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A current comparator for the precision measurement of d-c ratios

A magnetic d-c ratio device has been developed that is capable of attaining accuracies approaching 1 part per million. The operating characteristics and some of the design problems are discussed, and construction details of an experimental model, rated at 4,000 ampere-turns and capable of handling ratios up to 400 to 1, are given. The use of this device for the scaling of fundamental resistance standards is proposed

The current comparator is a magnetic device which can be used to determine the ratio between two currents with a high degree of accuracy. It operates on the principle that when ampere-turn equality is achieved between two windings of opposite polarity on a magnetic core, no flux will be induced in that core. The initial development of this device was carried out at the power frequencies where the zero flux condition is easily detected by an additional winding on the core itself. An a-c comparator capable of carrying out measurements of ratios up to 400 to 1 at currents as high as 2,000 amperes, with an accuracy of better than one part per million, has been developed.[1,2]

A large number of current ratio measurements are, however, concerned with direct current and the question arises as to whether accuracies of the same order could not also be obtained in d-c measurement by applying the same basic principle. The sensitivity of the a-c comparator is, of course, proportional to frequency; hence another method is required to detect the presence of direct flux in the magnetic core of the d-c device. Of the several well-developed magnetometer techniques available for this purpose, the second-harmonic flux-gate technique is of particular interest.[3,4] This article presents the results obtained with a comparator employing this method of detection.

CONSTRUCTION AND DESIGN FEATURES

The general scheme of the d-c comparator is shown in Fig. 1. Its essential components are:

1. Two inner measuring cores together with suitable windings for the detection of direct flux therein.
2. A magnetic shield that surrounds the two inner cores, protecting them from the effects of external magnetic fields.
3. Primary and secondary windings, which carry the currents to be compared.

The additional windings and shields enhance the usefulness of the comparator but are not fundamental to its operation. Of particular importance are: the deviation winding, which permits the resultant magnetomotive force of the primary and secondary windings to be adjusted by small, measured amounts; and the ripple suppression winding, which reduces the effect on the measuring cores of a-c components of the primary and secondary currents.

The two inner cores are toroidal in shape and are tape wound from magnetic material of high initial permeability. A detection winding consisting of a single layer of many turns of fine wire is uniformly wound on each core, followed by an electrostatic shield of thin copper foil and a modulation winding, the number of turns of which is dictated largely by the characteristics of the supply.

The two cores, together with their respective windings, are so arranged that the primary and secondary windings are common to both cores. Each core is modulated in such a way that, at any one instant, the magnetomotive force (mmf) of the modulation winding on one core aids the resultant mmf of the primary and secondary windings, while the same mmf's on the other core oppose one another. The voltages induced in the detection windings under these conditions contain a large component of twice the modulation frequency when direct flux is present

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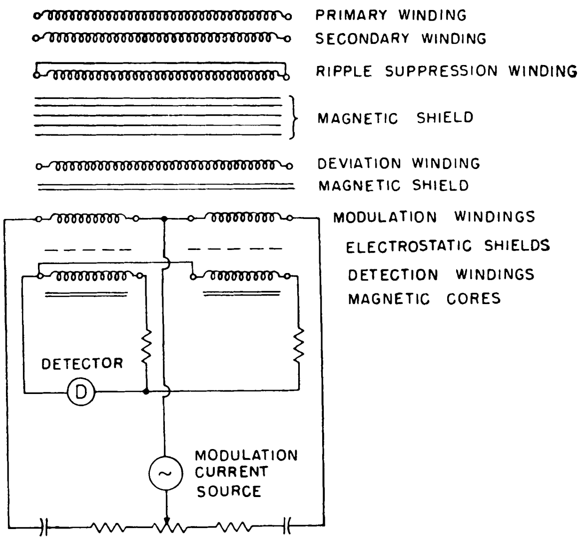


