[3] M. A. Jani and W. Ahmad, "Capacitance to time-period conversion using modified astable multivibrator," *IEEE Trans. Ind. Electron. Contr. Instrum.*, vol. IECI-22, pp. 430–432, Aug. 1975.
[4] D. Stankovic and M. Simic, "Monostable multivibrator as the bridge circuit with linear characteristic," *IEEE Trans. Instrum Meas.*, vol. IM-21, pp. 66–69, Feb. 1972.
[5] J. Millman, *Microelectronics: Digital and Analog Circuits and Systems.* New Delhi, India: McGraw-Hill Inc., 1979.

High-Stability DC-Current Source Using NMR Lock Technique

HITOSHI SASAKI, AKIRA MIYAJIMA, NAOKO KASAI, AND HISAO NAKAMURA

Abstract—**A high-stability constant current source has been developed using the nuclear magnetic resonance (NMR) field-frequency lock technique. The current is locked to the NMR frequency via the magnetic field of the electromagnet which has a highly stable coil constant. The current of 1 A has been stabilized to better than 0.2 ppm/h.**

I. Introduction

Stabilization of a current is generally realized by comparing the voltage drop across a reference resistor with a stable voltage source. Currents up to 1 A can be stabilized to better than 1 ppm/h using this conventional method [1]. For the currents over 1 A, thermal instability arises due to the increased power dissipation in the reference resistor. A dc-current comparator and a superconducting quantum interference device (SQUID) control system have been the only solutions to this problem [2]–[4].

In this paper, we describe a novel method of current stabilization which is based on the nuclear magnetic resonance (NMR) field-frequency lock technique. This method is fundamentally suitable for stabilizing a large current, and currents up to 100 A may be stabilized within 1 ppm/h. The system is easy to build and needs no cryogenic environments.

To test the potentiality of this method, a 1-A current source using a small electromagnet has been developed. The structure of the electromagnet and the performance of the current source will also be described.

II. Principle of Operation

The NMR field-frequency locking is a well-established scheme in the field of high-resolution NMR experiments [5]. The fluctuation of magnetic field is detected by NMR, and a compensation field is added via the coil current. Using this technique, a magnetic field can be stabilized to 10^{-9} or better [6].

The principle of current stabilization which is based on this NMR lock technique is schematically shown in Fig. 1. The high-stability magnet, which has a highly stable coil constant, is connected in series with the load. If the current flowing down the load varies, the magnetic field of the electromagnet also varies. The variation of the magnetic field is detected by the NMR detection circuit and the deviation signal is fed back to the coil current. Thus the current flowing down the load is stabilized via the magnetic field of the electromagnet.

In this method, both the sensitivity of current detection and the power dissipation in the magnet are functions of the field intensity, i.e., total ampere turn of the field coil. Hence, by a suitable choice of total turn numbers of the field coil, we could stabilize a wide range of currents while keeping a constant power dissipation.

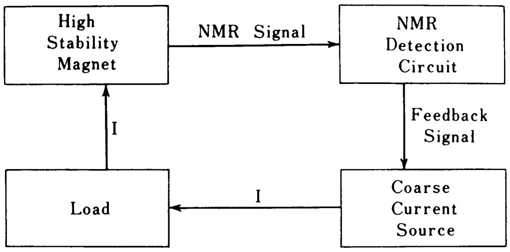

Fig. 1. Schematic diagram of current stabilization by NMR lock method.

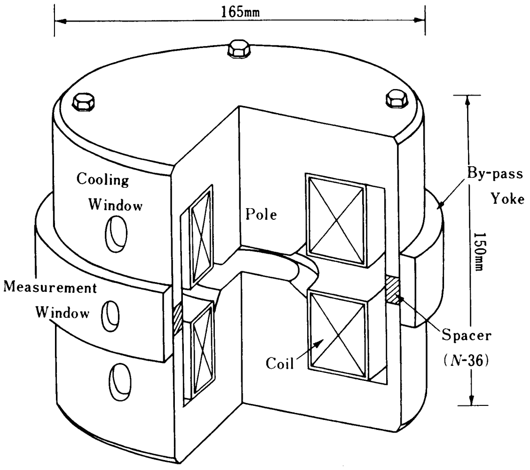

Fig. 2. Cross section of the high-stability electromagnet. The spacer is shown as the shaded portion.

