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ABSTRACT

Typical performance of this transductor circuit includes a long-term stability of a few parts in 10^5 , an output noise level less than 0.002% of full output voltage, and a pass band from 0 to 1 MHz. The circuit provides low-pass, band-pass, and high-pass sections, suitably designed to provide a uniform frequency response. The circuit configuration inherently filters out the commutation noise, thus providing a high signal-to-noise ratio.

INTRODUCTION

The most common signal source for high-precision magnet-current regulators is the water-cooled shunt. When properly designed and carefully built, the long-term stability of this device frequently exceeds one part in 100,000. However, it is usually necessary to dissipate several kilowatts of power in order to obtain a large enough signal to realize a comparable system stability. The problem of reducing the input noise level of the interconnecting cabling and circuitry associated with the shunt is formidable and tedious. Usually, the overall system stability is closer to a part in 10^4 than to a part in 10^5 .

While the inherent stability of a transductor^{1,2} is a little less than that of a precision shunt, the transductor provides a very favorable impedance transformation and a much higher signal voltage at a much lower power dissipation than the water-cooled shunt. Typically, signal levels of from 10 to 30 V are available at power dissipations of around 10 W. In addition, it provides circuit isolation from the magnet power supply. When all factors are included, the system stabilities are comparable, but the cost and effort required to check out the transductor system favors the latter.

The transductor studied employed a four-core circuit that provided three signal channels-- a low-pass channel, a band-pass channel, and a high-pass channel--so arranged that the frequency response is flat from dc to 1 MHz.^{3,4} The performance characteristics of this transductor were measured and it was found that the sensitivity to change in line voltage is 35 ppm/% change in line voltage, that the temperature coefficient of the device is -6 ppm/°C, and the sensitivity to stray magnetic field is 33 ppm/G change in stray magnetic field. The peak output noise voltage was 0.002% of full signal, measured over the full 1-MHz pass band of the device.

ANALYSIS

The physical picture of the operation of the four-core transductor can be determined from Fig. 1. Cores T1 and T2, transformer T5, and

the diode bridge comprise a standard transductor circuit that serves as a low-pass section of the four-core circuit. Core T3 and capacitor C serve as a low-pass filter to attenuate the commutation notches introduced by the carrier voltage and diodes of the low-pass section. Also, signal is coupled through core T3 to the transductor load resistor R. It is apparent that this channel passes no signal at dc and that for very low frequencies the voltage induced in core T3 is proportional to the frequency. As the frequency is increased, the reactance of capacitor C decreases, reducing the coupling from T3 to the load resistor R until at infinite frequency the coupling is zero; thus, core T3 provides a band-pass characteristic.

Core T4 couples signal from the input bus through capacitor C to load resistor R. The coupling is zero at zero frequency and, if we assume an ideal transformer, is determined by the turns ratio at sufficiently high frequencies; thus, core T4 and the associated circuitry provides a high-pass channel.

When a direct current flows in the input bus, the dc current produced by the low-pass section of the transductor is limited by the high impedance produced by cores T1 and T2 when the carrier current brings them out of saturation. This dc current, multiplied by the number of turns on T1 or T2, is equal to the ampere turns produced by the input bus. Let us assume the input circuit consists of a single turn--the usual case.

The dc current produced by the low-pass transductor also flows through cores T3 and T4 in such a way that the ampere turns produced by the input bus are cancelled; thus cores T3 and T4 are never saturated by the dc current flowing in the input circuit. If we neglect the commutation notch, the requirement is only that the number of turns on all four cores be equal. It should be noted that neither the core areas, nor the core diameters need be equal, although, ordinarily four identical cores are used.

The commutation notch reduces the transductor dc output current by a few percent. To compensate for this reduction, a few percent more turns are required on T3 and T4 than on T1 and T2.

Let us now consider the design requirements of the components of the four-core transductor circuit. First, the current-transformation ratio is approximately equal to the turns ratio. For example, if one wanted a transformation ratio of 1 kA input to produce 1A through the transductor load resistor, 1,000 turns would be chosen for the transductor-core secondary windings.