Fig. 1 Schematic diagram of d-c comparator

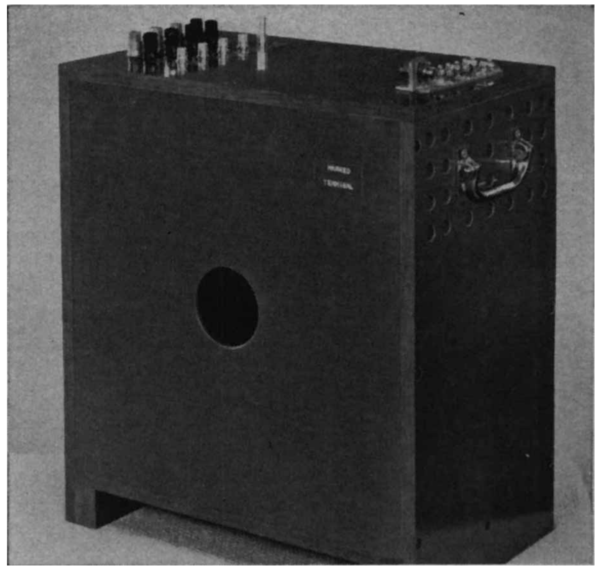


Fig. 2. Experimental d-c comparator

in the two cores. The two detection windings can be so connected with respect to the detector that the fundamental frequency components of the induced voltages cancel one another while the second harmonic components add. Other even harmonic voltages will also be present but these can be eliminated by tuning the detector. The net result of such an arrangement is a second harmonic voltage whose amplitude is reasonably proportional to the amplitude of the direct flux and whose phase is determined by the sense of the direct flux.

The deviation winding is placed around the two measuring cores, which are now fixed with respect to one another, in such a way as to encompass both cores simultaneously. The mmf's generated by this winding in the two cores will thus act in a manner similar to the resultant force of the primary and secondary windings; hence this winding can be used to adjust the total mmf which is being imposed on the measuring cores. The number of turns and resistance of the deviation winding should be such that the current through it can be supplied from the secondary circuit with a resistive network of convenient dimensions.

This assembly is now surrounded on all sides by a heavy magnetic shield which is coaxial with respect to the mean magnetic paths of the two measuring cores. The object of this shielding is to ensure that the flux induced in the measuring cores is only that which can be attributed directly to currents that link with the cores. The measuring cores must be shielded from external fields and from leakage fluxes arising from asymmetries in the distribution of the windings. Efficient shielding in the plane of the measuring cores

