MAGNETIC BEARING PROJECTS IN THE USA ELECTRIC UTILITY INDUSTRY

Thomas McCloskey
Electric Power Research Institute
Graham Jones
Technology Insights

ABSTRACT

EPRI is convinced of the technical merit and the potential cost benefit of magnetic bearings in the electric utility industry, as demonstrated by the two recently completed projects, funded by Empire State Electric Energy Research Corporation (ESEERCO), Electric Power Research Institute (EPRI) and New York State Energy Research Development Association (NYSERDA). However, due to the novelty of the technology and the multi-disciplinary nature, together with the high costs, the technology is not yet being commercially applied.

Accordingly, EPRI is initiating a program, with the overall objective of accelerating the commercial application, in the following areas:

- Assessment of the technology and it's cost benefits
- Reviewing the need for supporting technology development
- Providing industry guidelines to assist future users
- Supporting further demonstration projects where needed
- Providing methods and materials for technology transfer into operating plants

In parallel, ESEERCO is funding a study within the New York State utilities to determine if and how joint specifications/procurement can be used to make magnetic bearings more cost effective. This study could later be expanded through collaboration with EPRI.

An EPRI Advisory Committee on Magnetic Bearings has been initiated with the primary objective of providing industry guidelines that simplify and accelerate the commercial adoption of magnetic bearings in the electric utility industry. In addition, it is expected that the Committee will also provide guidance and data to support the other activities in the overall EPRI program. The five areas in which the Committee plans to develop guidelines are:

- Design Specifications
- Balancing
- Installation and Testing
- Controls & Redundancy
- Training Operation and Maintenance

This paper will present the results, status and plan of EPRI's overall magnetic bearing program.

INTRODUCTION

The U.S. electric utility industry has been investigating the benefits of magnetic bearings from as far back as 1986. The initial impetus for this activity was the selection of magnetic bearings for the helium circulator in the High Temperature Gas Cooled Reactor, to avoid any lubricant ingress problem, as experienced in the Fort St. Vrain reactor, due to the use of high pressure water bearings.

Two areas of concern were identified that needed support. The first was to develop a satisfactory auxiliary bearing that would operate on a vertical machine in the very dry helium environment of the primary coolant helium, which results in high friction coefficients. The second was to initiate a program to review the overall potential of magnetic bearings in the electric utility industry, and if there was sufficient potential initiate their introduction so that there would be a confidence base to support the adoption of magnetic bearings in a nuclear reactor.

This paper covers both those areas: (1) The development program for the helium circulator auxiliary bearing through EPRI which points out some of the current and future concerns regarding auxiliary bearings in high speed and vertical machines; and (2) the parallel and ongoing program through EPRI and ESEERCO to initiate demonstration programs within the electric utility industry for equipment on magnetic bearings, and to prepare for commercial applications.

HELIUM CIRCULATOR AUXILIARY BEARING DEVELOPMENT

Very early work sponsored by EPRI, and carried out by James Howden and Company, Limited of Scotland, developed and qualified under test conditions, an auxiliary thrust bearing for use on a vertical 5 MW helium compressor, operating in dry helium, where the friction coefficients were very high. On failure of the magnetic bearings, the top of the shaft will be centered by the conical surface of the auxiliary thrust bearing, but the lower end of the shaft will be free to accelerate with a conical pendulum mode within the constraints of the lower auxiliary journal bearing (Figure 1). The objective of the program was to develop a detail design that would withstand the drop load and which limited this whirling motion such that the bearing could survive 20 drops without failure.