Second, each transductor-core area must be chosen so that the total magnetic flux change absorbs the volt-seconds of a half period of the carrier voltage so that the cores do not saturate at zero primary current. In choosing core area it is desirable to have a margin of safety so that

the normal variation in carrier voltage does not produce core saturation. If we assume a 25% voltage margin, the expression for the core area in square meters is given by

$$A = \frac{1.25 V_{\max}}{n \omega B_m} \quad (1)$$

where n is the number of turns, B_m is the saturation flux density of the core in Teslas, V_{\max} is the crest voltage, and ω is the radian frequency (377 for 60 Hz) of the carrier voltage. Next, let us consider the relationship between the carrier voltage and the dc output voltage. Consider the low-pass section of the transductor in idealized form (Fig. 2). Obviously, one must compromise between output voltage and the size of the commutation notch. A reasonable choice is to make the maximum output voltage be about 1/4 of the peak value of the ac carrier voltage. The width of the commutation notch is given by

$$\cos \frac{\theta}{2} = \frac{e_0}{E_m} \quad (2)$$

where e_0 is the maximum dc output voltage. For an output voltage of 25% of E_m , the commutation notch is 29 deg.

In a practical transductor circuit the output voltage is further reduced by the effect of the resistance of the transductor windings. For four cores this is usually comparable with the load resistor, and typically restricts the maximum dc output voltage to about 1/8 of the peak value of the carrier voltage.

Next, consider the requirements of the four-core circuit in order to produce a flat frequency response. The circuit of Fig. 1 can be analyzed by means of the principle of superposition. The primary current can be divided into three components, one of which couples through the low-pass section of the transductor and produces a current in load resistor R . The second component couples through the high-pass section core T4, to load resistor R ; and the third component couples through the band-pass section, core T3, to load resistor R .

The transductor circuit can be broken down into the three equivalent circuits of Fig. 3. First, consider the low-pass section. For the purpose of this analysis, assume that each transformer has a magnetizing inductance L and negligible leakage inductance; the upper two cores, 60 Hz carrier transformer, and diodes, constitute a transductor and produce a signal current I_{S1} which is approximately

$$I_{S1} = \frac{I_{dc}}{n} \quad (3a)$$

where I_{dc} is the input current and n is the number of turns on each core. From Fig. 3B it is apparent that

$$I_{O1} = \frac{I_{S1}}{1 + sCR + s^2LC} \quad (3b)$$

Now consider the high-pass section of the transductor circuit. Using Fig. 3(d), we have

$$I_{S2} = \frac{I_{dc}}{n} \quad (4a)$$

and

$$I_{O2} = \frac{I_{S2}}{1 + \frac{R}{sL} + \frac{1}{s^2LC}} \quad (4b)$$

Now consider the band-pass section of the circuit, Fig. 3C. By breaking the circuit at point A, the circuit can be simplified by means of Thevenin's theorem. Writing the network equations of the resulting simplified circuit, we obtain

$$I_{O3} = \frac{I_{S3}}{3 + 2s^2LC + 2sRC + \frac{R}{sL}} \quad (5)$$

Letting $s = j\omega$, and $\omega_0^2 = 1/LC$, and $Z_0^2 = L/C$, and combining the three components, we get the expression for the transductor output current in terms of the input current:

$$\begin{aligned} \frac{I_{O}^n}{I_{dc}} = & \left[1 - \left(\frac{f}{f_0}\right)^2 + j \frac{f}{f_0} \frac{R}{Z_0} \right]^{-1} + \left[1 - \left(\frac{f}{f_0}\right)^2 - j \frac{f_0}{f} \frac{R}{Z_0} \right]^{-1} \\ & + \left[3 - 2 \left(\frac{f}{f_0}\right)^2 + j \left(\frac{2f}{f_0} - \frac{f_0}{f} \right) \frac{R}{Z_0} \right]^{-1} \end{aligned} \quad (6)$$

If equal winding resistances, R_w , of the cores are included, Eq. (6) becomes

$$\begin{aligned} \frac{I_{O}^n}{I_{dc}} = & \left[1 - \left(\frac{f}{f_0}\right)^2 + j \frac{f}{f_0} \frac{(R+R_w)}{Z_0} \right]^{-1} + \left[1 - \left(\frac{f}{f_0}\right)^2 - j \frac{f_0}{f} \frac{(R+R_w)}{Z_0} \right]^{-1} \\ & + \left\{ 3 - 2 \left(\frac{f}{f_0}\right)^2 + \frac{2R_w}{Z_0} (R+R_w) + j \left[2 \frac{(R+2R_w)f}{Z_0} - \frac{(R+3R_w)f_0}{Z_0} \right] \right\}^{-1} \end{aligned} \quad (7)$$

The three components of current were plotted and are shown in Fig. 4 with R/Z_0 as a parameter. It was assumed that $R_w = 0.3 R$. The sum of the three currents are shown in Fig. 5. It is apparent that the optimum value of R/Z_0 is 0.3 for a uniform frequency response.

