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MAGNETIC BEARINGS with ZERO BIAS

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ABSTRACT

A magnetic bearing operating without a bias field has supported a shaft rotating at speeds up to 12,000 rpm with the usual four power supplies and with only two. A magnetic bearing is commonly operated with a bias current equal to half of the maximum current allowable in its coils. This linearizes the relation between net force and control current and improves the force slewing rate and hence the band width. The steady bias current dissipates power, however, even when no force is required from the bearing. The power wasted is equal to two-thirds of the power consumed at maximum force output. This paper examines the zero bias idea and finds both advantages and drawbacks.

Various workers have recognized that with digital controls the linearization ordinarily provided by the bias field could be accomplished within the control code simply by directing the power supplies to provide currents proportional to the square root of the desired force. Only those coils toward which force is needed would be energized. In situations where only a steady force is required, this technique saves substantial power. For zero force, no power is required at all.

In dynamic situations, current and force slew rate problems arise which require compromise of the zero-bias ideal but can be solved in a variety of ways with substantially less power consumption than the usual bias method.

Without bias, it is possible to reduce the number of controllable power supplies from the two usually required per bearing axis to only one per axis by using diodes in series with the coils on opposite sides of the bearing and connecting the two sides in parallel to a single supply. Then current of positive sense from the power supply flows through one coil and of negative sense through the other. In dynamic situations inductive effects cause currents to flow in both sides at once, again compromising the zero-bias ideal, giving errors in the desired force and thus generating higher harmonics in the force, but actually improving the force slewing rate. This method has been demonstrated successfully on the test rig at speeds up to 12,000 rpm.

Computer simulations of time histories of coil currents, power supply voltages, individual coil forces and net axis forces are shown for a few possible control strategies. The slew rate problems are not prohibitive at frequencies normally encountered in rotors. Performance data is presented for those strategies which have been actually implemented.

Any control law (such as the PD law in the first equation can be used to calculate a net force desired from the magnets acting on one axis of a bearing as shown in the figure. The force actually exerted by the magnets is given by the second equation. In the usual bias current approach, linearization and other advantages are obtained by setting $I_1 = I_b + I_c$ and $I_2 = I_b - I_c$, where I_b is the constant bias current and I_c is the control current. The net force obtained is proportional to I_c.

$$F = -kx - c\overset{\circ}{x} - \cdots$$

$$F = \alpha \left(I_1^2/g_1^2 - I_2^2/g_2^2 \right)$$
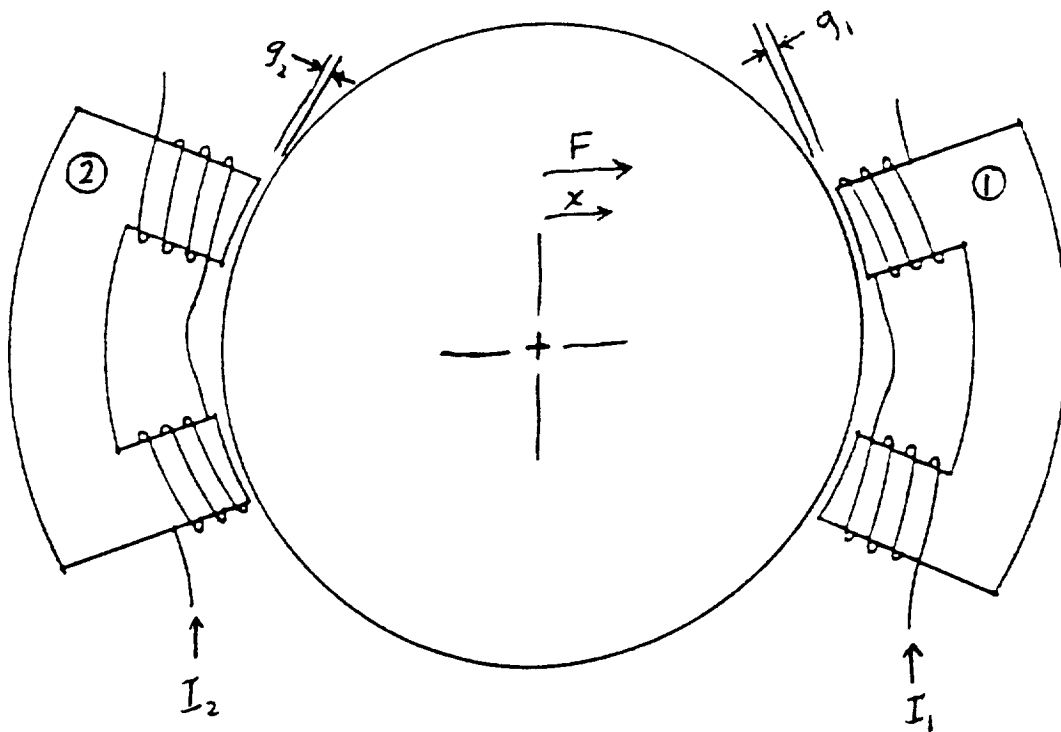
There are a number of favorable and unfavorable consequences of this commonly used linearization scheme, which include the following:

BIAS CURRENT LINEARIZATION

ADVANTAGES

LINEAR FORCE vs CONTROL CURRENT

REDUCED POSITION DEPENDENCE OF FORCE

MAXIMUM FORCE SLEWING RATE

DISADVANTAGES

WASTED ELECTRICAL POWER

HIGHER COIL TEMPERATURE, HENCE LOWER LOAD CAPACITY

INCREASED ROTOR EDDY CURRENTS (typical configurations)