This involved a drop load of 22,400 lbs. and the main requirement in the thrust bearing project was to optimize the contact surface detail design and the surface treatments to withstand the required 20 drops during a rapid rundown with a shaft speed half life of 3 to 4 seconds from 6000 rpm. The thrust bearing design incorporated a conical surface with a shrunk-in insert of carbon that was designed to slip while allowing the ball bearings to accelerate without slipping. This surface was thus the sacrificial surface that was designed for replaceability. Even after significant wear and cracking, it continued to stay in place and serve its function. The ball bearings employed were angular contact type with the brass

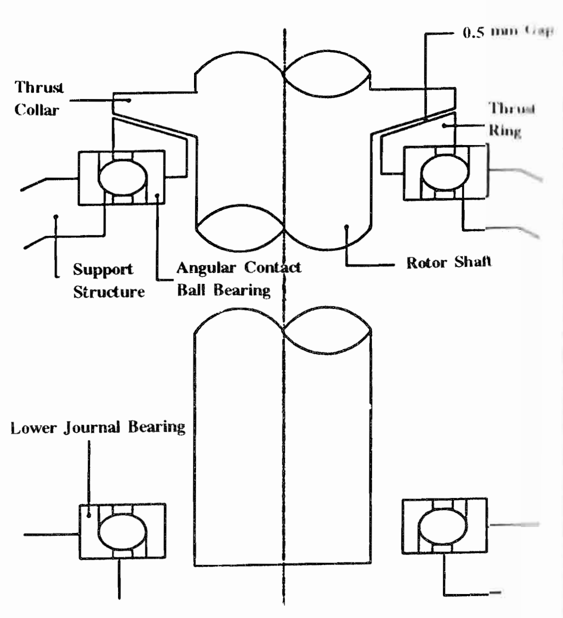

FIGURE 1: Helium Circulatory Aux. Bearing Arrangement

cage machined from the solid. Variables that were optimized during the test were the grease employed in the ball bearings, the material for the carbon surface, the angle of the contact surface, and two types of cage, an inner ring centered and a rolling element centered cage. The thrust ring was shown to accelerate to shaft speed in about 30 milli-seconds.

The developed thrust bearing withstood up to 27 drops in the final configuration.

Howden then started to develop the theory for the motion and forces involved in the lower auxiliary journal bearing on failure of the magnetic bearing, as they found no analytical tools that would provide this data. They proceeded as far as testing their initial code on a small rig, before the project was canceled for programmatic reasons.

The initial analytical study confirmed that a balanced rotor with no destabilizing magnetic forces from the rotor or from aerodynamic loads would, in all probability, not initiate reverse conical pendulum precession mode in a short rundown. It would be initiated if the rundown time was long as would be experienced at low helium pressure. Once contact is established the tangential friction force will accelerate the shaft into an orbital mode. As the orbital speed increases, so will the tangential friction force and hence, if there are no limiting conditions, an exponential increase in orbital whirl speed.

Thus, a full scale test was envisaged where a destabilizing force could be employed and where a significant rundown time would allow the shaft to be driven into a reverse precession by contact friction at the lower auxiliary journal bearing.

In preparation for this full scale test the 1/4 scale test was carried out with some interesting conclusions:

- If initiated, whirling speed is not limited by dynamic phenomenon, but by equalization of damping energy with energy input due to friction.
- The major friction energy is the rolling element friction, which is amplified in the ratio of bearing diameter/bearing clearance in being transferred to the shaft center.
- For normal structural damping the whirling speed is below first critical but still high forces are involved.
- Forces which initiate whirling are random and many of the initiating forces (gravity, hydrodynamic bearing forces, steady side load, corriolis effect), and with the exception of out-of-balance forces, were stabilizing and did not induce whirl.
- In practice, decaying motor magnetic forces, decaying bearing forces, and impeller aerodynamic loads will have a significant impact, but it will be impossible to predict the forces involved accurately.
- Orbital speed is independent of support stiffness.

The results of this work, and that of other contributors in the field were clearly conflicting in some areas, and a summary report was prepared on the subject of auxiliary bearings, which is now included in the EPRI Guidelines. It concluded that until more industry-wide code development and correlation, and bearing testing was completed, that individual prototypical projects would have to bear the load of time consuming auxiliary bearing qualification testing in most medium to high speed applications.