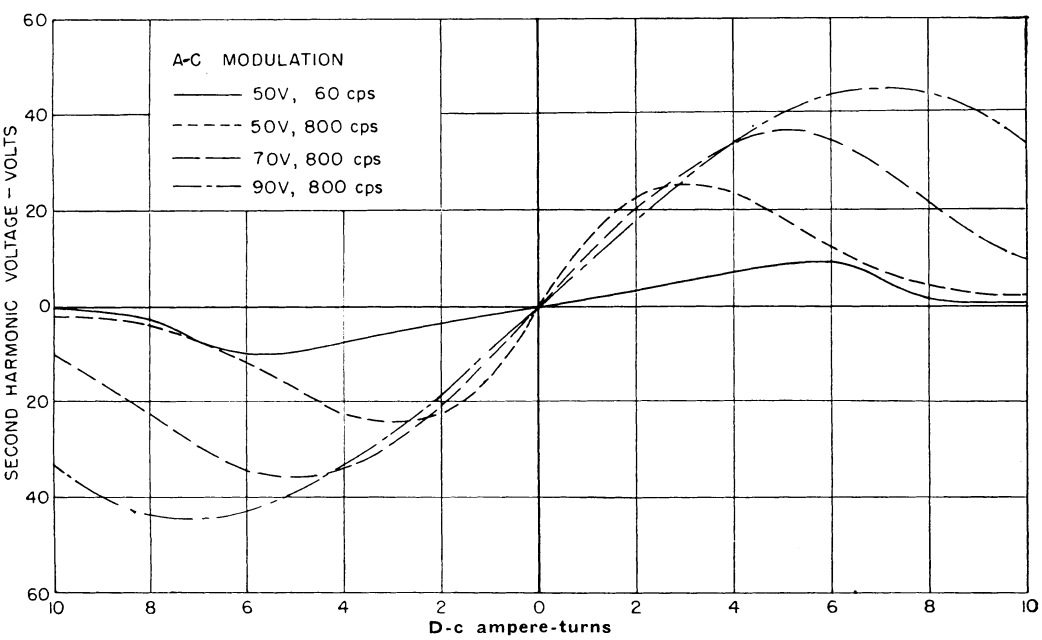


Fig. 3. Sensitivity characteristics

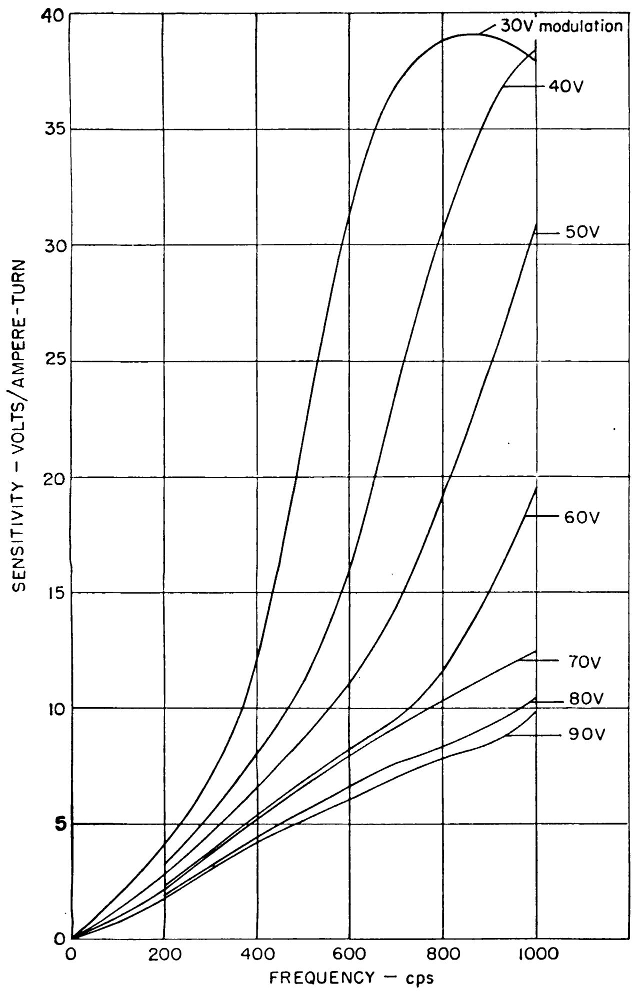


Fig. 4. Sensitivity vs. modulation frequency

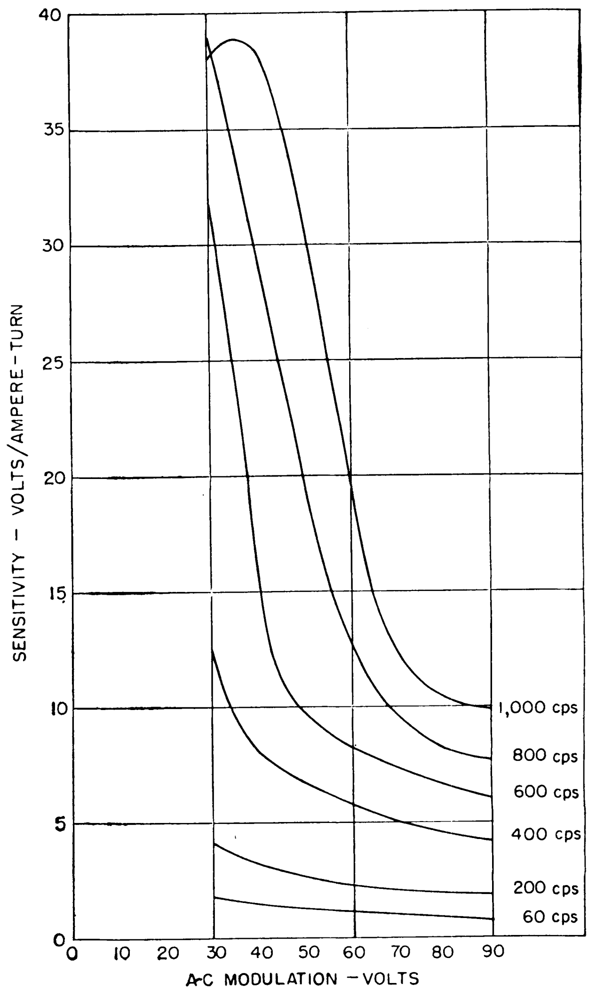


Fig. 5. Sensitivity vs. modulation amplitude

can be obtained by the use of grain-oriented silicon steel toroids of suitable dimensions. The two sides can be protected either by rings or by the use of toroids which "nest" with the main shielding cores. Some advantage may also be realized by using a second shield of a high permeability material in the low field region inside both the main shield and the deviation winding.

