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TRANSDUCTORS FOR CURRENT SENSING IN THE DIPOLE AND QUADRUPOLE MAGNET CIRCUITS OF THE FERMILAB MAIN RING

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Summary

Transductors are used as current measuring devices in the main accelerator quadrupole power supply feedback loop and as monitors in the dipole circuit. The development of these transductors is described, starting with the basic series - connected (Kraemer) transductor circuit, and adding the features of biasing and a voltage follower to obtain improved linearity and high slewing rate.

Introduction

Current transductors are members of the magnetic amplifier family[1,2], and are sometimes called D.C.C.T.'s or D. C. Current Transformers[3]. Like the saturable reactor, the transductor can be series[4] or parallel[5] connected. Fry[6] gives a comparison of the series and shunt connection schemes, as does Jackson[7]. Test results[8] are available on some commercial units and custom designs[9].

At Fermilab, transductors are used as current measuring devices in the main accelerator quadrupole power supply feedback loop. Precise current regulation is required both at injection time and at extraction time. At injection the effective aperture in the accelerator is a sensitive function of the quadrupole current. The tolerance at injection for stable operation is ±40mA out of a current of 88 amps. At high energy good regulation is required to insure a smooth slow spill out of the machine when resonant extraction is used. At a peak current in the quadrupoles of 6500 amps at 500 GeV the quadrupole current must be regulated to ±200mA. In order to accomplish this degree of regulation over the range 88 - 6600 amps it was necessary in the past to employ a number of different current or field probes, each with a limited range. The switching from one probe to another was a constant source of difficulty. The transductors are able to function over the entire range of quadrupole current. The only switching required is in the analog to digital converter which communicates with the power supply control computer.

Discussion of Problem Areas

Existing transductors appear well suited to the measurement and control of constant or slowly-changing currents, but fail to meet our requirements for good sensitivity over a wide dynamic range of current, and in addition fail to track a rapidly-changing current with sufficient accuracy. Let me restate these problems and add a third problem.

1. Insensitivity at low current.
2. Serious lag errors at high rates of change of current.
3. Annoying drift with temperature change.

Because the magnet circuits would be dangerous if exposed, it was desirable to design the transductor coil head as a package separated from the associated electronics by an interconnecting cable. The coil head is mounted on busbars inside a locked magnet cage, Figs. 1 and 2. The 60 foot cable permits the electronics chassis to be outside the cage in a conventional rack-and panel confirguration.

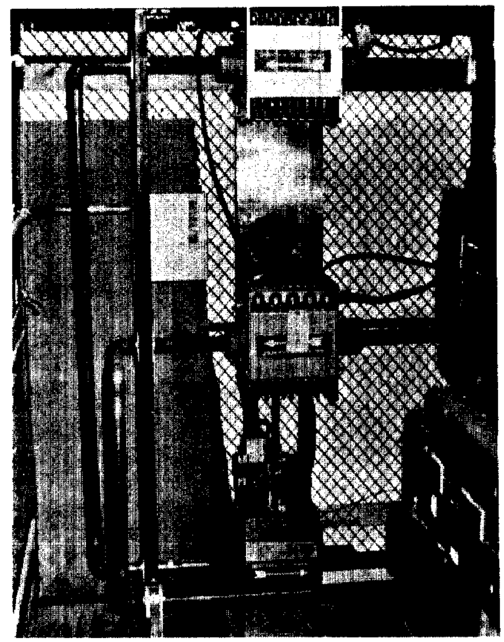

Fig. 1 7,500 Amp Transductors Monitoring Bend Current. View inside magnet cage.

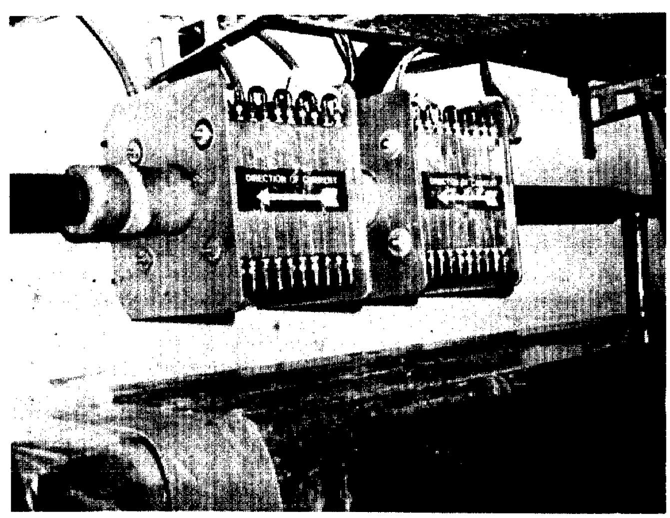

Fig.2 Two 500 Amp Transductors Measuring the Bend minus Quad Difference Current. View inside magnet cage.

