A Self-Balancing Direct Current Comparator for 20,000 Amperes

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Abstract—The direct current comparator is a current ratio device which uses a two-core magnetic modulator as an ampere-turn balance detector. The applications of this comparator to precision measurements are very limited, unless it is made self-balancing by feedback.

A transistorized self-balancing direct current comparator for 20,000 amperes which employs two stages to obtain a maximum ratio of 20,000/1 is described. The self-balancing circuit has a range of ±10 percent and an open loop gain of over 10^6. An analysis is made of the errors of the comparator including the effects of large external magnetic fields, magnetic memory, and alternating currents in the ratio windings. The total error increases with the amount of self-balancing required, but does not exceed 10 parts per million, provided the comparator is operated near its rated ampere-turn level.

Applications of the comparator to the calibration of transductors (dc current transformers) and dc shunts at full rated current are discussed.

Introduction

The current comparator is an ampere-turn balance indicator based on the detection of the zero flux condition in a magnetic core. For alternating current operation, the detector consists of a single magnetic core with a uniformly distributed detection winding [1]–[3]; for direct current operation, a double core magnetic modulator is used [4]. A magnetic shield, which completely surrounds the detector, is required for high accuracy.

The application of the current comparator to the precise measurement of alternate current ratios has been very successful [5]. The extension of these applications to direct current has been difficult because of the absence of the self-balancing effect which, for ac operation, is supplied by current transformer action. This paper describes a 20,000-ampere direct current comparator which is made self-balancing by automatic feedback using a magnetic modulator-type detector and a transistor amplifier.

Similar devices, using a magnetic amplifier and a magnetic amplifier-type detector, have been used in Germany for the measurement of very large direct currents as encountered in electrochemical plants [6]–[8]. The current comparator described here is believed to be more accurate, primarily because of the better zero stability of its detector.

The Self-Balancing Direct Current Comparator

The main components of a direct current comparator are illustrated in Fig. 1(a). They consist of a double-core magnetic modulator, with associated demodulator, a magnetic shield, and the primary and secondary ratio winding. This comparator can be made self-balancing by the addition of an amplifier, as shown in Fig. 1(b). This elementary self-balancing direct current comparator has several limitations. Theoretically, the error can be made as small as required by increasing the gain of the amplifier. In practice, however, the gain is limited by stability considerations. Another limitation, particularly for industrial applications, is that it is often impossible to avoid large transients and ac ripple which would saturate and possibly damage the feedback amplifier.

These limitations can be overcome by the use of a composite secondary winding consisting of three separate windings: the bias winding, the feedback winding, and the ripple suppression winding, as shown in Fig. 2. These windings each have the same number of turns, so their currents can be added together to form the secondary current I<sub>s</sub>. Most of the direct secondary current flows through the bias winding from a manually adjusted dc power supply. The remainder of the direct secondary current flows through the feedback winding from the amplifier. The maximum current to be carried by the feedback winding depends on the stability of the primary current. In industrial applications, a typical stability is ±10 percent. If the maximum stable dc loop gain is 10<sup>6</sup>, the maximum error at full output would be one part in 10<sup>5</sup>. This represents an increase in...
accuracy by a factor of ten over what would be achieved without the use of a bias winding. In laboratory applications, where \( I_p \) is very stable, the adjustment of the bias current is limited by the resolution of the power supply setting. A typical limit of resolution is ±1 percent. Again assuming a dc loop gain of \( 10^4 \), an overall accuracy of one part in \( 10^6 \) can be achieved.

The ac components in the primary current \( I_p \), such as transients and ripple, are balanced approximately by secondary currents induced in all three secondary windings by current transformer action. For some applications it may be convenient to have the bias current supplied from a source with a high internal impedance, which forces most of the transient and ripple currents to flow through the feedback and ripple suppression windings. Since the current-carrying capacity of the feedback amplifier is much less than the total secondary current, the amplifier could be damaged if the ripple suppression winding were not present. The ripple suppression winding also serves to stabilize the feedback loop by ensuring that the load impedance of the feedback amplifier remains low, even when the bias winding power supply impedance is high.