Apart from its shielding function, the magnetic shield also makes possible the use of a ripple suppression winding. Alternating components of the primary and secondary currents arising, for example, from rectifier supplies could interfere with the detection of the residual direct flux in the measuring cores, particularly if the frequency is the same as the second harmonic of the modulation frequency. A winding around the outside of the magnetic shield, which is closed upon itself, will provide an effective short circuit for any voltage induced by these a-c components. It will not, however, short-circuit the voltage induced in the detection windings because, to these windings, the ripple suppression winding will appear to have a large reactance in series with it. The main requirement in the design of the ripple suppression winding is low resistance; hence the copper cross section should be large. Care must also be taken in making joints because contact potentials may cause currents to flow in the short-circuited winding, resulting in a measurement error.

To complete the construction of the comparator, the primary and secondary windings must be added. While in general it is possible to wind these on as required, it is convenient to have a number of fixed windings for the lower currents since these usually require a fairly large number of turns. The actual number of turns is either dictated by the sensitivity required or by the ratio, depending on the magnitude of the current.

OPERATING CHARACTERISTICS

A d-c comparator that covers ratios from 1-to-1 to 400-to-1 and that has a maximum rating of 4,000 ampere-turns is shown in Fig. 2. Constructional details are given in the Appendix.

Modulation of the cores and detection of the second-harmonic voltages were obtained by an arrangement proposed by Williams and Noble, as shown in Fig. 1. There are other possible circuits, but these have the advantage of a grounding scheme which has symmetry with respect to the two cores and the auxiliary instruments. The circuit used for modulating the cores contained two 1,000-ohm resistors to impede the flow of second-harmonic currents, a balancing potentiometer of 1,000 ohms, and two 8-μf capacitors to block the direct currents arising from contact potentials. In use, the balancing potentiometer in the modulation circuit was adjusted for minimum second-harmonic output when no direct currents link the cores. The two resistors that form a voltage divider in the detection circuit were 2 megohms each so as not to load the detection windings. These resistors should be chosen for zero fundamental frequency voltage at the terminals of the detector, but complete elimination of this component is not necessary if the rejection capability of the detector is adequate. The detector input impedance was of the order of 0.5 megohm.

The characteristics of the comparator depend, in part, upon the modulation current waveform. For all the results presented in this article a sinusoidal voltage source was used. This, because of the series impedance, produced almost sinusoidal current at the lower frequencies. At higher frequencies, where the magnetizing impedance becomes equal to or greater than the series impedance, the current waveform becomes more and more distorted.

Sensitivity • Comparator sensitivity is defined as the ratio of second-harmonic output voltage to the applied d-c ampere turns. It depends, in part, upon the magnetic characteristics and geometry of the core, and also upon the characteristics of the modulation, such as magnitude, frequency, and waveform.[3]

Fig. 3 shows the overall relationship between the second-harmonic output voltage and the applied d-c magnetization for various modulation amplitudes and frequencies. It is apparent that a fairly linear region exists in these characteristics near the null point and that the slope or sensitivity is dependent upon both the frequency and amplitude of the modulation. Variations of the sensitivity against these two parameters at a d-c magnetization of 0.010 ampere turn are shown in Figs. 4 and 5.

Errors • The current comparator is basically a current-null detector; accuracy which can be achieved with this device in any application will depend on how well it performs this function. It is therefore necessary to take into account those factors which lead to a false indication of current null, and either to measure and correct for their effect or to include special design features which will reduce their influence to negligible proportions. In the development of the current comparator, the latter alternative has been followed, and calibration is replaced by measurements which determine the maximum possible value of error.

An analysis of the a-c comparator has shown that its errors can be classified into two types—magnetic and capacitive.[2] In the d-c comparator, capacitive errors do not, of course, occur but two additional errors are present that are characteristic of d-c operation. One of these is due to the effects of residual magnetism in the cores and the other to the a-c modulation which is required to determine the state of the direct flux in the measuring cores. Both of these new errors cause a zero shift which is independent of current.