Transductors of two different current ranges have been installed: -25 to +500 Amps, and -25 to +7,500 Amps. For simplicity, the coil heads and the inter-

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connecting cables for the two current ranges were made identical. The electronics chassis contain different burden resistors, 100 ohms and 5 ohms respectively, for the two cases. The 500 Amp transductor has an output of 40 millivolts/amp turn, while the 7,500 Amp transductor has an output of 2 mV/amp turn.

The techniques adopted to minimize the stated problems included biasing of the transductor operating point, cancellation of IR drop and displacement current via a voltage follower, and water-cooled packaging. For clarity, these techniques will be discussed separately, although the reader will recognize that there is significant interdependence.

Description of Tape-wound Magnetic Cores

All cores are identical in size and encased in phenolic core boxes. The dimensions of the uncased cores are: I.D. = 7 inches, O.D. = 7-1/2 inches, tape width = 1/2 inch, tape thickness - 4 mils. The material of cores 1 and 2 is Super Square 80 (Magnetic Metals Company) and the material of cores 3 and 4 is Super Perm 80 (Magnetic Metals Company). All cores are wound with exactly 2500 turns of #18 Heavy Formvar copper magnet wire; the winding resistance is approximately 5 ohms, the inductance (very approximately) 50 henries.

Insensitivity at Low Current

Figure 3A, the transfer function between busbar current and signal output, illustrates this problem. At currents approaching zero, the output of the simple circuit ceases to be a function of the input, and there is a characteristic offset related to the magnetizing current of the magnetic cores. Figure 3B is the solution adopted; the zero current working point is repositioned to a linear part of the transfer function by means of bias. Figure 4 shows the bias circuit; 55 ampere-turns of constant current is inserted in square-loop 4-79 permalloy cores 1 and 2 but bucked out before it reaches the output. The 250 turn windings are used, rather that the full 2500 turns, to reduce the required compliance voltage of the 220 mA regulator to 16 volts; otherwise the voltage would be 160 volts. The two current regulators use a common zener voltage reference, and to first order, reference instability is canceled. A slight trimming of the 22 mA circuit adjusts for zero offset at the output.

Figure 5 shows the effectiveness of the bias; the transfer function 5A very close to zero current has the same slope as the full-range relationship 5B. For the 7,500 Amp transductor, the 22 mA bias current is modulated slightly downward with increasing busbar current to linearize the high current end of the transfer function.

Lag Errors and the Voltage Follower

Lag errors are related to the filtering one employs, yet some filtering is necessary. It is clear that obtaining a curve like 5A would be difficult if the output noise were appreciable. A voltage follower to be described permits very low noise without lag. In the completed device, the noise corresponds to 1.5 mA of busbar current; the main noise component is 120 Hz sinewave (= 2x power frequency).

Figure 6 shows the ripple filtering arrangement, using coils 3 and 4 simultaneously as filter inductors and also as wideband current transformers coupled to the busbar. This resembles the Windsor circuit mentioned by Jackson but C2 of Fig. 6 does not connect to ground but to a point B instead. Point B, for signal voltage, "bounces" with point B'. This bouncer technique eliminates a velocity lag error that would otherwise come about due to capacitor charging current in C2. A further important difference is that core 3 contains exactly the same number of turns (2500) as the other cores. The network R1-C1, R2-C2, Coil 3, Coil 4 is approximately critically damped. R1 = 470Ω, C1 = 500μf, R2 = 330Ω and C2 = 100μf.

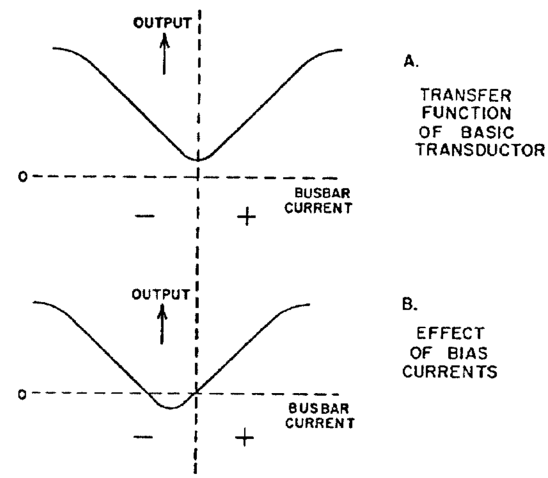

Fig. 3. Extension of Dynamic Range by Biasing.