TWO POWER SUPPLIES REQUIRED PER AXIS

To see how much power is wasted by the ever-present bias current, consider the top figures below which show the currents and power consumed in an example bearing under zero load (left figure) and at maximum load toward the top magnet (right figure). (Each electromagnet has 1 ohm resistance.) The power at no load is 2/3 of the power at maximum load. By comparison the lower figures show the power consumed by a bearing operating under zero and maximum load without bias. The power saving from eliminating bias is 100% at zero load and 33% at maximum load.
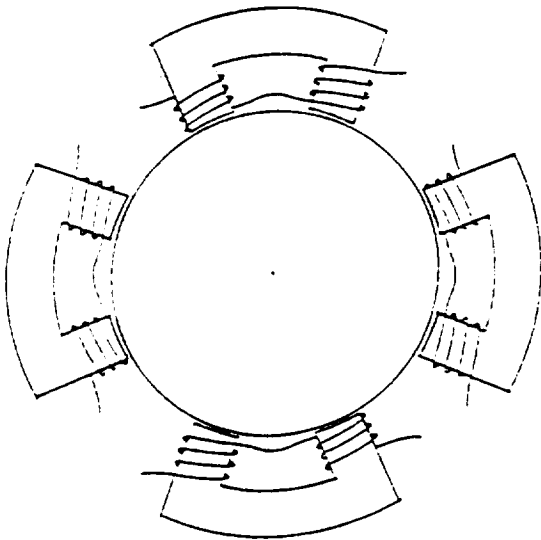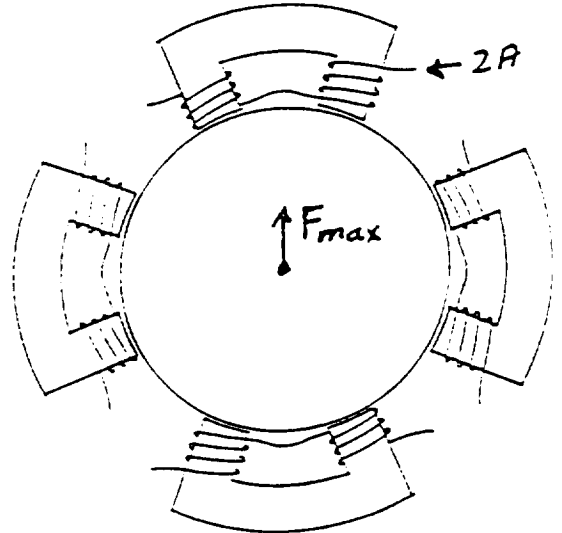
BIASED
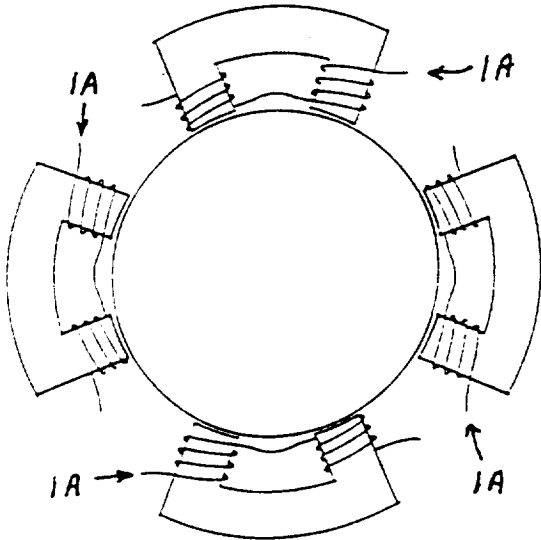
4 WATTS
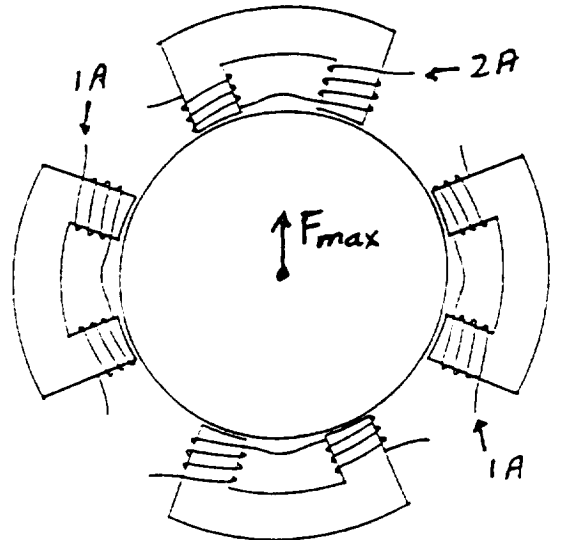
6 WATTS

UNBIASED

0 WATTS

4 WATTS

The "root" method of linearization has been considered by several researchers [1-4] and has been actually implemented [4]. The simplest philosophy is to use the control law, equation 1, to calculate a desired force and then to choose currents I_1 and I_2 to give that desired force consistent with equation 2. The minimum power consumption is obtained if one activates only that magnet toward which force is required. The required currents are then given by equation 3.

$$F = -kx - c\overset{\circ}{x} - \ldots \qquad (1)$$

$$F = \alpha \left(I_1^2/g_1^2 - I_2^2/g_2^2 \right) \qquad (2)$$

$$\text{for } F > 0 : \quad I_2 = 0, \quad I_1 = g_1 \sqrt{F/\alpha}$$
$$\text{for } F < 0 : \quad I_1 = 0, \quad I_2 = g_2 \sqrt{-F/\alpha} \qquad (3)$$

[1] Bleuler, H., "Decentralized Control of Magnetic Rotor Bearing Systems," Ph.D. Dissertation, Swiss Federal Institute of Technology, ETH report number 7573, Zurich, Switzerland, 1984.

[2] Maslen, E., Hermann, P., Scott, M., and Humphris, R. R., "Practical Limits to the Performance of Magnetic Bearings: Peak Force, Slew Rate, and Displacement Sensitivity," Transactions of the ASME, Journal of Tribology, Vol. 111, pp 331-336, April, 1989.

[3] Higuchi, T. et al, "Digital Control system for Magnetic Bearings with Automatic Balancing", Proceedings of the Second International Symposium on Magnetic Bearings, Tokyo, Japan, 1990.

[4] Ishida, S., "Linear Compensation for Magnetic Bearings", Proceedings of the Second International Symposium on Magnetic Bearings, Tokyo, Japan, 1990.

Root method linearization has been accomplished with analog controls but is perhaps more appropriate for digital controls, which can be used to ameliorate the slew rate problems. The major problems and advantages of the root method are as follows:

ROOT METHOD LINEARIZATION

DISADVANTAGES

ROOT AND MULTIPIER CIRCUITS FOR ANALOG CONTROL

FORCE SLEW RATE PROBLEMS, HENCE PHASE SHIFTS AND

    HARMONIC GENERATION

STRONGER POSITION DEPENDENCE OF FORCE (if neglected)

REQUIRES SWITCHING POWER SUPPLY FOR FULL POWER SAVING

ADVANTAGES

REDUCED ELECTRICAL POWER

LOWER COIL TEMPERATURE, HENCE HIGHER LOAD CAPACITY

REDUCED ROTOR EDDY CURRENTS

ONE OR TWO POWER SUPPLIES PER AXIS

A simple magnetic actuator and power supply circuit (one for each electromagnet) for use with the root method is represented below. The bipolar power operational amplifier can supply an output voltage between V_{max} and $-V_{max}$ with respect to ground. These voltage limits imply current slew rate limits in the inductive load, which are similar whether linearization is attained by bias current or by the root method. However the force slewing rate is generally lower in the root method, reaching zero when the current is zero.