OVERALL APPLICATION OF MAGNETIC BEARINGS TO THE ELECTRIC UTILITY INDUSTRY

With the objective to determine whether the electric utility industry in the U.S. was ready to accept magnetic bearings in plant applications, EPRI in conjunction with ESEERCO and the Public Service Company of Colorado, initiated a study (Reference 1) to assess the potential benefits of magnetic bearings to the U.S. electric utility industry. The study concluded that there was a strong incentive to use magnetic bearings in equipment such as pumps, fans, turbines and generators, but that each application would need a demonstration project that would ensure that the unknowns were eliminated prior to procurement for commercial applications. This led to a second study, supported by ESEERCO,to identify the best applications on which to start the demonstration process. This study (Reference 2) concluded that a small boiler feed pump with the bearings operating in air would be the best place to start, primarily to prove the operability of the bearings in a utility environment. Assuming that this was successful, the second project was identified as a large gas recirculation fan where the very significant problems associated with continuously developing imbalance could be tackled.

FEEDPUMP PROJECT

The boiler feedpump selected was one of three 50% pumps rated at 600 hp, 3,580 rpm. The pump is located machine at New York State Electric and Gas's Greenidge Plant where procurement of three new Ingersoll-Rand pumps was in process to replace three ageing pumps. With ESEERCO funding the incremental costs, one of these three was switched to a magnetic bearing unit, with bearings manufactured by Magnetic Bearings Inc. (MBI), during the procurement phase. The pump (Figure 2) has been in service for three years and after the initial tuning process has run very reliably. It is noted that during the tuning process, a lot was learned about the bearing loads that was not known previously. Specifically the areas where bearing loads were significantly underpredicted were journal bearing loads due to a small, and within normal tolerance, initial misalignment with the drive motor, and the thrust load associated with cavitation in rotors on one side of the pump centerline only. Sufficient margins had been allowed in the magnetic bearing design to handle these loads. We would expect that with the very close positioning of the shaft during all normal operations and the consequent lack of wearing parts, this machine should be in excellent shape internally as far as wear of the seals and other components is concerned. Details of the project have been reported in Reference 3.

In this non-demanding application magnetic bearings are a commercially available technology that would

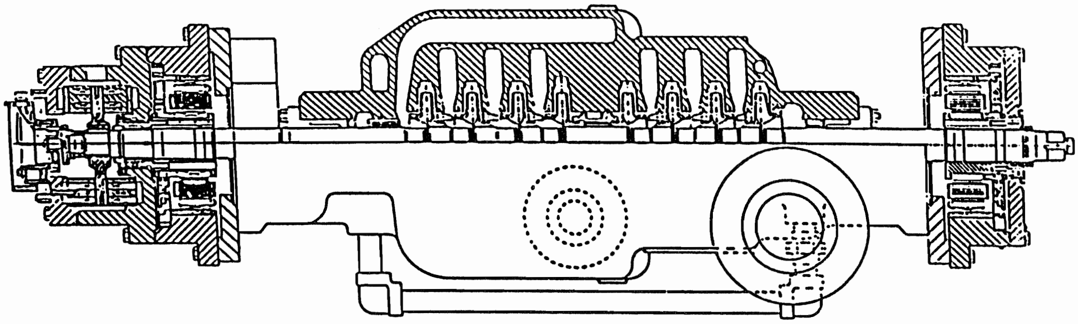

FIGURE 2: Feed Pump Section - 8 Stage Boiler Feed Pump with Magnetic Bearings

have a payback of about a year in a non-redundant pump due to improved reliability. This payback was based on the actual operating and the maintenance history of the three pumps over the previous nine years.

LARGE FAN PROJECT

The fan application was selected for two reasons. First, gas recirculating and induced draft fans have a long history of unavailability due in large part, directly or indirectly, to imbalance problems caused by dust buildup. Secondly, a gas recirculating fan can be taken out of service without taking a unit off-line, and so the time required to demonstrate the magnetic bearing capability would only result in reduced plant output or slightly increased emissions, and not loss of power. The project was funded by ESEERCO, EPRI and the New York State Energy Research and Development Authority.