It should be mentioned that the ripple voltage across the bridge rectifier is reduced to 2 volts pk-pk by R1-C1. The ripple voltage remains almost constant at 2V over the whole current range. Also, the D.C. voltage difference between the + and - terminals of the bridge rectifier is maintained negligible (a few millivolts) throughout the busbar current range by driving the - bridge terminal to "follow" the + bridge terminal, as the reader can observe by following the signal path through the operational amplifier.

The voltage follower technique does a number of useful things:

1. IR drop in the burden resistor and in coils 3 and 4 is compensated; as far as the basic 2- core transductor is concerned (coils 1 and 2), it is operating into a D.C. short-circuit. This improves linearity at the high-current end of the transfer function Fig. 5B.
2. The restriction on current slewing rate is lifted because it is now possible to find a point B that follows B'. The circuit follows current changes at rates from zero to greater than 1,000 amps/microsecond.
3. The A.C. voltage at the bridge remains small (~2V.) at all times, rather than varying with the busbar current.

Maintaining this A.C. voltage small improves the temperature coefficient, partly because displacement and loss currents in the wire winding dielectric are low, and partly becuase the flux operating points of cores 1 and 2 are better stabilized.

The schematic for the 500 Amp transductor is

Fermilab 0435.06-EE-46041; the 7,500 Amp, EE-45928.

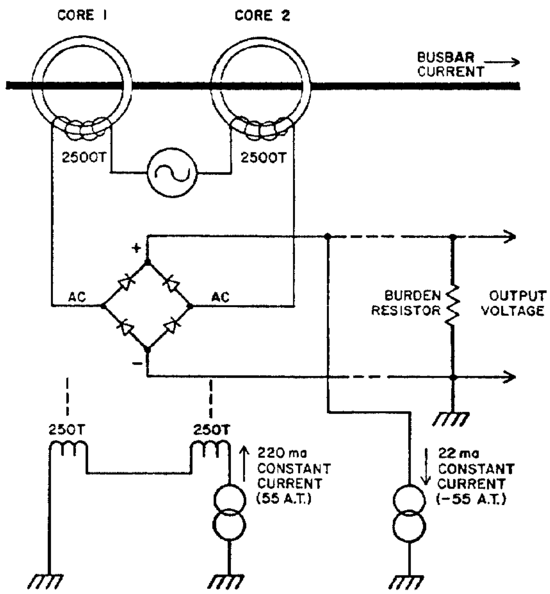

Fig. 4. Bias Circuit.

Drift with Temperature

Good heat transfer certainly aids thermal stability. For this reason and for shielding, the transductor coils are potted in aluminum shells (water-cooled) with high thermal conductivity epoxy. Because of time limitations extensive heat runs have not been made; it was measured that at zero busbar current, the temperature coefficient is below 1 mA/°C.

Comparisons

Transductors present advantages and disadvantages. I list a few pertinent to high performance applications:

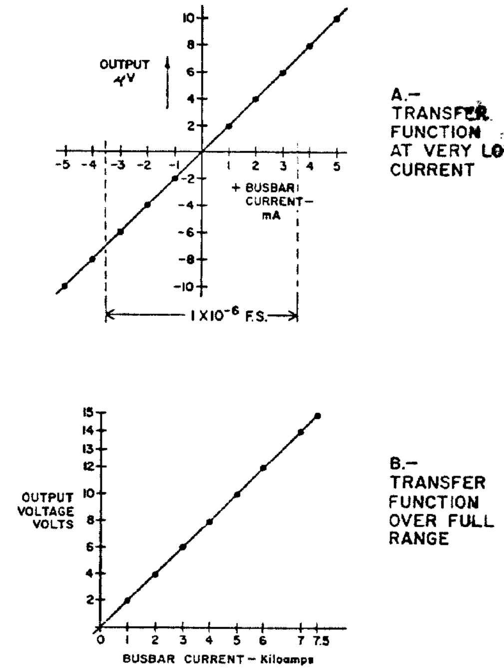

Fig. 5. Result of Bias.