Circuit parameters used in subsequent simulation calculations are V_{max} = 25 volts, L = 10 mh, R_{coil} = 0.8 ohms, R_s = 0.1 ohms.
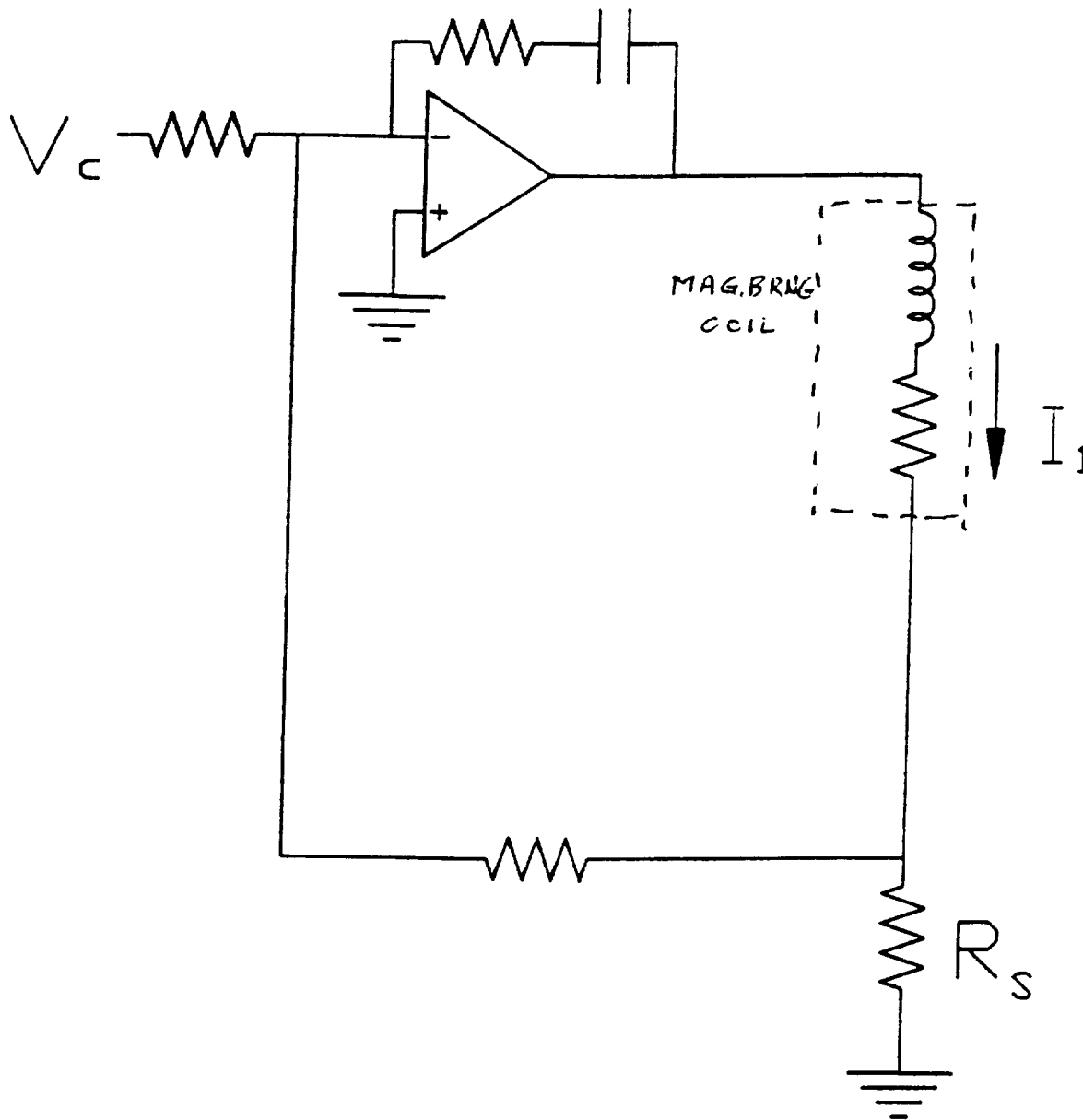
To show clearly the force slewing problem details, some computer simulations were performed for the two opposing magnets on an axis, each driven as shown in the previous figure. Shaft displacement is presumed negligible. Consider a purely dynamic load for which the control law asks for a force proportional to cos Ωt. We consider just one half period. The root method requests $I_1 \propto \sqrt{(\cos \Omega t)}$ and $I_2 = 0$ in the first quarter period and $I_1 = 0$ and $I_2 \propto -\sqrt{(-\cos \Omega t)}$ in the second quarter period. The negative sign is added before the root in I_2 only for plotting clarity. These currents requested from the power supplies are plotted as functions of time in the figure as I_s. The actual value of I_1 follows I_s until the power supply reaches its negative rail at time A and thereafter I_1 decreases to zero at an approximately linear rate, producing too much force in the positive direction. Worse, I_2 cannot start at the infinite requested rate, producing less force than requested until time B. The resulting force error (which generates a phase lag and harmonics) is shown, plotted on a scale where the requested cosine force has an amplitude of 1. The frequency and the current amplitude (half the bearing maximum current) were chosen to yield a sizable error and are higher than required in many applications.

The total force exerted could be Fourier analyzed to see whether its harmonics would excite higher shaft frequencies.

A small rotor has been run to 12000 rpm, through two critical speeds, using this method.

TWO POWER SUPPLIES PER AXIS
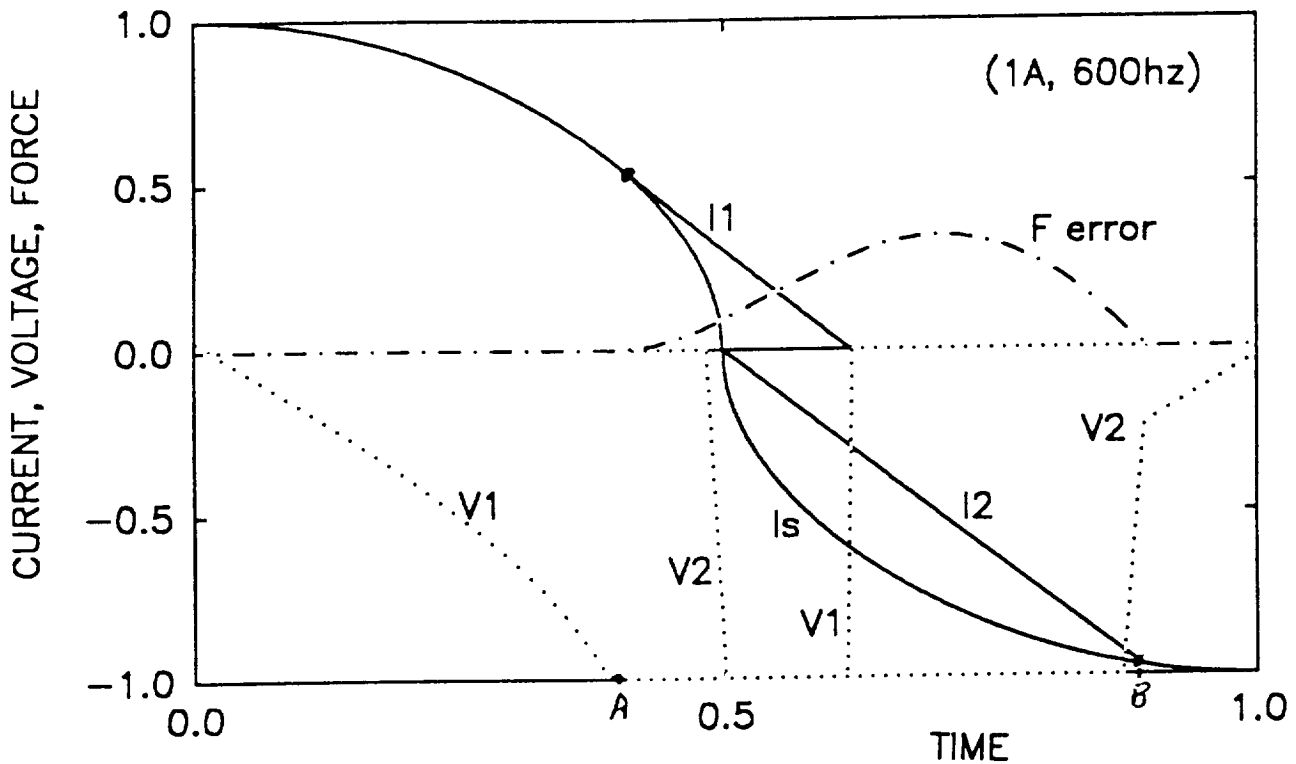
Experimental measurements of I_1 and I_2 were made with a rotor supported by conventional bearings with a magnetic bearing near one of the conventional ones. A pure cosine signal was fed to a digital controller which consequently requested $I_1 \propto \sqrt{(\cos \Omega t)}$ and $I_2 \propto \sqrt{(-\cos \Omega t)}$ in alternate half cycles. The results are plotted below for $-\pi \leq \Omega t \leq \pi$. The solid curves are the requested currents and the dash - dot and dash curves are the actual I_1 and I_2 respectively.