The design procedure consists of the following steps:

1. Choose the current transformation ratio and maximum output voltage. This determines the number of turns on the cores. Usually, a single turn is used for the primary so the number of turns on each core is the same as the transformation ratio. The secondary current and the maximum output voltage determines the transductor load resistor R .

2. Include the IR drop in the four transductor cores by adding this to the circuit's output voltage and make the carrier voltage about four times this value.

3. Compute the cross-sectional area of the transductor cores from the relation

$$A = \frac{1.93 \times 10^3}{n \omega B_m} \times V_{\max} \quad (8)$$

where A is in in^2 , and B_m is in Teslas.

4. Calculate the core inductance from the expression

$$L = 1.17 \times 10^{-8} \mu_0 n^2 h \log_{10} \frac{d_2}{d_1} \quad (9)$$

where n is the number of turns, d_1 and d_2 are

respectively the inner and outer diameters in inches, and h is the axial thickness in inches.

5. From the relation $R/Z_0 = 0.3$, calculate

$$C = 0.09 \frac{L}{R^2}. \quad (10)$$

PERFORMED TESTS OF A TYPICAL FOUR-CORE TRANSDUCTOR CIRCUIT

The transducer tested was designed for use with magnet currents up to 200A (see Fig. 6). The 2.5-in.-o. d., 2-in.-i. d., 0.5-in.-thick Super-malloy cores are type 50017-2F made by Magnetic Inc., Redwood City, California. The secondary winding on the cores consists of 1000 turns of number 22 Formvar-insulated wire. The 10- Ω load resistor is wound from Karma wire. The carrier voltage is 14 V rms. The coupling capacitor is 100- μ F, 50-V tantalum capacitor. The diode bridge was assembled from Texas Instruments type-IN3775, 3/4 A 600-V silicon diodes.

The magnetic requirements of cores 1 and 2 are quite different from those of cores 3 and 4. The circuitry associated with cores 1 and 2 requires that the inductance increase abruptly when the net ampere turns becomes zero; a rectangular hysteresis loop is necessary. Core 3 serves as an inductance and as a transformer and core 4 serves only as a transformer. For cores 3 and 4 it is desirable that the inductance remain high, even though the net ampere-turns is not quite zero. Cores 3 and 4 preferably should be wound on material of low magnetic remanence, and therefore a material without a rectangular hysteresis loop.

We have not investigated the case where different core materials are used for the two sets of cores in this transducer circuit. We used Super-malloy for all four cores. It does not have a truly rectangular loop, but the change in permeability near 0 mmF is abrupt enough to meet the needs of cores 1 and 2, while the remanence is low enough for cores 3 and 4. We have observed, however, that because of the remanence of this material, the value of μ_0 used in Eq. (9) is only about 2000 rather than the manufacturer's rating, which is in excess of 60,000. We investigated this and found that if the core is demagnetized, the value of μ_0 indeed considerably exceeds the manufacturer's rating.

Fortunately, except for the band of frequencies in the vicinity of the cross-over frequency between the low- and high-pass channels, the current in the magnetizing inductance of the transformers is small compared with the current in the load resistor. The load current masks the nonlinear magnetizing current so that the output waveform is a very good reproduction of the input.

The frequency response of each of the three pass bands was obtained by adding a second winding to the appropriate core. The results of each channel are shown in Fig. 7. The total frequency response of the complete transducer is shown in Fig. 8. To obtain this curve the input current was modulated by means of a power transistor. Except for the small dip at the resonant frequency, the response of the circuit is uniform from dc to about 1 MHz. The high-frequency response of the circuit is limited by the time constant associated with the leakage inductance of the core T4 and the load resistance. The small dip at the resonant frequency is consistent with the basic circuit analysis, as determined by the computer run shown in Fig. 5.