The project involved replacing the original drive motor with a new Reliance Electric motor supported on two MBI magnetic journal bearings. The fabrication and testing of this motor was a very uneventful project which says a lot for the technology and the two organizations involved. Suffice to say that everything worked as planned the first time, including five full speed drops onto the auxiliary bearings.

The fan was expected to be, and was, more of a challenge than the motor. First, it was decided to reduce the critical speed from just above the operating speed which was 890 rpm to about 600 rpm. This involved reducing the shaft diameter to about 13 inches from about 20 inches. This step was taken in order to be able to show that running up through a critical speed with high levels of imbalance was feasible on magnetic bearings, hence paving the way for future applications where a large shaft diameter would no longer be required to keep the first critical speed above the running speed. This in turn allows a more efficient flow path and an increased aerodynamic efficiency of between 1 and 5% depending on the fan design.

Secondly, it was planned to handle very large imbalances, with the project specification being 4,335 in-oz imbalance capability which is more that four times that under which the fan would previously have been run. The softer bearing system and the magnetic bearing control algorithm resulted in a significantly increased shaft motion due to imbalance, but an equally significant reduction in bearing housing motion and hence bearing housing reaction loads. This increased shaft motion is of course limited by the clearance between the shaft and the internal diameter of the auxiliary bearing, with the design set so that contact would be made between the shaft and the auxiliary bearing at the design limit of 4,335 in-oz.

Active magnetic bearings work in attraction and one interesting aspect of the design for the magnetic bearings for the fan was that only the upper quadrant magnets needed to be installed. This was despite the high imbalance specification and as a result of the high weight and low speed of the shaft. Using two upper quadrants only instead of two upper and two lower, the two amplifiers normally used for opposing quadrants, one lower and one upper, were combined to provide more capacity where it was needed in each upper quadrant. Some of those associated with the project took a little convincing that this was indeed an adequate means of support, and this convincing was done with the aid of a design review by the University of Virginia, who gave the design a clean bill of health.

Testing of the fan was carried out both in the factory and on the site up to just over half the design level imbalance and the shaft motion was well within the design prediction. Furthermore the sensitivity of the bearing housing motion to fan shaft imbalance was reduced by a factor of 35 from that seen when running on conventional bearings. A cross section of the fan is shown in Figure 3.

A complicating factor in acceptance testing of machines equipped with magnetic bearings is that even with high imbalance, the bearing housing motion may be very small right up to the limiting point where the shaft contacts the auxiliary bearing and magnetic bearing control stability is jeopardized. That is, conventional balancing specifications may need to be reconsidered, with the key control parameter now being the shaft motion that is acceptable, leaving a sufficient margin before contact with the auxiliary bearing, and not the housing motion.

Several other interesting observations were made during the initial testing period. Significantly more amplifier current was needed for bearing control at higher frequencies where aerodynamic forces became apparent. This was within the control system capability, but the currents were large enough that they should be anticipated in future designs. Also, there were two other large fans on the same foundation mat, and the forces required to react to the foundation movements caused by an unbalanced adjacent fan were noticeable in the amplifier control currents, and again should be allowed for in future designs. Figure 4 shows the proportions of the amplifier current needed for static lift, imbalance control, aerodynamic forces and foundation movement.

Normally, the fan is circulating gas at up to 650 °F and the shaft entering the bearing housing is still relatively hot. At one point during test runs, it is believed that a combination of some misalignment and the thermal expansion of the shaft caused a rub on the auxiliary bearing inner race which started turning, and eventually overheated and failed. There is sufficient preload on these bearings to prevent turning under normal operating conditions. The resulting damage was significant enough to cause the control system to trip the fan and it came to rest, still levitated on the magnetic bearing. Examination of all four auxiliary bearings (two pairs for each magnetic bearing) showed that the other three were in excellent