The operation of the self-balancing direct current comparator can be analyzed with the aid of the equivalent circuit shown in Fig. 3. This was developed from the classical equivalent circuit of the ac current transformer which comprises an ideal transformer, winding impedances, and a magnetizing impedance \( Z_m \). The feedback circuit which extends the useful operating range down to zero frequency generates the voltage \( e_2 \).

The error current \( I_e \) has two effects. It magnetizes the core, thus inducting a voltage \( I_e Z_m \) in all three secondary ratio windings. It also produces a voltage \( I_e Z_m \) at the output terminals of the feedback amplifier, where \( Z_m \) is the equivalent modulator impedance referred to the secondary. It is related to the magnetic modulator sensitivity \( S \) by the following equation:

\[
Z_m = S \times G \times n
\]

where

\( S \) = magnetic modulator sensitivity in volts per ampere-turn

\( G \) = voltage gain of feedback amplifier

\( n \) = number of turns of the secondary winding.

All impedances appearing in the equivalent circuit are frequency dependent. It is to be noted that \( \lim Z_e = 0 \) as \( \omega \to 0 \), and \( \lim Z_m = 0 \) as \( \omega \to \infty \). For satisfactory performance it is essential that the sum \( (Z_e + Z_m) \) remains large with respect to the secondary winding impedances and the burden, at all frequencies from zero to the highest frequency of interest in the primary current. The maximum value of \( Z_m \) is limited by the need to maintain feedback loop stability and should be chosen to produce a stable but slightly underdamped response with the bias circuit open. The maximum load impedance imposed on the feedback amplifier at any frequency is \( Z_1 + Z_2 + Z_3 \), which is essentially the resistance of the windings. If the ripple suppression winding is removed, as in Fig. 1(b), the load impedance on the amplifier becomes larger and approaches \( Z_3 \). This increases the loop gain and the circuit may oscillate.
The 20 000-Ampere Self-Balancing Direct Current Comparator

Construction

A 20 000-ampere self-balancing direct current comparator has been constructed. It was designed primarily for in situ calibration in industry of large dc current measuring devices such as those encountered in aluminum production. It is of the feedthrough type, and is illustrated in Fig. 4. The number of turns of each secondary is adjustable to 2000, 1750, and 1500. For each number of turns, the secondary remains uniformly distributed because the windings have been divided into eight sectors which can be adjusted individually. Major dimensions are given in Fig. 5. Additional construction details are given in the Appendix.

The large cross-sectional area of the magnetic shield was considered necessary because of the large ambient magnetic field expected in industrial surroundings. The stability of the primary current was estimated to be better than ±10 percent, consequently, the amplifier was designed for ±10 percent of rated current, i.e., one ampere.

The electronic circuits are shown in Fig. 6. They consist of a square wave-type magnetic modulator operating at 245 Hz, followed by a phase sensitive detector as the demodulator. The reversible dc output of the detector is displayed on meter M-1. The feedback amplifier is of the push-pull type, with a voltage gain of about twelve and an internal impedance of about one ohm. When operated with the 2000-turn feedback winding, the dc loop gain is about 14 000, and no special loop stabilizing circuits are required.

The output characteristic of the magnetic modulator-detector, as measured on meter M-1, is shown in Fig. 7. The feedback amplifier saturation level is much lower than that of the modulator, and this limits the normal operating range of the modulator to a small fraction of its linear range, as indicated. The sensitivity of the magnetic modulator-detector is six volts per ampere-turn.

It is interesting to note that the output of the magnetic modulator-detector is zero not only at the normal operating point C corresponding to zero ampere turns, but also at points A, B, D, and E. Points B and D are unstable when the feedback loop is closed. Points A and E are stable, however, and some means is required to indicate to the operator that the current ratio is not correct. This is accomplished by the core saturation indicator (Fig. 6). At either point A or E the modulator cores are completely saturated so that the voltage drop across their windings is much lower than normal. This is detected and indicated on lamp 1 or lamp 2. Two lamps are used to give an indication of the polarity of the saturation, thus giving a clear signal to the operator to either increase or decrease the bias power supply current.