At low frequencies the deviations due to the current slew rate limits can hardly be seen, but at higher frequencies become serious.
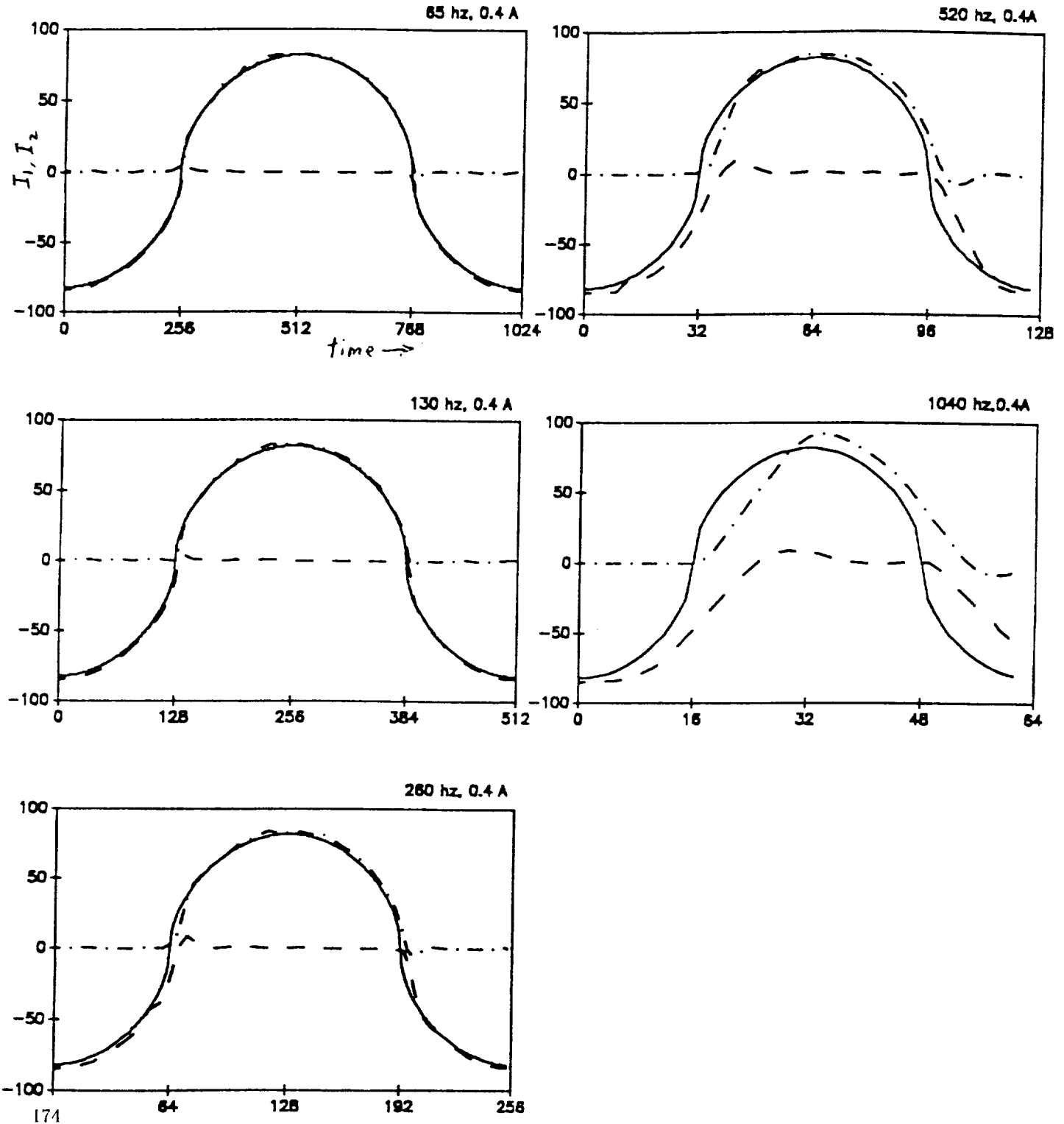
One obvious method of reducing the force error is to start the current I_2 earlier, for example when I_1 reaches its slew limit. (One could either measure or calculate when V_1 reaches its rail.) The result, shown below from a numerical simulation, is to substantially reduce the force error. Even earlier initiation of I_2 might virtually eliminate the contribution of the force error to the fundamental frequency, removing most of the phase lag.

The goal of using only one at a time of the opposing magnets has been compromised, of course, slightly increasing power consumption in order to improve frequency response.