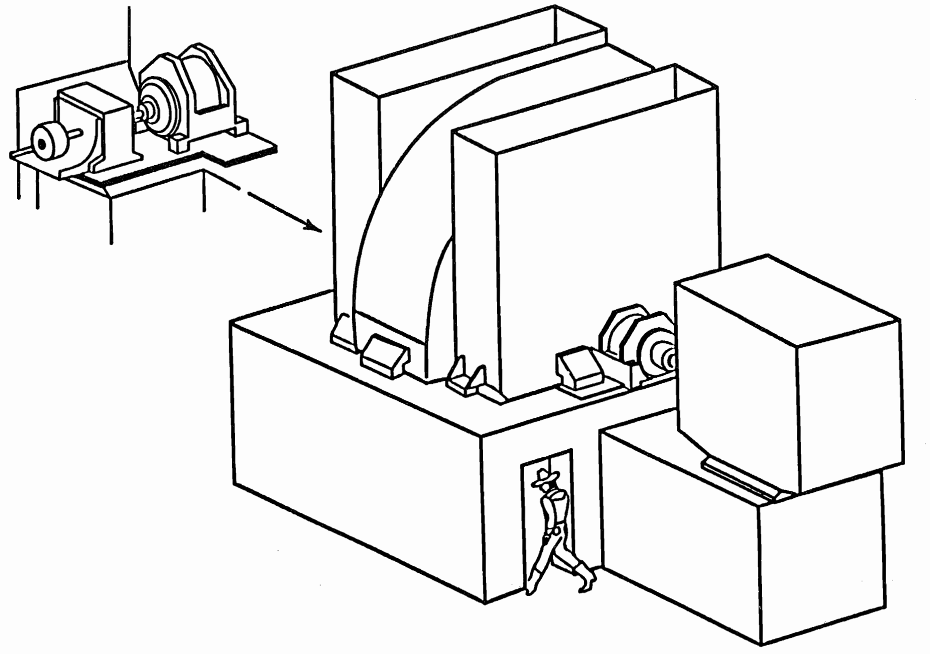

FIGURE 3: 3500HP Fan/Motor

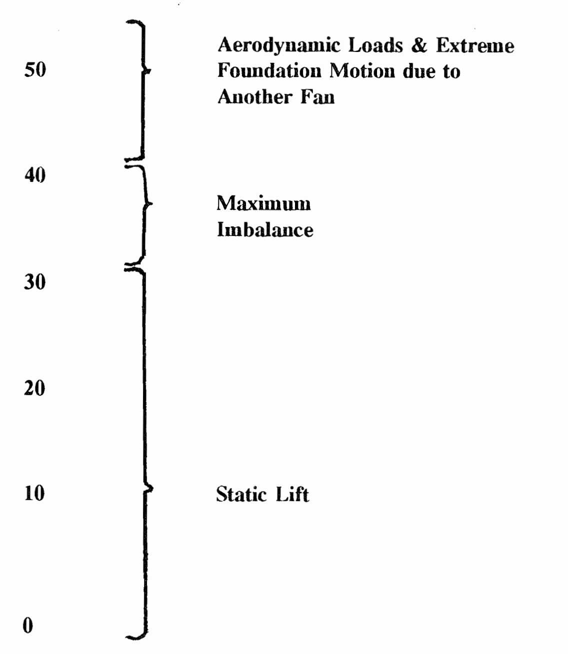

FIGURE 4: Bearing Current Requirements

condition, having seen service in the factory tuning and testing, site tuning and testing and having run many hours at turning gear speed and seen six operator activated trips onto the auxiliary bearing. The failed bearing was replaced after the examination and after increasing the clearance between the inner race and the shaft. The positive news from this event was that unless they are engaged under normal operating conditions, the auxiliary bearings appear to be a sound design, and that failure due to this engagement results in the planned shutdown. The magnetic bearings on this fan are 20 inches long, and for the restart after replacing the auxiliary bearing, instrumentation was connected to check the clearance at both ends instead of just one end, and to trip the fan when and if necessary.

It had also been difficult to tune the axial bearing which had been designed based on gas loads expected. The capability of this design was increased to make it fully capable of handling significant axial vibrations of the shaft associated with the kick-in of the turning gear at 60 rpm which operates through a right angle gear drive and with oscillations of the motor on coast-down when magnetic centering is lost (there is no thrust bearing on the motor).