Next, the sensitivity of the circuit to variation in input line voltage was measured. The results are shown in Fig. 9. The sensitivity is about 35 ppm/% change in input line voltage. This variation is probably caused by the change in the width of the commutation notch as the carrier voltage is changed. For transducers operating with stabilities in excess of one part in 10^4 , the input line voltage must be regulated.

The temperature sensitivity of the transducer was determined and is shown in Fig. 10. For this test, the entire transducer circuit, except for the transducer load resistor, was installed in an oven and the temperature was varied. The temperature coefficient is about -6 ppm/ $^{\circ}$ C. There are three possible mechanisms within the transducer circuit, each of which produces a negative temperature coefficient which may account for this temperature sensitivity. First, the change in winding resistance of the four cores changes the width of the commutation notch by varying the total transducer output voltage. Second, the back resistance of the diode bridge decreases with increasing temperature, thus lowering the rectification efficiency. Third, the leakage resistance of the coupling capacitor increases with temperature and shunts some of the output current around the output load resistor. In addition to the transducer-circuit temperature sensitivity, one must, of course, add the temperature sensitivity of the load resistor. This depends upon the particular resistor selected.

A 8-hour stability run using a precision shunt as a standard is shown in Fig. 11. The 120 Vac supply for the carrier voltage was stabilized by means of a Sola transformer. It is apparent from this run that the stability of this typical transducer is about 100 ppm.

CONCLUSION

In a typical case the four-core transducer circuit has a current stability of about 100 ppm, a bandwidth of about 1 MHz, a negative temperature coefficient of about 6 ppm/ $^{\circ}$ C, a sensitivity to change in input line voltage of about 35 ppm/% change in input line voltage, and a sensitivity to stray magnetic field of about 33 ppm/G change in stray field. Operation with a higher degree of stability can be obtained by regulating the input line voltage and by controlling the temperature of the transducer components. Temperature compensation can be obtained by choosing a load resistor with a positive temperature coefficient that matches the negative coefficient of the transducer circuit.

In installing a transducer, care should be taken that it is not located in a changing stray magnetic field. For a one-part-in- 10^4 device, the change in stray field must be kept below 3 G.

The value of capacitance required for the coupling capacitor usually runs in the range of 50 to 500 μ F. This is inconveniently large for paper capacitors, but we have found that liquid-electrolyte tantalum capacitors are satisfactory. The leakage current at rated voltage of a 50- μ F, 60-V tantalum capacitors is about 0.2 μ A at room temperature and rises by about a factor of 3 by 75 $^{\circ}$ C. This contributes about minus 0.4 parts per million per degree C to the temperature coefficient.

In a high-performance magnet regulator several practical advantages show up in comparing this transducer with a good water-cooled shunt:

(1) For comparable performance, the fact that the

transductor is not electrically connected to the power supply simplifies the problem of reducing the ground-loop noise in the regulator input circuit. (2) The higher output voltage of the transductor circuit reduces the significance of the thermal potentials associated with dissimilar metals at connectors and terminals. (3) The transductor is usually less costly, basically because the transductor can be assembled out of mass-produced components, whereas a precision shunt requires costly precision machine work. Also, the cost of the plumbing and temperature-regulated low-conductivity water required for the shunt is an appreciable cost not required for the transductor.

ACKNOWLEDGMENT

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2. E. Besag, "Measurement of Large Direct Currents over Long Distances," *Electrotech. Z.* **40**, 436 (1919).
3. A. A. Windsor, "A D-C Transformer with Low Noise and Wide Frequency Response," IEEE Conference paper No. CP-63-249, January 1963.
4. A. A. Windsor, "D. C. Instrument Transformer System," U. S. Patent No. 3,136,948, June 9, 1964.

ILLUSTRATIONS

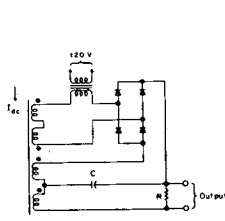


Fig. 1

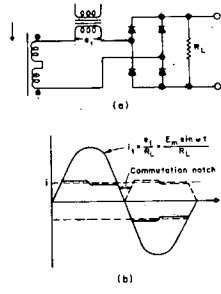


Fig. 2

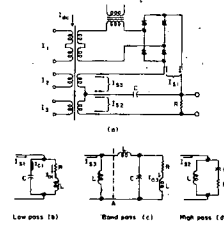


Fig. 3

Fig. 1. Schematic of the four-core transductor.