TWO POWER SUPPLIES PER AXIS
## WITH SLEW LIMIT IMPROVEMENT
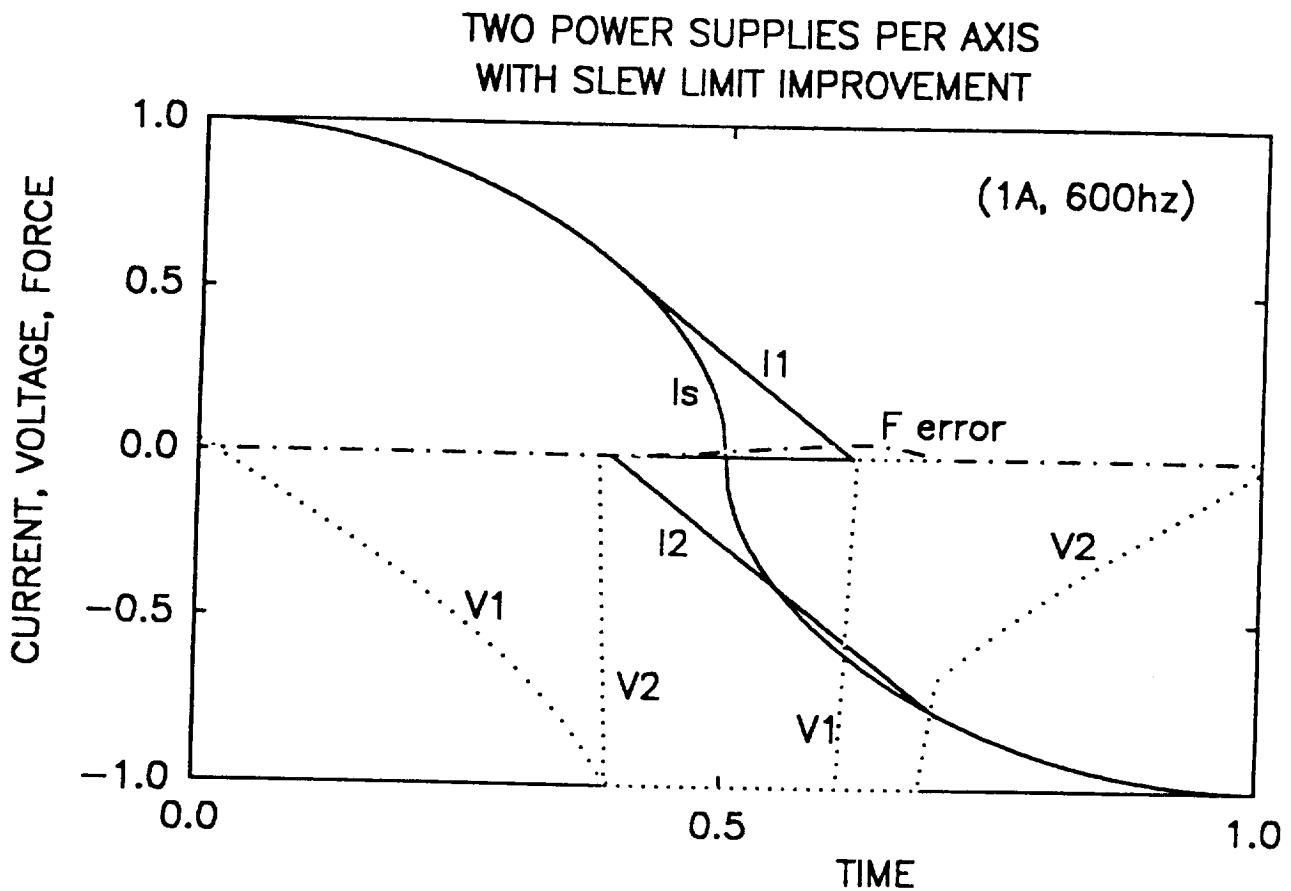
In the previous simulations one notes that the two power supply voltages have the same sign (negative) during most of the half cycle. One is tempted to use a single supply to power both coils in parallel, providing diodes to insure that under steady conditions only one coil carries current. Under dynamic conditions both coils carry current because of inductive behavior. But positive power supply vltage increases I_1 and decreases I_2 (subject to $I_1 \geq 0$ and $I_2 \leq 0$). The power supply sense resistor R_s carries $I_1 + I_2$.
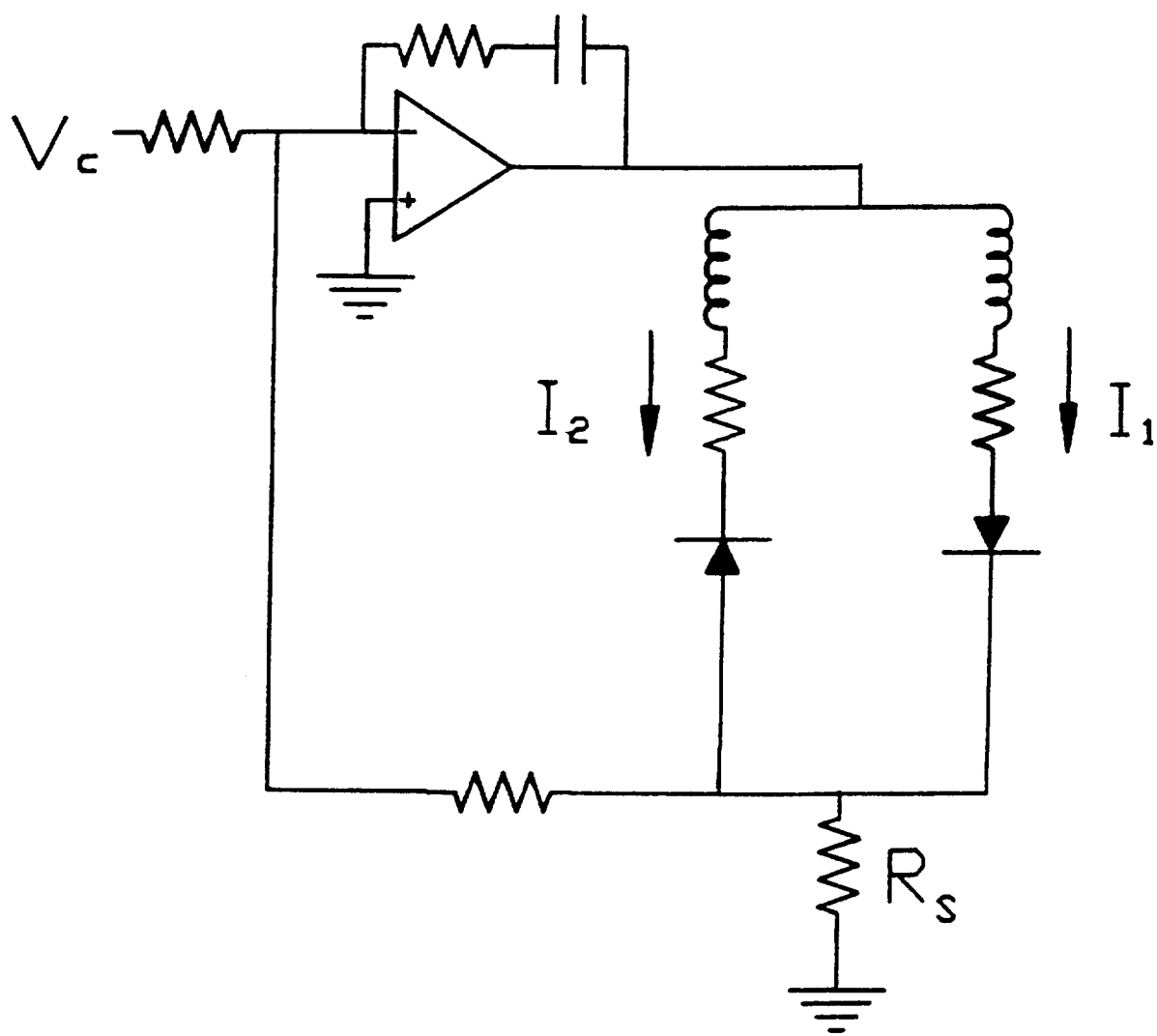
The numerical simulation bears out that both coils usually are active, but in such a way that force slewing is improved. (Actually the force lags even worse early in the half cycle but leads later, contributing less to the fundamental frequency of the force error.) The controller asks the single power supply for the current I_s, which is equal to $I_1 + I_2$.