Magnetic errors which are common to both a-c and d-c comparators, such as those caused by ambient and leakage fields, are attenuated by the magnetic shield. The effectiveness of this shield may be tested by observing the variation in the detection winding voltage when the comparator is subjected to the influence of various external fields. Of particular interest is the field produced by a long, narrow coil or probe, which can be inserted through the window of the comparator. Although the net current that passes through the toroid under these conditions is zero, the resultant field is similar to that produced by winding irregularities and hence this technique provides a very significant test. Fig. 6 illustrates the overall arrangement and shows how the deviation winding may be used with a resistive network to

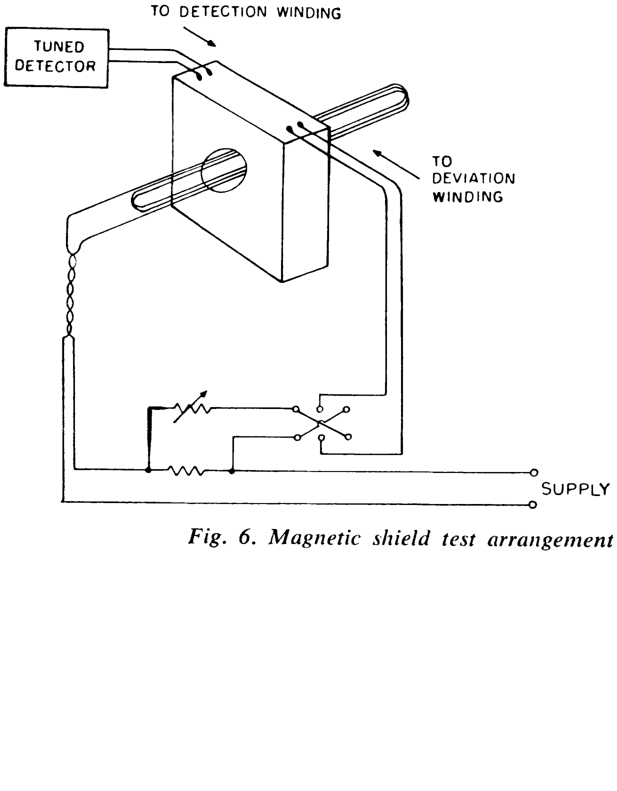


Fig. 6. Magnetic shield test arrangement

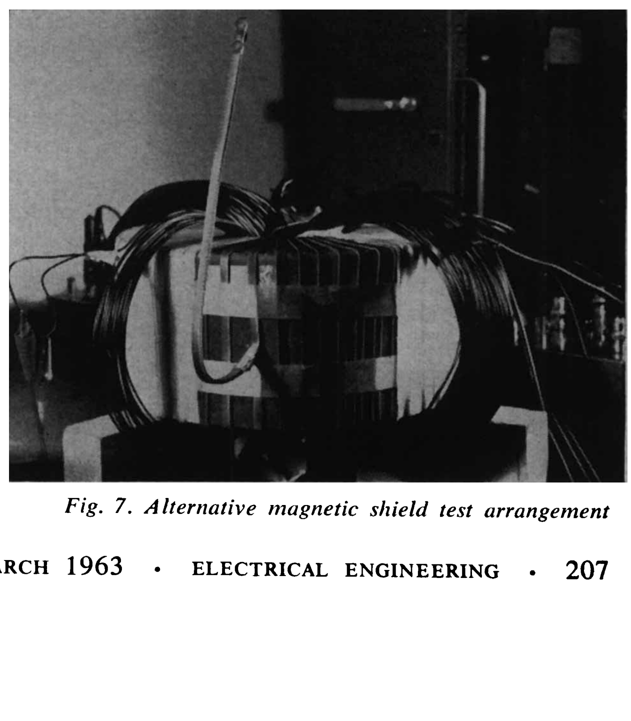


Fig. 7. Alternative magnetic shield test arrangement

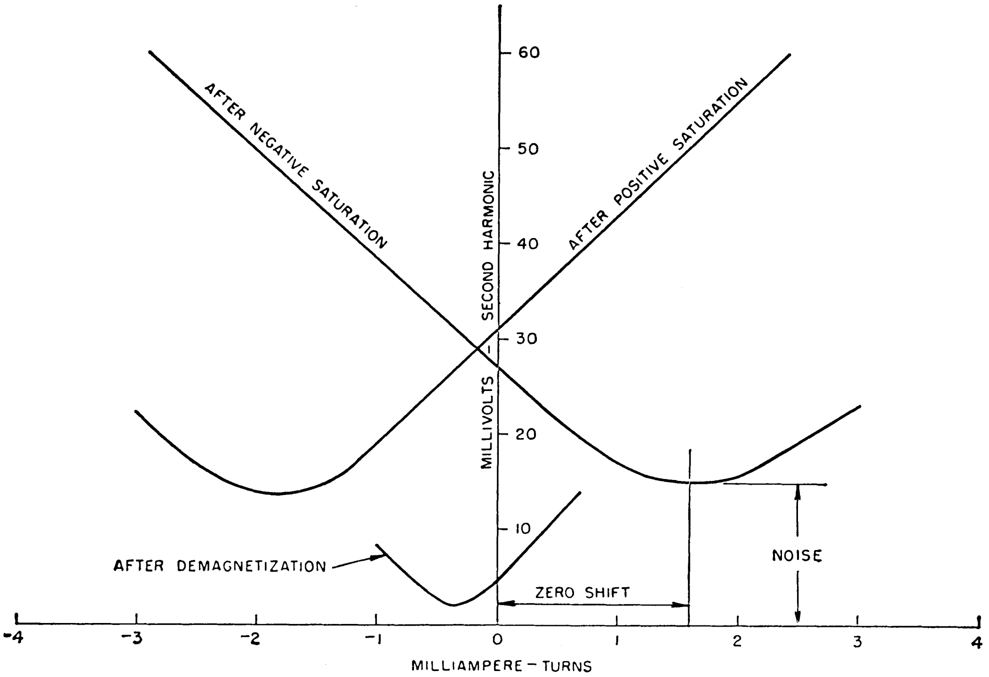


Fig. 8. Null characteristics for 70 volts, 800 cps modulation

measure the actual error caused by the coil. A typical probe of this type would consist of 100 ampere turns in a coil 1½ inches wide.

For the comparator described, the shielding was such that the 1½-inch 100-ampere-turn probe produced no measurable variation in the detection winding output voltage. As an alternative, two concentrated but movable windings of the same number of turns were wound on the toroid, connected so that their mmf's tend to cancel one another. Fig. 7 shows a typical arrangement of these bundles on the comparator when it was being tested during construction. Tests made with 2,000-ampere-turn bundles in various configurations indicated that, with the shielding provided, the resultant detection winding voltage was less than that arising from a one-part-in-a-million unbalance in the net ampere turns of the two bundles.

The residual magnetism which remains in the cores following d-c magnetization will cause an error which is essentially a zero shift or offset of the null point. This zero shift can be reduced, but never completely eliminated[3] by exciting the cores with alternating current to well past their saturation point and then reducing this excitation slowly to zero. In d-c comparators employing flux-gate magnetometer-type detection, however, the