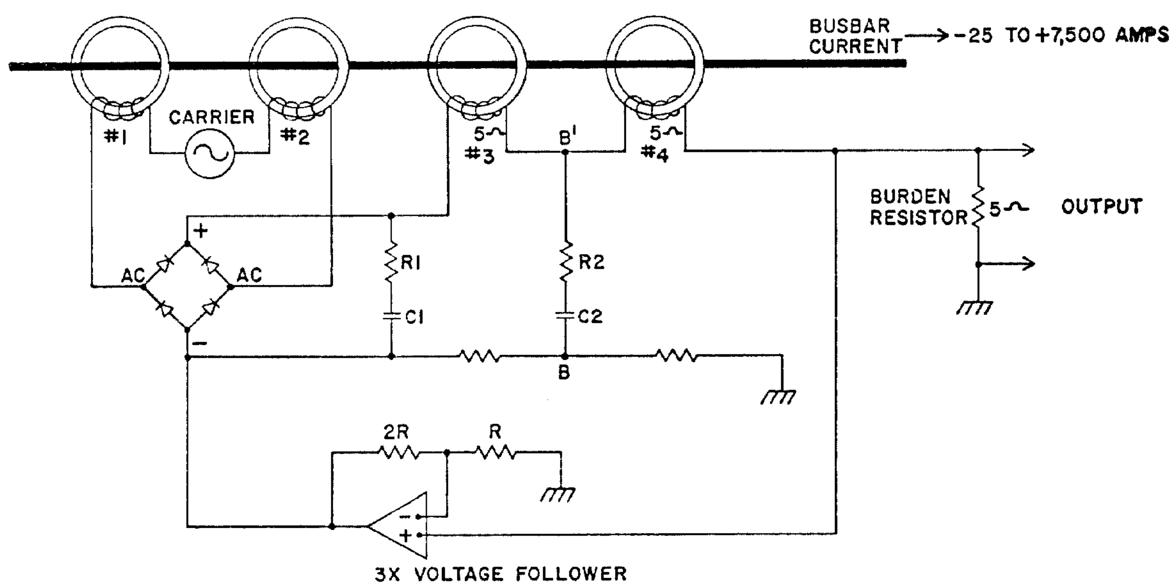

Fig. 6. Voltage Follower Compensation of IR Drop in Burden Resistor and Coils 3 and 4.

Transductor Disadvantages

1. Some sensitivity to stray magnetic field. Busbar should be centered, return circuits either far removed or coaxial, and stray fields above a few gauss shielded out.

2. Magnetic cores may have to be selected. Windings must be symmetrical and uniform. Stray capacitances are to be kept constant or balanced. Stable dielectrics around the AC windings are necessary.

3. The burden resistor must be stable to achieve a stable voltage transfer function.

4. Cores 1 and 2 introduce a small 2nd harmonic voltage into the circuit being measured.

Transductor Advantages

1. The device is long-term stable and rugged. Severe overloads of either forward or reverse current produce no permanent offset.

2. Electrostatic shielding is easy to add, and can be made excellent if required.

3. Current summing or differencing can be performed on high-potential isolated circuits.

4. There is no added power loss in the high current circuit.

5. The output is a high-level signal.

Special Features of the Present Units

1. Linearity is preserved down to zero current.

2. The output follows from D.C. to rates of current change above 1000Amps/microsecond.

3. Signal transport delay is negligible. Excluding cables, the delay is less than 50 nanoseconds. There are no amplifiers after the burden resistor. The bandwidth is flat ±3dB from D.C. to > 1MHz.

4. The zero-current offsets are very small:

Parameter	Range of Parameter	Equivalent Busbar Current
Line Voltage	110-125 V.A.C.	± 1 mA
Line Frequency	58-63 Hz	-1.1 mA/%
Ambient Temperature	8°-42° C	-0.6 mA/°C
Current Regulator Reference Voltage	± 1%	± .2 mA/%

Conclusions

These transductors were placed in service in May 1974, and have performed well. They passed unscathed through a two week shutdown in December 1974, involving busbar rearrangement and relocation of coil heads. The 500 ampere difference transductors (Bend minus Quad) have at times been subjected to the full bend current or the full quad current with no detectible after-effects the magnetic history of cores 1 and 2 is indeed erased by the AC carrier.

An esthetic objection one could have for the 7,500 ampere transductor design is the 45 watt dissipation in each coil and in the burden resistor at full scale, when all one really needs is a voltage for an A to D converter. It is tempting to try (next time) a two-stage, cascade transductor in which the busbar current is stepped down from 7,500 Amps to say, 0.1 Amp to reduce coil loss and keep the burden resistor power down to a watt. It is clear that the performance of a 2 stage unit would be quite acceptable.

Acknowledgement

Rae Stiening of the Accelerator Division Main Ring group initiated this project and provided unfailing assistance.

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