A small rotor was supported under this scheme to 12000 rpm through two critical speeds.

ONE POWER SUPPLY PER AXIS
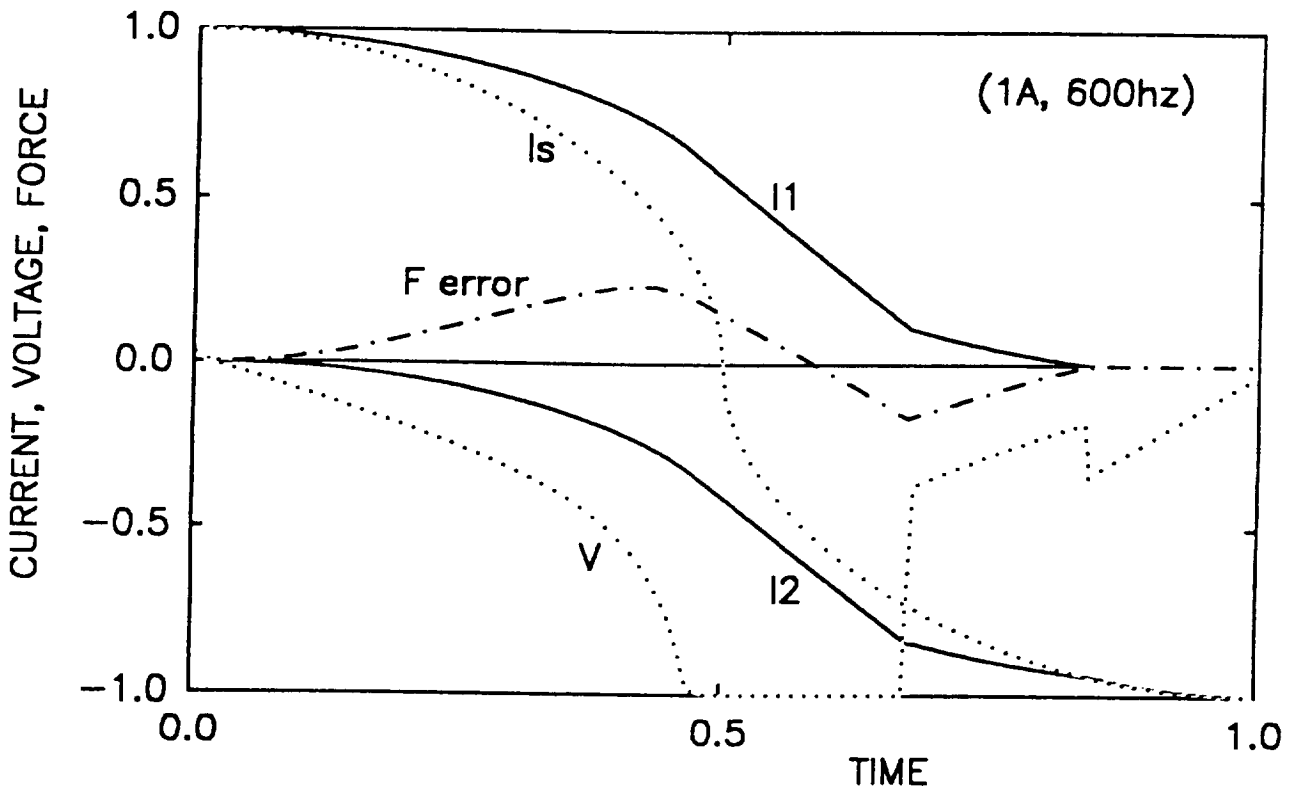
Experimental currents, measured under the same conditions as
before, again show reasonable fidelity to the requested values at
low frequency and large deviations at high frequency. Additional
kinks in the curves may be related to diode switching (forward
drop was neglected in the simulation) or to rotor motion.
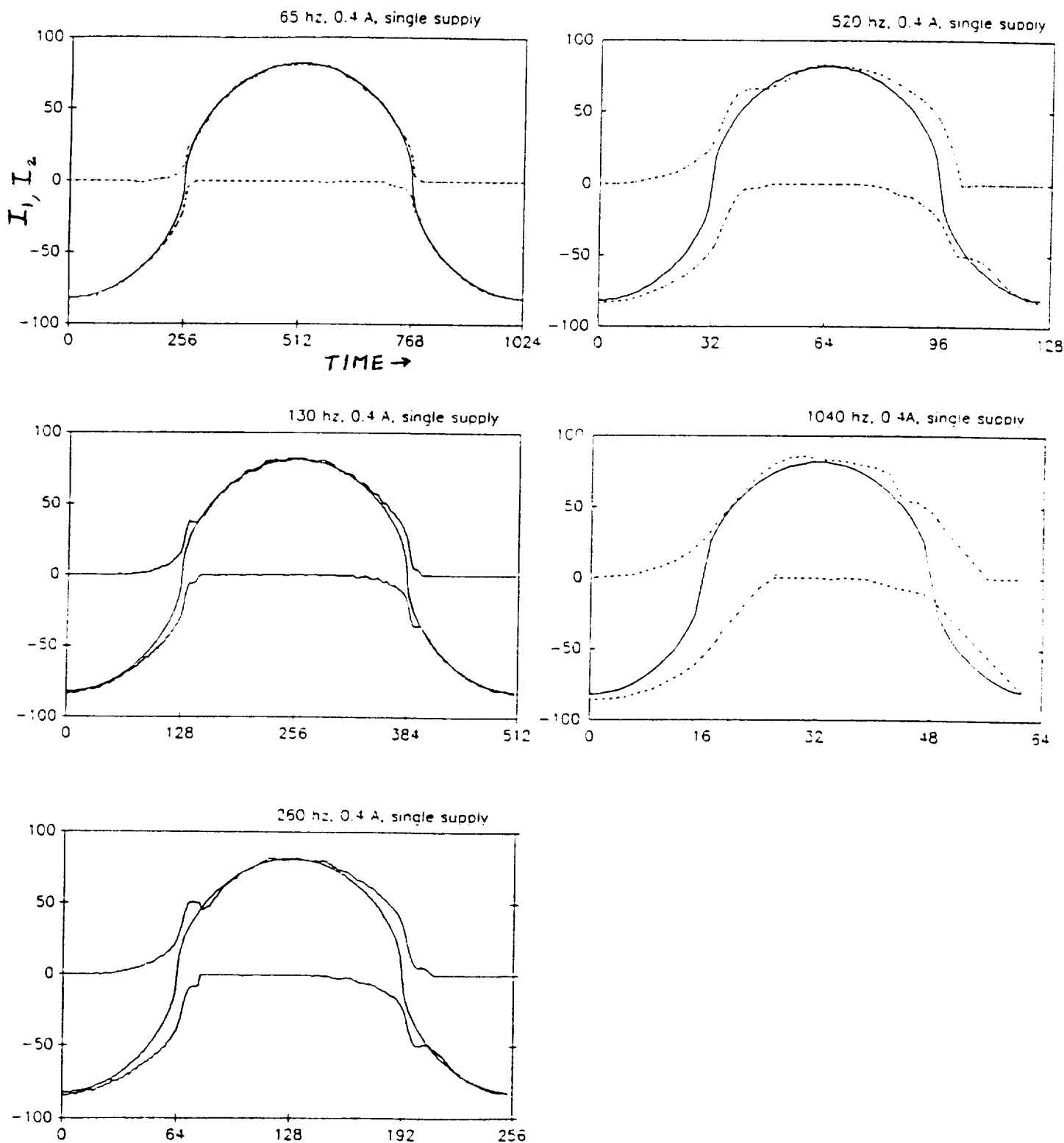
The force error produced by a single power supply per axis could no doubt be reduced by taking account in the controller that currents flow in both magnets at once but that the sense resistor can sense only their difference.