cores are being excited continually by the a-c modulation and, if the modulation intensity is sufficiently high, the cores will be undergoing depolarization continuously. The resulting zero shift then is a function of modulation amplitude and frequency. The degree to which it is present can be determined by observing the difference between the outputs of the detection system before and after the application of a d-c magnetization to the comparator. In the experimental comparator described the zero shift can amount to as high as 0.8 ampere-turn for modulations of 30 volts at 800 cps. This can be reduced by either increasing the voltage applied to the modulation circuit or by decreasing the modulation frequency. At 90 volts, 800 cps, the zero shift is reduced to 0.5 milliampere-turn or less and similar results can be obtained if the frequency is decreased to 100 cps or lower without changing the voltage. This appears to be the limit which can be consistently achieved by this means, however; hence operation of this comparator at a level of at least 500 ampere-turns is necessary if 1-part-per-million accuracies are desired. (It is to be noted that the modulation voltage required to overcome the effects of residual magnetism is not a linear function of frequency because of the series impedances in the modulation circuit.

The fact that a-c modulation is used to find the state of the direct flux in the measuring cores gives rise to additional causes of zero shift. The modulation current itself may contain a second-harmonic component, which, because of asymmetries in the modulation circuitry or the magnetic characteristics of cores, will result in a second-harmonic voltage in the detection windings. Part of this voltage may be in quadrature with that caused by ampere turns and this will lead to difficulties in obtaining a sharp null. The remainder, which is in phase, is a direct source of error. The obvious solution to this problem is, of course, better equipment and closer balancing of the modulation circuitry. A practical solution is reached when the error from this source is of the same order as that caused by residual magnetism.

Fig. 8 shows some typical null characteristics taken with the experimental comparator at 70 volts, 800 cps, where the zero shift resulting from residual magnetization and the effect of quadrature voltage are well defined.