III. High-Stability Electromagnet

Fig. 2 shows the cross section of a high-stability electromagnet which has been manufactured for this purpose. It is a small cylindrical electromagnet with 11-mm gap width, and the outer dimension is 165 mm in diameter and 150 mm in height. This type of electromagnet is mechanically stable and the return yoke acts as a magnetic shield for the environmental magnetic field. The access to the pole gap is made through four measurement windows, and the field coils are cooled by convection through eight cooling windows. The magnetic flux density of 0.2 T has been used in this experiment. At the field of 0.2 T, the protons in a spherical sample of natural rubber 3 mm in diameter give a sharp NMR signal with signal-to-noise ratio higher than 100. As the intrinsic linewidth of the protons in natural rubber is about 2×10^{-5} T, the field resolution of better than 1 ppm may easily be obtained. The operating current has been chosen as 1.018 A, so that the current can be measured precisely by a 1-Ω high-power standard resistor and a 1.018-V standard cell.

A specific feature of this electromagnet is the spacer inserted in the return yoke. The field uniformity of an electromagnet is mainly determined by the parallelism of the pole faces. Therefore the pole face and the return-yoke edge have been lapped on the same plane,

Manuscript received September 14, 1985; revised March 3, 1986.
The authors are with the Electrical Standard Division, Electrotechnical Laboratory, 1-1-4, Umezono, Niihari-gun, Sakura-mura, Ibaraki, 305 Japan.
IEEE Log Number 8610427.

0018-9456/86/1200-0642$01.00

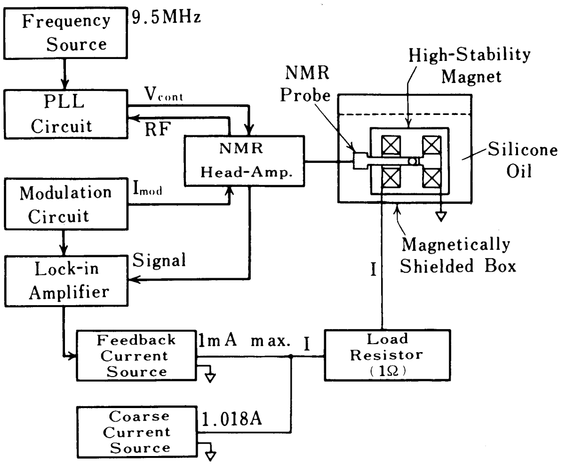

Fig. 3. Diagram of the constant current source.

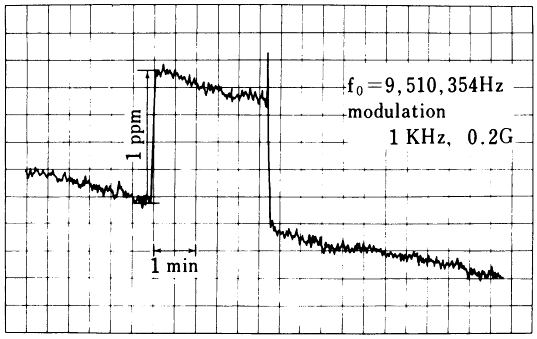

Fig. 4. Noise performance of the constant current source.

and a spacer with good parallelism has been inserted in the return yoke. The magnetic circuit interrupted by the spacer is supplemented by a "hoop" of bypass yoke. By this technique, the field uniformity of $\pm 2 \times 10^{-5}$ for 5-mm sphere has been obtained. The spacer also acts as a stabilizer for temperature variation of the electromagnet. As the height of the spacer is the same as the gap width, the thermal expansion of the gap width is determined by the expansion coefficient of the spacer. Thus the Fe-36-percent Ni alloy has been employed as the spacer material, which has the temperature coefficient of less than 1 ppm/°C at room temperature.