Performance

The self-balancing direct current comparator is essentially a current transformer whose useful operating frequency range has been extended down to zero frequency. However, the inclusion of a bias winding supplied from a dc power supply gives it a dc error characteristic which is quite different from that at any other frequency. Only at zero frequency can the ratio error of the current comparator be adjusted so that the detector output is zero. At all other frequencies some error is required to induce the secondary current. For this reason, the dc performance is treated separately from the ac performance.

1) Direct Current Performance: Even when the bias power supply is adjusted so that the magnetic modulator output is zero, a small residual error remains which corresponds to the modulator-detector error. One of the characteristics of the magnetic modulator in this and many other applications is that its sensitivity can be made greater than its zero stability. In spite of the precautions taken in the design of the electronic circuitry, the output of the modulator is subject to a spontaneous zero drift. This drift could be due to changes in the circuit components, including the modulator cores. Temperature changes may be a contributing factor.

When measured, the drift rate was generally substantially less than one milliampere-turn per hour,
though occasionally it rose to two milliampere-turns per hour. These drift rates are, however, noncumulative, and the maximum observed drift during any 12-hour period ranged from one to two and one-half milliampere-turns. The long term zero stability is estimated to be about ±10 milliampere-turns.

In addition to this spontaneous zero drift, a zero shift may be produced, following a current unbalance large enough to saturate the cores. This zero shift, called memory, has been investigated in detail by others [9]. The polarity and magnitude of the memory depend mainly on the intensity of the core modulation. The measured memory of the 20 000-ampere current comparator was about ±10 milliampere-turns.

Another source of error is the ambient magnetic field and the leakage fluxes generated by the ratio windings. The resulting error, called the magnetic error, can be reduced substantially by the use of a magnetic shield [4]. The effectiveness of the magnetic shield used was tested by subjecting the comparator to equal but opposing ampere-turns on two diametrically opposed sections, as indicated in Fig. 8(a). The output of the detector should remain zero. In practice, however, some output signal is produced which varies with the ampere-turn level applied. Figure 8(b) gives the results obtained when the two opposed sectors were chosen to produce maximum signals, from which the following conclusions may be drawn.

a) The magnetic error has a decided hysteresis charac-
that is, at all frequencies for which \( \text{PP} \).

I\(_2\), operated at 20 000 ampere-turns, the maximum error frequency approaching the modulation frequency. tally with a burden of one ohm, and was found to be 8.5 would be 70/10, or 5-

8.

stantially larger than impedance feedback-amplifier controlled. The effective modulator current transformer action, represented by \( I' \) (Fig. 6) which is calibrated in milliampere-turns. The maximum value of this current can be estimated by referring to Fig. 3.

\[
Z_m = S \times G \times n = 6 \times 12 \times 2000 = 144\,000 \text{ ohms}
\]

\[
Z'_2 + Z_2 + Z_b \approx 10 \text{ ohms}.
\]

Assuming that the burden \( Z_b \) is small, so that the voltage \( I_2 Z_b \) can be ignored,

\[
e_b = I_1 Z_m \approx I_2 (Z'_2 + Z_2 + Z_b)
\]

\[
\frac{I_2}{I_2} \approx \frac{Z'_2 + Z_2 + Z_b}{Z_m} \approx \frac{10}{144000} = 70 \text{ parts per million (ppm)}.
\]

If \( I_2 = 0.1 I_b \), which corresponds to the limit of the operating range of the amplifier when the current comparator is operated at 20 000 ampere-turns, the maximum error \( I_b/I_2 \) would be 70/10, or 7 PPM. This was checked experimentally with a burden of one ohm, and was found to be 8.5 PPM.