Fig. 2. Simplified form of the low-pass section of the four-core transductor circuit. This section is a standard two-core transductor. When this circuit feeds a resistive load, the commutation notch reduces the average output current.

Fig. 3. (a) Four-core transductor circuit. For analysis this can be broken down into (b) low-pass, (c) band-pass, and (d) high-pass circuits. By superposing the three signal currents, the total transfer function of the four-core transductor can be obtained.

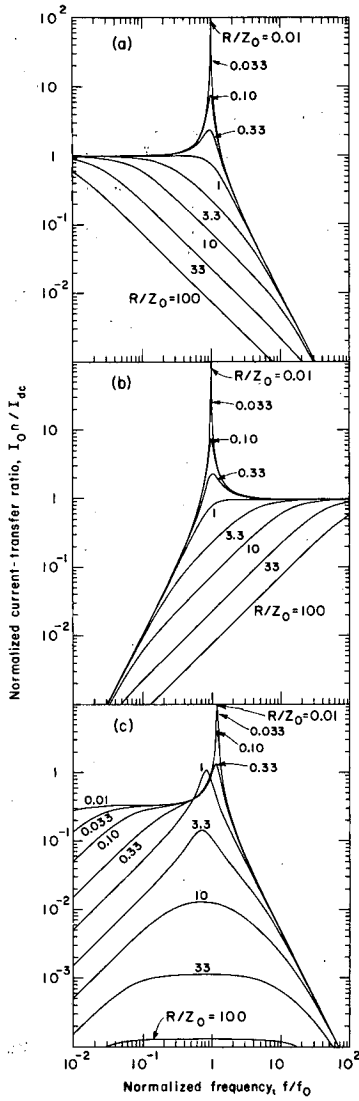


Fig. 4. The three current components of Fig. 3 plotted with R/Z_0 as a parameter. We assumed the winding resistance R_w to be $0.3 R$. Expressions for the three currents:

(a) low-pass case

$$I_{LP} = I_{dc} n^{-1} \left[1 - \left(\frac{f}{f_0} \right)^2 + j \frac{f}{f_0} \left(\frac{R+R_w}{Z_0} \right) \right]^{-1}$$

(b) high-pass case

$$I_{HP} = I_{dc} n^{-1} \left[1 - \left(\frac{f_0}{f} \right)^2 - j \frac{f_0}{f} \left(\frac{R+R_w}{Z_0} \right) \right]^{-1}$$

(c) band-pass case

$$I_{BP} = I_{dc} n^{-1} \left\{ 3 - 2 \left(\frac{f}{f_0} \right)^2 + 2 \frac{R_w (R+R_w)}{Z_0} + j \left[2 \left(\frac{R+2R_w}{Z_0} \right) \frac{f}{f_0} - \left(\frac{R+3R_w}{Z_0} \right) \frac{f_0}{f} \right] \right\}^{-1}$$

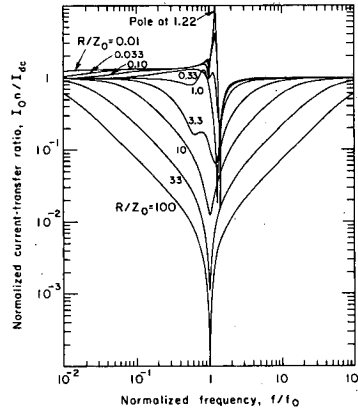


Fig. 5. Superposition of the three current components of Fig. 4. A choice of $R/Z_0 = 0.3$ provides the most uniform frequency response.

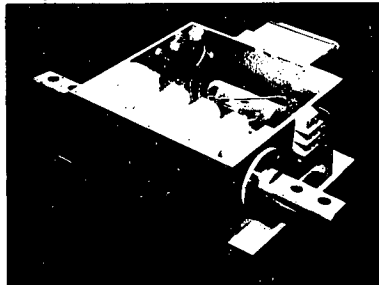


Fig. 6. Construction details of the test transducer. The transducer enclosure is aluminum.