Ripple Suppression • The ripple suppression winding attenuates the influence of sharp transients and a-c components in the main winding current which would tend to saturate the detection equipment or otherwise interfere with the measurement. It may be tested by supplying currents of various frequencies, first to the deviation winding, and then to the secondary winding. Since the deviation winding is located inside the magnetic shield, the ripple suppression winding will appear to have a large reactance in series with it and very little attenuation of the mmf of the deviation winding will be realized. The secondary windings, however, lie outside the shield and currents in the short-circuited ripple suppression winding provide heavy demagnetization. Measurement of the ampere-turns required in each winding to produce a specific detection winding output voltage will then give an indication of the effectiveness of the ripple suppression winding. The following are the measured values of the attenuation achieved at various frequencies in the experimental comparator:

Frequency, cps	*Attenuation*
2,000	1,490 to 1
1,600	1,250 to 1
1,200	960 to 1
800	660 to 1
400	430 to 1
120	120 to 1

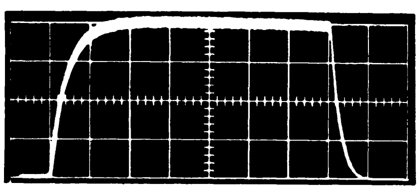
Further tests have indicated that, at the level of 500 ampere turns and 90-volt, 800 cps modulation, a 1-part-per-million variation in ampere-turn balance is readily distinguished in the presence of 5 per cent ripple.

Response Time • Comparator response to d-c magnetization changes is characterized by a time delay caused by the action of the ripple suppression winding. Any attempt to change the net ampere turns applied to the measuring cores by the primary or secondary windings is opposed by a current induced in this winding which decays very slowly. The actual delay depends upon the degree of coupling which is present and this in turn depends upon the magnetic state of the shield. Thus, if the cores and shield have already been subjected to magnetization in one sense, another attempt to magnetize them in the same sense will obtain much faster response than if magnetization in the opposite sense were sought.

In the experimental comparator, the response for small variations approximates that of a single time constant delay with time constants of from 2 to 6 seconds. In instances where large flux reversals take place in the magnetic shield, however, the response is more complex, and equivalent time constants of 20 seconds or more may prevail.

Fig. 9 shows some typical responses, taken at 90 volts, 800 cps. In Fig. 9(A), d-c magnetization was applied in the same sense as the residual polarization in the shield while in Fig. 9(B), the two opposed one another.

In evaluating the practical effect of such time constants, it is necessary to take into account the amplitude of the applied variations, since this will affect the total time required for the rate of change to reach a value that is significant with respect to accuracy desired. For example, an applied variation of 1,000 times that representing 1-part-per-million change will require a delay of some seven time constants before a reading of that accuracy can be taken.



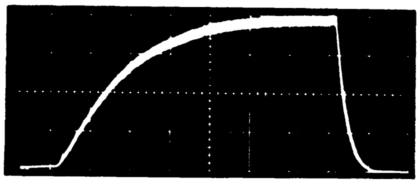


Fig. 9. Transient response

APPLICATIONS

Applications of the comparator include the calibration of large shunts at full rated current and the scaling of resistance standards in the range below 1 ohm. The possibility of establishing ratios between large currents with a high degree of accuracy but without the usual problems associated with heat dissipation and circuit isolation is a feature of particular importance.

Another application of this device, which has already received some attention in Germany,[5] is in the measurement of large direct currents such as those which exist in electrochemical plants. The current comparator, with its low inherent error and freedom from environmental effects, should be of considerable use in calibrating such systems and, with the addition of suitable auxiliary electronic feedback apparatus, be capable of continuous measurement.

CONCLUSIONS

The concept of a current comparator for d-c applications has been presented and the operating characteristics of an experimental model have been described. The results indicate that the techniques which were used so successfully in a-c comparators to overcome the effects of nonuniform winding distribution and ambient fields can also be applied effectively in a d-c version. Other factors were found, however, which limit the overall accuracy that can be attained in practice, but in spite of these, an accuracy of 1 part per million in the determination of d-c ratio can be achieved if the comparator is operated at a sufficiently high ampere-turn level. The results presented were obtained with the device as described and with the use of commercially available auxiliary instrumentation.

The use of the current comparator in d-c measurement offers the advantage of circuit isolation, relative freedom from temperature effects and ambient fields, and adequate sensitivity without corresponding power dissipation. Further, the action of the ripple suppression windings permits its use in industrial areas where the filtering of the d-c supplies is perhaps less than ideal. On-site calibration of shunts and other d-c measuring systems is therefore possible.