2) Alternating Current Performance: At low frequencies, that is, at all frequencies for which \( Z_m \) remains substantially larger than \( Z_e \) (Fig. 3), the performance is mainly feedback-amplifier controlled. The effective modulator impedance \( Z_m \) remains essentially constant up to a frequency approaching the modulation frequency.

The high-frequency performance is controlled mainly by current transformer action, represented by \( Z_e \) in the equivalent circuit. \( Z_e \) is approximately proportional to frequency. The measured value at 60 Hz was 100 kHz.

At intermediate frequencies, at which \( Z_m \) and \( Z_e \) are of the same order of magnitude, the performance is controlled by the combined effects of the feedback amplifier and current transformer action. It is of interest to note that \( Z_m \) and \( Z_e \) are essentially 90 degrees out of phase so that their effects cannot be added algebraically. In addition, the bias winding resistance is smaller than the feedback winding resistance so that the current transformer action is relatively more pronounced than the ratio \( Z_e/Z_m \) would indicate. It was found that the current transformer action was predominant at frequencies above 20 Hz. The current comparator was calibrated at 60 Hz and the error \( \epsilon \), as defined by the equation \( I_e = (I_p/n) (1 + \epsilon) \) was found to be (12 + 34) PPM. If this alternating current represents a 10-percent ripple on the primary current, the error expressed in percent of the total current would be (1.2 + 3.4) PPM.

Applications

Industrial Applications

Large direct currents, as used in the electrochemicals industry, are measured using shunts or transducers (dc current transformers). Both are significantly affected by ambient conditions, so that in situ calibration is highly desirable. The 20 000-ampere dc comparator was specifically designed for this application [10], [11]. Its error has been found to be negligible compared to the stability of the devices to be calibrated.

For the calibration of transducers, it is desirable that the turns ratio of the current comparator be equal to the nominal ratio of the transducer so that differential calibration methods may be used [5]. Nominal ratios for transducers have not yet been standardized in North America. In general, however, they are significantly larger than the 2000/1 ratio of the 20 000-ampere current comparator. For this reason, a second self-balancing current comparator, rated at 2000 ampere-turns, was built to be connected in cascade. The secondary windings have 2000 turns and are tapped at 1800, 1600, 1400, 1200, and 1000 turns. The fixed primary has 200 turns. This second-stage comparator is similar in design and operating characteristics, but is considerably smaller in physical dimensions than the large comparator (see Appendix).
For special applications requiring high accuracy, the current comparator can be used for metering in industry. Such applications invariably are associated with control problems, for which the current comparator seems to be very well suited. If the bias current is supplied from a regulated current source, the feedback current can be used directly to perform the control function desired. Current regulated power supplies of up to 10 amperes at 36 volts are readily available with a regulation of ±0.05 percent. The current comparator makes possible the transfer of this regulation characteristic to the full input current of 20000 amperes, essentially without deterioration in performance.

The control cabinet used for in situ calibrations in industry is shown in Fig. 9. At the top is a commercial regulated power supply for the 10-ampere bias current of the 20000-ampere comparator. The second and third racks contain the electronic circuitry for the automatic feedback of the main and the second stage current comparators, respectively. The bottom rack houses the 2000-ampere-turn current comparator. A separate power supply is used for the one-ampere bias current of the second-stage comparator.

**Laboratory Applications**

The calibration of dc shunts at full rated current is often required. To do this with conventional bridges, a reference standard is needed which also can carry the full rated current. Such a standard is not always available. Reference standards which can take the same voltage drop are quite readily available, however. The self-balancing dc comparator can be used to generate and measure currents in the ratio required to produce the same voltage drop in the shunt and reference standard.

The same technique can be used for the scaling of standard resistors below one ohm [5]. In such applications, the full accuracy capabilities of the direct current comparator, approaching one PPM, can be exploited.

**Conclusions**

A self-balancing 20000-ampere direct current comparator has been described. Its main features are the use of a magnetic modulator-type detector and a transistor feedback amplifier. It is estimated that for industrial applications the error of this comparator is of the order of 10 PPM, provided that it is operated near its rated ampere-turn level. In the laboratory, its full accuracy capability, which approaches one PPM, can be achieved.