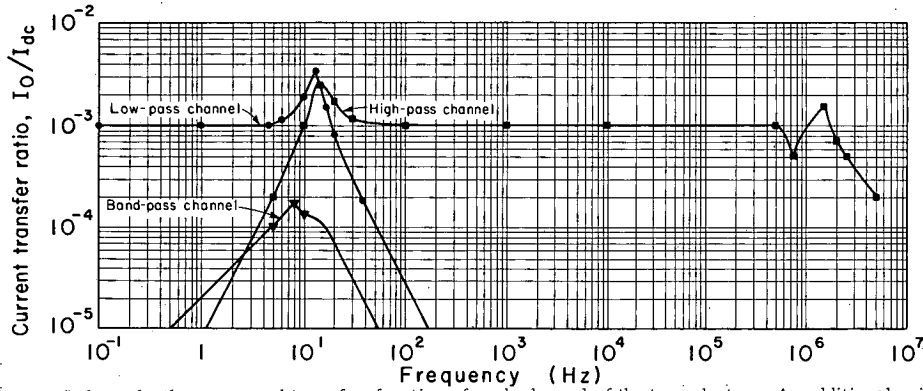


Fig. 7. Independently measured transfer function of each channel of the transductor. An additional primary winding of a few turns was applied to each core so that each channel could be excited by an audio oscillator. The low- and high-pass channels agree quite well with the calculated curves of Fig. 4. The band-pass channel seems to have less coupling to the load than the theory predicts. Perhaps the difference is a result of the core losses which are neglected in the theory.

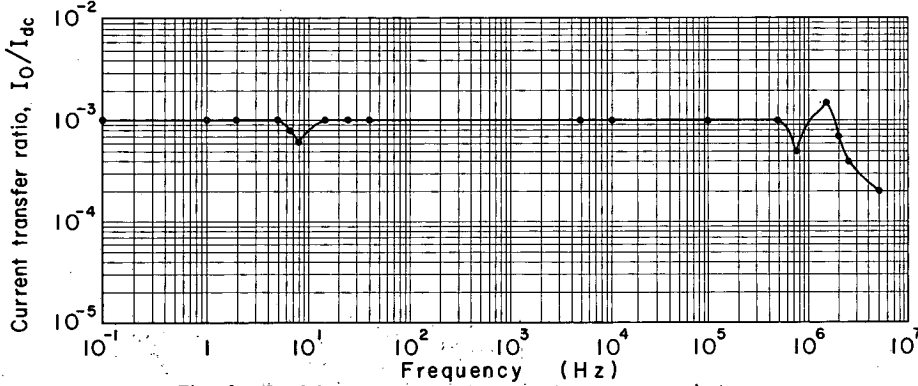


Fig. 8. Total frequency response of the four-core transductor.

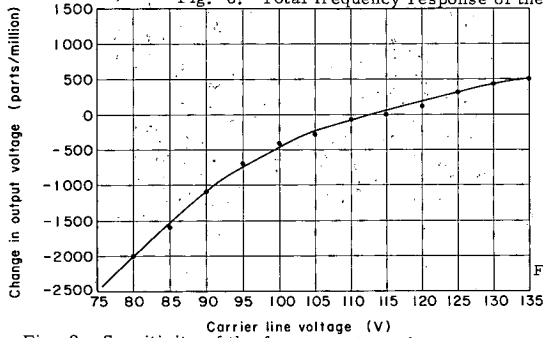


Fig. 9. Sensitivity of the four-core transductor to variation in input line voltage. The sensitivity at 30°C is about 35 ppm/% change in line voltage.

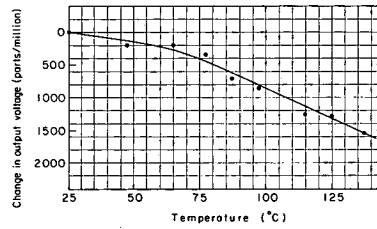


Fig. 10. Temperature sensitivity of the transductor. For this test the entire transductor circuit, except for the transductor load resistor, was installed in an oven and the temperature was varied. The temperature coefficient is about -6 ppm/°C.

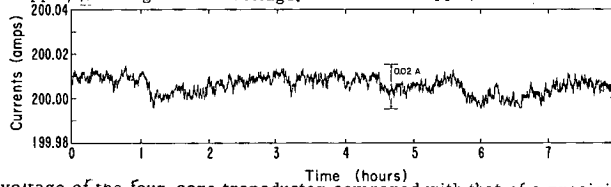


Fig. 11. Output voltage of the four-core transductor compared with that of a precision shunt in order to determine the overall stability of the transductor. It is apparent from this run that the stability is better than 100 ppm over an 8-h run.

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