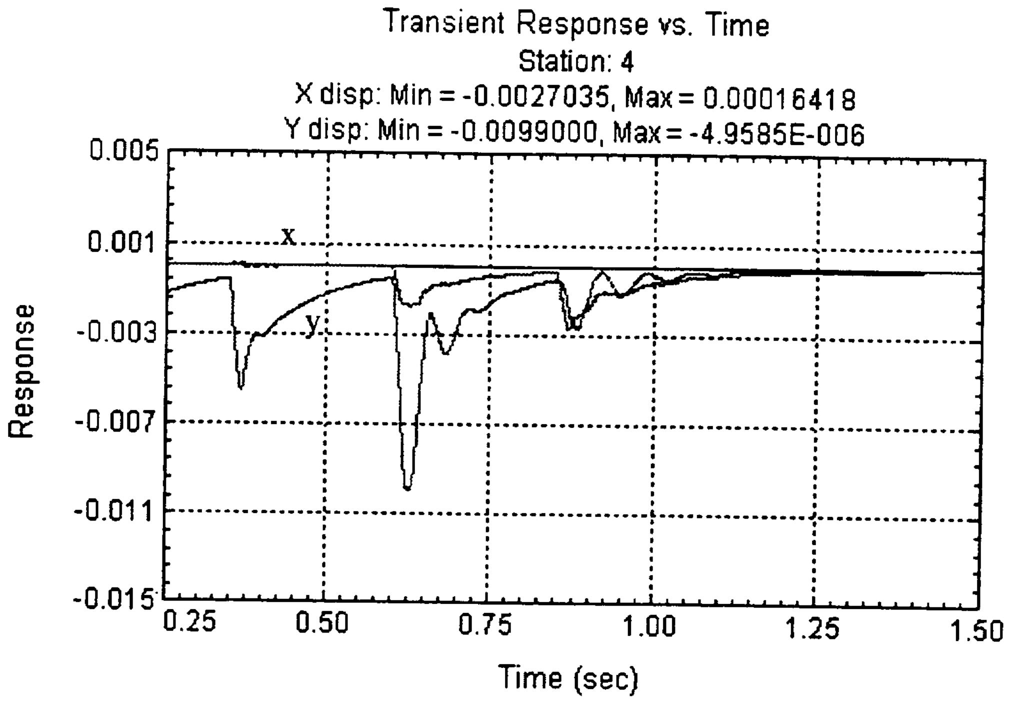

Figure 7. Simulated transient response at self-healing bearing due to pole failures

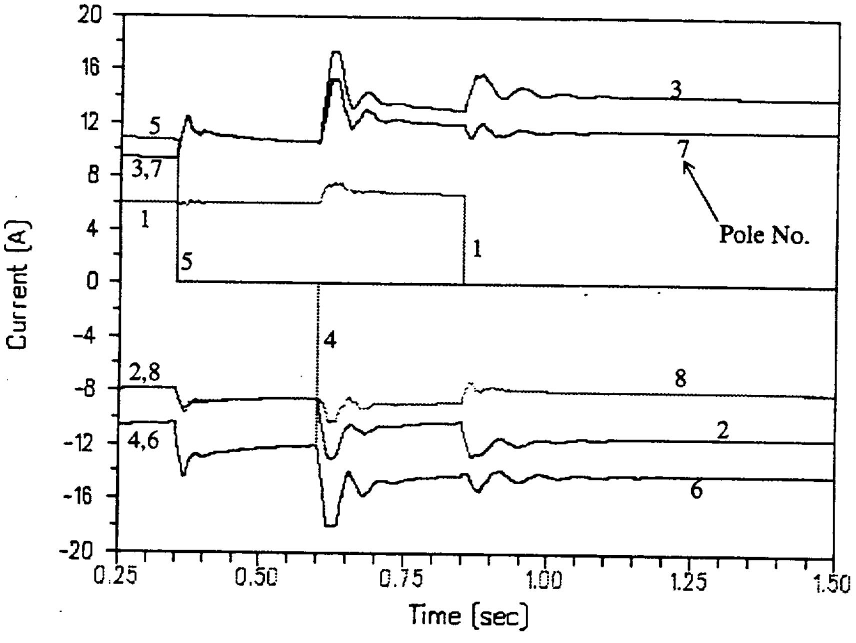

Figure 8. Simulated transient top-pole coil currents due to pole failures

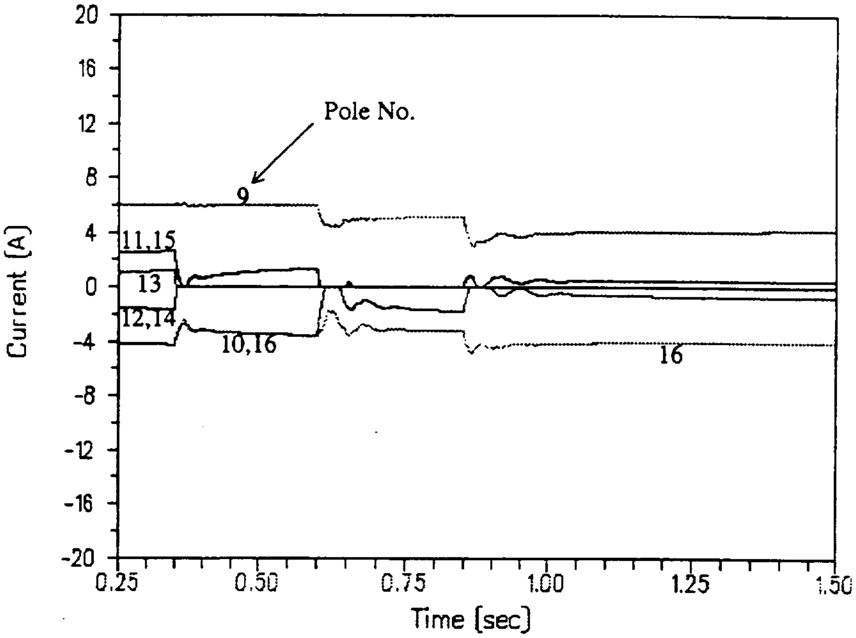

Figure 9. Simulated transient bottom-pole coil currents due to pole failures