**Appendix**

**Construction Details of Main and Second-Stage Direct Current Comparators**

- **Main Comparator**
  - Rating: 20000 ampere-turns
  - Modulator cores (HyMu 80)
  - ID 19/8", OD 19/8", Ht 1/2"
  - Detection winding: 600 turns, No. 24 formex wire
  - Electrostatic shield: Copper foil over each core
  - Modulation winding: Detection winding used
  - Magnetic shield (cross section): 12 in² (0.012" Hypersil)
  - Bias winding: 2000 turns, No. 10 wire, tapped
  - Feedback winding: 2000 turns, No. 14 wire, tapped
  - Ripple suppression winding
  - Primary winding: Feedthrough
  - Window diameter: 12¼"

- **Second-Stage Comparator**
  - Rating: 2000 ampere-turns
  - ID 7", OD 7½", Ht 1/2"
  - Modulator cores (HyMu 80)
  - Detection winding: 1447 turns, No. 28 formex wire
  - Electrostatic shield: Copper foil over each core
  - Modulation winding: 600 turns, No. 24 formex wire
  - Magnetic shield (cross section): 2½ in² (0.012" Hypersil)
  - Bias winding: 2000 turns, No. 19 wire, tapped
  - Feedback winding: 2000 turns, No. 19 wire, tapped
  - Ripple suppression winding
  - Primary winding: 200 turns, No. 12 wire
SCR Switch Aids Protection of Superconducting Coils

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Abstract—When a high field superconducting coil becomes resistive, degradation or failure of the coil may occur if the energy stored in the magnetic field is dissipated in the initial resistive portion of wire. By sensing the onset of the normal transition, it has been possible to disconnect the external power from the coil and transfer the coil energy to an external energy sink rapidly enough to reduce the likelihood of damage to the coil.

A controlled rectifier static switching circuit has been employed, which is capable of interrupting 450 amperes dc and blocking 475 volts. The initiating signal for triggering the switch operation is obtained from a mutual inductor carrying the superconducting coil current. Obtaining a reliable initiating signal is complicated by "flux jumps" which occur in the superconducting coil. Although many different types of energy sinks can be employed to store the coil energy, a precharged capacitor has proved very effective for small size superconducting solenoids.

Introduction

High field superconducting coils of relatively modest size can readily store thousands of joules of energy. If the critical current of the coil is exceeded, a portion of the superconducting wire becomes resistive, forcing the coil current and magnetic field to collapse rapidly. The stored energy, if dissipated in the initial resistive portion of wire, generally damages the coil. The damage may be manifested by a reduced value of critical current, or open or shorted turns.

Several methods of protection have been recognized and employed in some manner [1, 2]. They include: 1) the use of cooper plating on the superconductor to provide a low resistance shunt path around the high resistance normal portion; 2) magnetically coupled circuits (usually produced by interleaved secondary windings of normal metal) which prevent rapid collapse of flux and absorb much of the energy; 3) subdivided coils in which normal resistors of low resistance are connected across sections of the coil so as to short circuit the voltages developed during the transient (they do not carry current during steady-state superconducting operation); 4) the use of external sensing and switching circuits which interrupt the current from the power supply and divert the coil current into an external energy sink.

It is the last scheme which will be considered in this paper. This approach offers the advantage that no intrinsic alteration of coil design is required, and a large fraction of the coil energy can be dissipated external to the coil and liquid helium.

General Approach

The protection scheme is shown in block diagram form in Fig. 1. Under normal operation, the power supply delivers current through the controlled rectifier (SCR) and the superconducting coil. A mutual inductor monitors the superconducting coil current. When the current decreases, a voltage is induced in the secondary winding of the mutual inductor. This voltage actuates the trigger circuits which trigger the SCR commutating circuit. The action of the commutating circuit permits SCR to regain its blocking state, thus disconnecting the superconducting coil from the power supply. Energy in the field of the superconducting coil then transfers to the energy sink.