APPENDIX • Construction details of the experimental d-c comparator

Magnetic cores—7.0-inch inside diameter (ID); 7.5-inch outside diameter (OD); 0.5-inch high; 4 mil Hymu 80; with aluminum case

Detection windings—single layer of approximately 1,450 turns no. 28 Formex wire on each core

Electrostatic shield—0.005-inch copper foil over each detection winding

Modulation windings—200 turns no. 18 Formex wire equally spaced in single layer on each core; the two cores are then taped together

Magnetic shield (inner)—formed from high-permeability magnetic material, two layers 0.030-inch thick inside and outside; single 0.030-inch layer on each side with 1/32-inch bakelite insulator on one side; shield surrounds both cores.

Deviation winding—100 turns no. 16 Formex wire equally spaced in single layer

Magnetic shield (outer)—formed from two toroidal cores of Hipersil; 3⅞-inch ID; 5⅝-inch OD; 4½ inch high (inside); 9¼-inch ID; 10⅞-inch OD; 4½ inch high (outside); four disks of 0.030-inch non-grain oriented magnetic material, 5⅝-inch ID, 10⅞-inch OD on each side; internal volumes not occupied by magnetic material are filled with corrugated cardboard and wooden spacers

Suppression winding—51 turns, 1/16-inch by ¼-inch glass-insulated flat copper strip

Main windings—two 120-turn windings and one 80-turn winding in separate layers; eight 10-turn windings; all of no. 12 Formex wire.

Window—2.75-inch diameter

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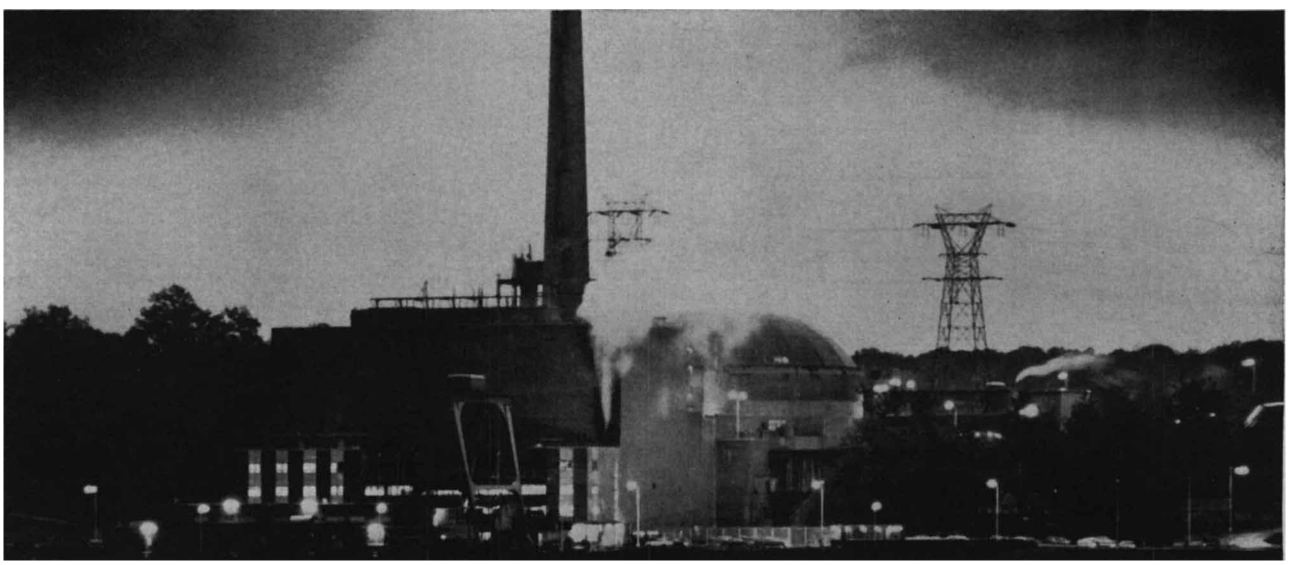
Indian Point reactor at full power



Full power operation has been achieved at Con Edison's Indian Point atomic electric generating station in Buchanan, N.Y., 35 miles from the center of New York City. At full power, Indian Point generates 275,000 kw for Con Edison's 6-million-kw system serving New York City area residents. The reactor's core is good for about two years, according to Babcock & Wilcox, its designers.