IV. Stabilization of Current

A 1-A constant current source has been developed using the high-stability electromagnet which is described in the previous section. The diagram of the constant current source is shown in Fig. 3. The NMR detection circuit consists of a reference frequency source, a phase-locked-loop (PLL) circuit, a field modulation circuit, a phase-sensitive detector, an NMR head amplifier, and an NMR probe. The marginal oscillator method has been used for the detection of NMR signal. The frequency of the marginal oscillator (9.5 MHz) is phase-locked to the stabilized frequency source. A deviation from the resonant condition due to a variation of the current is detected by the NMR detection circuit, and the feedback signal is sent to the feedback current source. The coarse current source produces the 1.018-A constant current with a stability better than 10 ppm/h. The electromagnet has been enclosed in a magnetically shielded box, which was made of 2-mm-thick 78-Permalloy plates. The box was filled with silicone oil to stabilize the temperature of the electromagnet.

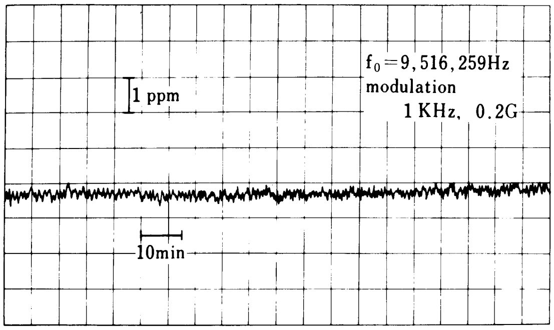

Fig. 5. Short-term stability of the constant current source.

To test the stability, the current was fed to a 1-Ω standard resistor (ESI model SR1010). The voltage drop across the resistor was compared with electromotive force (EMF) of a standard cell using a photocell galvanometer (Guildline model 9460A) and a digital nanovoltmeter (Keithley model 181). The standard resistor has been immersed in an oil bath (Guildline model 9730CR) and the standard cell has been put in an air bath (Guildline model 9152TP4). All of the measuring circuits were placed in a temperature controlled electromagnetic shielded room.

Fig. 4 shows an output trace of the photocell galvanometer. A 1-ppm marker was generated by adding a 1-MΩ resistor in parallel with the 1-Ω standard resistor. The observed noise was 0.1 μA (0.1 ppm) peak to peak in the frequency range 0.01 ~ 1 Hz. The drift, which can also be observed in the figure, lasted for several hours after feeding the current to the electromagnet. It is probably due to a thermal inequilibrium inside the electromagnet.

In the stability measurement, the voltage difference was directly measured by the digital nanovoltmeter to avoid the zero drift of the photocell galvanometer. Fig. 5 is the data measured when 18 h had passed after feeding the current to the electromagnet. From the figure, the current stability has been estimated to be better than 0.2 ppm/h.

V. Conclusion

A high-stability low-noise constant current source has been developed using the NMR field-frequency lock technique.

By inserting a spacer to the return yoke, we have fabricated an electromagnet which has both a highly stable coil constant and a wide high-uniformity region. Using this electromagnet, a current of 1 A has been stabilized to better than 0.2 ppm/h.

These results imply a high potentiality of the NMR lock technique to stabilize a large current.

Acknowledgment

The authors would like to thank T. Yokoi and T. Namae of Tokin Corporation for producing the stable electromagnet.

References

[1] M. W. Retsky and J. Wall, "One ampere current supply stable to one part per million per hour," *Rev. Sci. Instrum.*, vol. 43, no. 3, pp. 384–385, 1972.

[2] S. N. Erne and H. Luther, "High-precision dc-current source," *IEEE Trans. Instrum. Meas.*, vol. IM-24, no. 4, pp. 345–348, 1975.

[3] J. C. Gallop, "Use of persistent supercurrents in SQUID current stabilizers and their application to a resistivity measurement on niobium," *J. Phys. D: Appl. Phys.*, vol. 9, no. 14, pp. 2111–2115, 1976.

[4] K. Weyand, "DC-current control using SQUID-gradiometer systems," *IEEE Trans. Instrum. Meas.*, vol. IM-29, no. 4, pp. 324–328, 1980.

[5] R. C. LaForce, G. LaForce, and G. R. Hansen, "A proton magnetic field controller," *Rev. Sci. Instrum.*, vol. 43, no. 11, pp. 1695–1698, 1972.

[6] S. Kan *et. al.*, "Automatic NMR field-frequency lock-pulsed phase locked loop approach," *Rev. Sci. Instrum.*, vol. 49, no. 6, pp. 785–789, 1978.