Another type of approach is to put sense resistors (or other current sensors) in both legs as shown below and use the resulting values of I_1 and I_2 in the controller. One such approach that has been simulated numerically avoids taking square roots altogether and instead compares the desired force and an "observed" force $I_1^2/g_1^2 - I_2^2/g_2^2$ to form an error function and an output to the power supply, as in the equation below. The power supply can be used as a simple voltage amplifier.
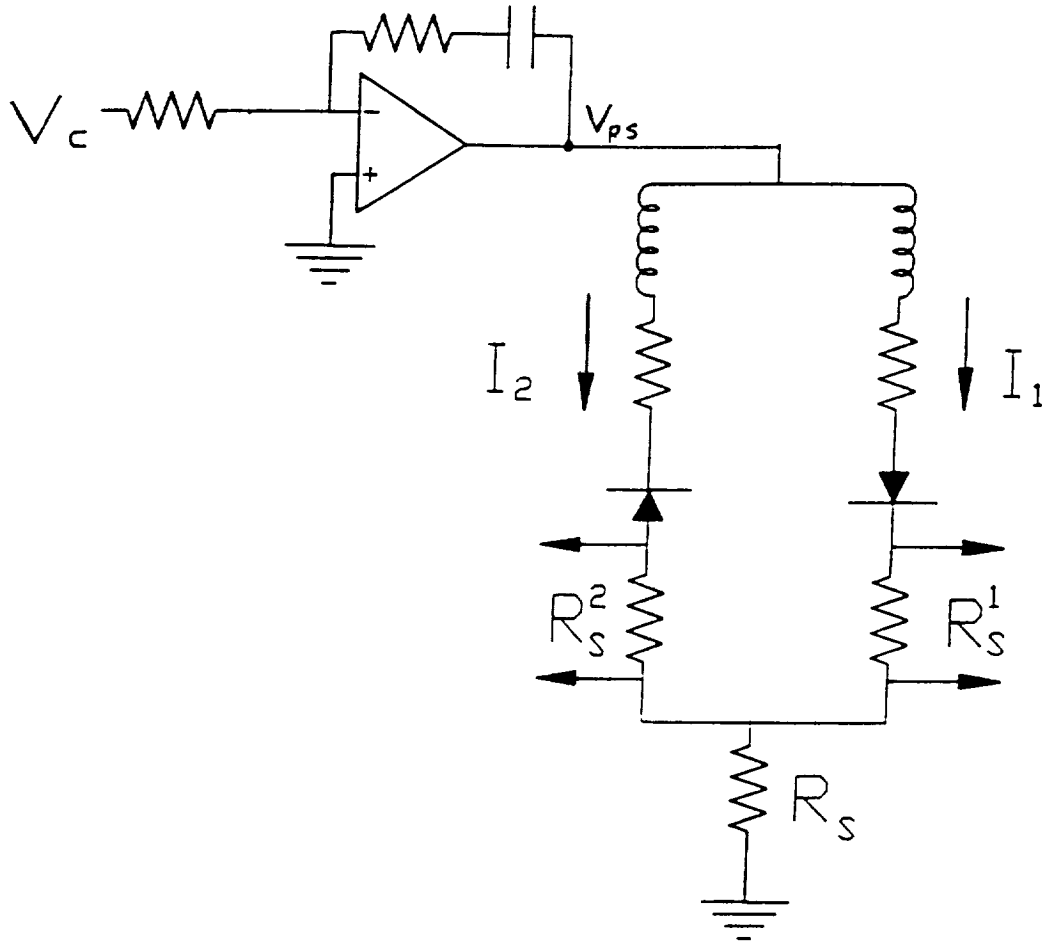
The result (simulation shown below) is remarkably similar to the behavior of the biased system, shown in the following figure at maximum dynamic load. Differences are mainly due to the different effects of resistive voltage drops in the two cases. The present method is superior to the bias case with respect to power consumption because at smaller dynamic load both currents reach zero in every cycle rather than having a fixed DC offset. On the other hand increasing dynamic loads will not be followed as quickly in the present case.

ONE POWER SUPPLY PER AXIS

BIAS

(1A, 600hz)