As part of the initial testing program a controller made by Noise Cancellation Technologies was coupled to the magnetic bearing control system and

TABLE 1 ADVANTAGES OF MAGNETIC BEARINGS IN LARGE FANS
1. Increased Efficiency
2. Increased Availability
3. Elimination of Lubricating Oil
4. Foundation Weight/Size Reduction
5. Reduced Maintenance Costs
6. Predictive Maintenance
7. Improved Balancing
8. Quick Shutdown with Structural Failure or Overload
9. Reduced Balance Requirement
10. Reduced Time to Start Up with a Bowed Shaft
11. Elimination of Primary Bearing Wear
12. Reduction of Shaft Critical Speed - Fan Efficiency
13. Reduction of Bearing Stiffness - Lower Vibration Loads
14. Shaft Weight Reduction
15. Potential Longer Periods Between Rebalancing
16. More Flexibility in Scheduling Rebalancing
17. Improved Fan Diagnostics

used to cancel the synchronous imbalance load, when running at operational speed with 2,168 in-oz imbalance, and allow the fan shaft to float on its axis of inertia instead of its geometric axis. This controller was allowed to phase in over a two-minute period and was shown to be a very safe and controllable way of further reducing the imbalance load to the foundation. Due to pressure to put the fan back on-line this testing was only carried out for a very short time, and full optimization remains to be demonstrated. However, it appears a very significant capability.

In summary, the overall magnetic bearing design achieved all that was required with some margin in terms of running through and above the first critical speed and in handling large imbalances with insignificant loads to the foundation. The problems with the auxiliary bearing emphasize the need to ensure that the bearing cannot be engaged other than following a magnetic bearing failure or delevitation. This project is fully reported in Reference 4 and

TABLE 2
DIAGNOSIS OF POTENTIAL FAN PROBLEMS

ROOT CAUSE	POTENTIAL DIAGNOSIS	POTENTIAL TO RECTIFY USING BEARING
Low Pedestal Stiffness	Yes	Retune Bearing
Changing Pedestal Stiffness	Yes	Retune Bearing
Improper Tie-Down	Yes	---
Impeller Imbalance	Yes	Can be controlled & monitored up to design level. Rebalance requirements can be determined.
Shaft Critical Speed Near Running Speed	Yes	Retune Bearing
Vibration Induced at Blade Passing Frequency	Yes	
Flow Instability/Surge	Yes	
Misalignment of Fan/Drive Motor	Yes, if coupling loads are generated	
Bent Shaft	Yes	
Bad Grout	Yes	
Shaft Rub	Yes	
Warped Thrust Collar	Yes	
Loose Rivets on Wheel	Possibly	
Bad Shrink Fit of Wheel on Hub	Possibly	
Dust/Ash Build-up	Yes	Can be controlled & monitored up to design level. Rebalance can be determined.
Blade Erosion	Yes	Can be controlled & monitored up to design level. Rebalance can be determined.
Wheel Warpage	Possible	
Flow Excitation	Yes	
Across Obstructions Vortex Shedding	Yes	
Inlet Box Vortex	Yes	
Rotating Stall	Yes	
Blade Failure	Yes	
Lub System Failure	N/A	Eliminated

summarized in Reference 5. Table 1 gives a summary of the many advantages that were recognized during the course of the project. Table 2 is a list of the problems that have historically plagued large fans of this type with an indication of where, with experience and training, the problems can be diagnosed and cured using the standard information obtained from the magnetic bearings control system.

TECHNOLOGY TRANSFER

Following the progress in the above projects, EPRI has initiated a magnetic bearing program with several objectives:

- Assessment of the technology and it's cost-benefits
- Providing industry guidelines to assist future users
- Reviewing the need for supporting technology development
- Supporting further demonstration projects where these are needed
- Providing methods and materials for technology transfer into plant operating units

Through this program, an industry advisory committee has been formed, comprising members from the magnetic bearing manufacturers, the OEMs and the end users. Guidelines have been prepared for the assessment, specification, acceptance testing and use of magnetic bearings (Reference 6).

Reliability is the key to most of the economic benefits of magnetic bearings and the EPRI program reviewed the industry experience that was available. From this it was concluded that while many prototype installations operated reliably from day one, many others took a period that was often as long as a year to experience all the operating transients that would challenge the bearing limits, and cause alarms or trips, or equipment failure. The lesson was to allow a significant period to gain this experience before committing to the follow-on units so that any necessary redesign could be accomplished. With this caution, nothing was seen that would prevent very high reliability being achieved in utility applications.

Utility workshops are planned to accelerate the technology transfer and the planning for the future on the commercial application of magnetic bearings. Further demonstrations are being encouraged through joint utility/EPRI funding.

Also, ESEERCO is pursuing the idea of standardization of specifications that will allow the design and tuning costs of magnetic bearings to be spread over a significant production quantity, instead of the one at a time process experienced to date.

CONCLUSIONS

The key conclusions drawn from the programs discussed are:

Magnetic bearings offer attractive potential to be wear-free, environmentally sound, and economically viable with a life of the in-machine elements potentially being as long as the machine itself.

The development of the detail design for any one type of machine, so as to achieve the required reliability to make them cost effective, can require significant refinement. Time, and expensive mistakes, can be avoided by the use of multi-disciplinary, multi-organizational team efforts early in the design stage.

The auxiliary bearings in high speed machines are still in the stage where designs have to be developed and tested on individual prototypes, with a reasonably high but not 100% chance of success with the first design. This should be changed by the funding of the necessary development programs, either commercially or at the national or international level.

Reliability improvement will continue through feedback of the learning experience and the development of operational guidelines, such as fostered by EPRI.

Quantity production could allow the costs to be reduced to that commensurate with the materials and components of the bearing systems. The initiative being sponsored by ESEERCO seeks to further such quantity production.

EPRI foresees the day when this technology will be common in large and small machinery in the electric utility industry.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the industry efforts in making the progress to-date in the electric utility industry. Key individuals include:

Jim Burger & Debbie DiMeo - ESEERCO
Gerald Janik & Harley Mossman - NYSEG
Doug Schmidt, Ray O'Sullivan & Barney Baxter
Orange & Rockland
Frank Pinckney & John Connelly - MBI
Paul Cooper & Gordon McGuiness - Ingersoll-Rand
Joe Ricci & Ray Zeaman - Howden Sirocco
Rich Markarian & Bob Daly - Reliance Electric
Paul Allaire, Eric Maslan & Carl Knospe
University of Virginia

REFERENCES

1. "Applications for Magnetic Bearings on Electric Generating Plant Equipment", Olson, E.A.J., S.M. Stoller Corporation, Grandal, W.M., Novacorp International Consulting, under ESEERCO Contract RP-2079, December 1988.

2. "Magnetic Bearings Applications Study Phase 2", EP88-10, Jones, G. Gas-Cooled Reactor Associates under ESEERCO Contract RP-2079, July 1990.

3. "Magnetic Bearing Boiler Feedpump Demonstration", EP89-39, Jones, G., Gas-Cooled Reactor Associates under ESEERCO Contract, October 1992.

4. "Project Report: Orange & Rockland Bowline Point Gas Recirculation Fan Magnetic Bearing Demonstration Project", Jones, G., Gas-Cooled Reactor Associates, June 1993.

5. "Active Magnetic Bearings on a Large Utility Fan", Connelly, J.H., Magnetic Bearings Inc., Schmidt, D.W., Orange & Rockland Utilities, Jones, G., Technology Insights, Paper for Power Gen '93 Conference, November 1993.

6. "EPRI Guidelines for the Assessment, Specification, Acceptance Testing and Use of Magnetic Bearings in Turbomachinery", TI-004, Developed by Technology Insights under EPRI Contract, June 1994.