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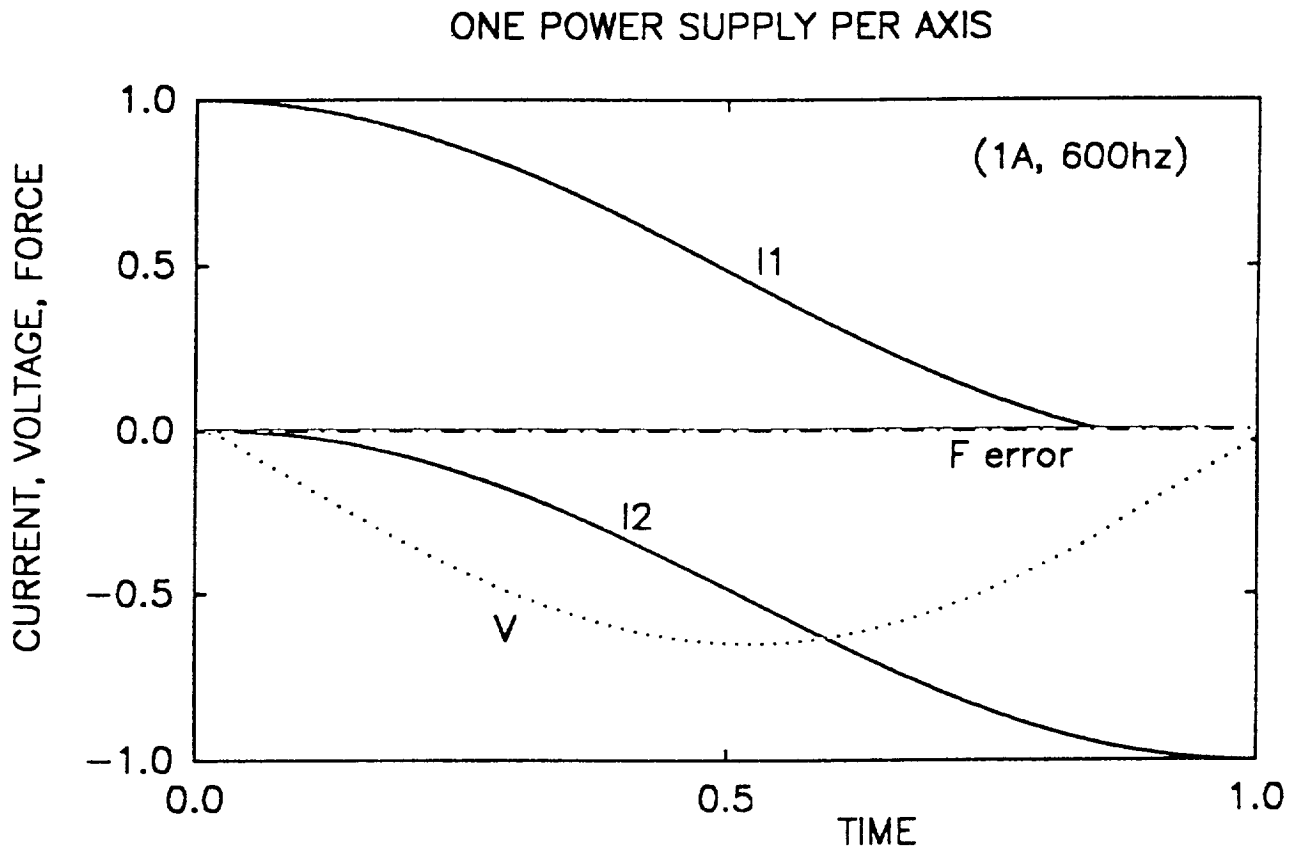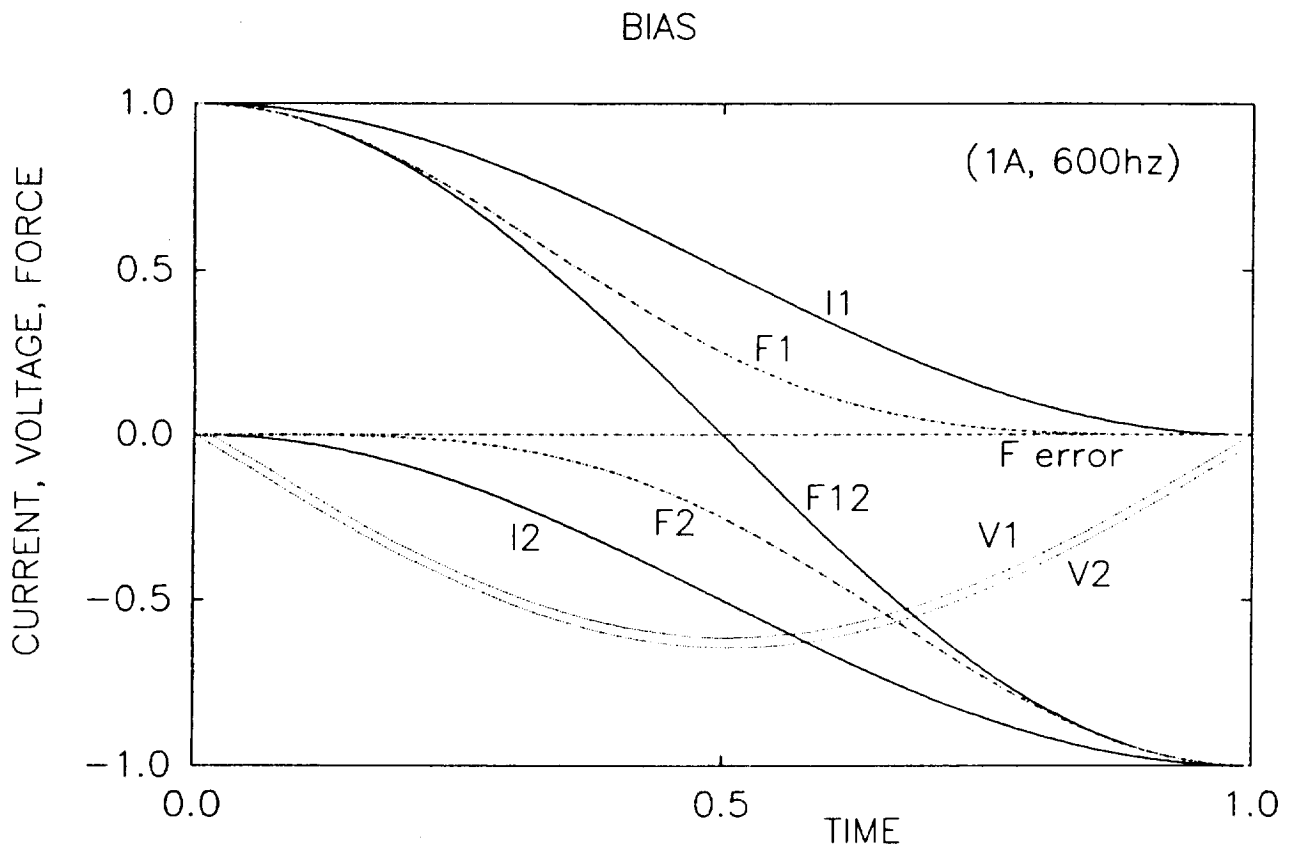
CONCLUSIONS

ELECTRICAL POWER CAN BE SAVED

COIL HEATING CAN BE REDUCED

ROTOR EDDY CURRENTS CAN BE REDUCED

HARMONICS ARE GENERATED IN THE SIMPLEST METHOD

MANY IMPROVEMENT STRATEGIES ARE POSSIBLE

REDUCED NUMBER OF POWER SUPPLIES IS POSSIBLE

METHOD IS MORE SUITED TO DIGITAL THAN ANALOG CONTROL

SIMPLEST METHOD DEMONSTRATED ON A ROTOR TO 12000 RPM

    WITH ONE AND TWO POWER SUPPLIES PER AXIS

FURTHER INVESTIGATION WARRANTED