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ON-SITE CALIBRATION OF A 15,000-AMPERE D.C. BUSBAR METERING SYSTEM IN AN ALUMINUM PLANT

M. P. MACMARTIN AND W. J. M. MOORE

OTTAWA

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ON-SITE CALIBRATION
OF A 15,000-AMPERE D.C. BUSBAR METERING SYSTEM
IN AN ALUMINUM PLANT

- M.P. MacMartin and W.J.M. Moore -

INTRODUCTION

Systems which are used for measuring large direct currents in industry usually consist of a ratio device and a low-current measuring instrument. The low-current instrument may be easily removed for calibration in the laboratory. The ratio device, however, because of its sensitivity to environmental conditions and the high cost of the necessary power supplies, is more advantageously calibrated in situ. The problem, then, is to provide precision calibrating equipment that is unaffected by the same environmental conditions.

In January 1962 an inquiry was received from the Canadian British Aluminum Company (CBA) concerning the accurate measurement of large direct currents used in aluminum production. About this time the Electrical Engineering Section of the National Research Council (NRC) was developing a current comparator [1] for precise measurement of direct current ratios, and it appeared that this device might have some application in solving this problem. After discussions with the Company, an agreement was reached whereby the National Research Council would develop a direct-current comparator for the specific purpose of calibrating the ratio of one of their 15,000-ampere busbar current-measuring systems, and the Company would provide their facilities for the testing of this equipment. This report describes the measurements made at the Company's plant in Baie Comeau, Que., during October 1963.

The equipment developed by NRC for these measurements possesses several advantages over other ratio devices presently used for the measurement of large direct currents. Some discussion of how the method might be applied to continuous plant metering service is therefore appended.

MEASURING EQUIPMENT AND METHODS

1) The NRC Measuring System

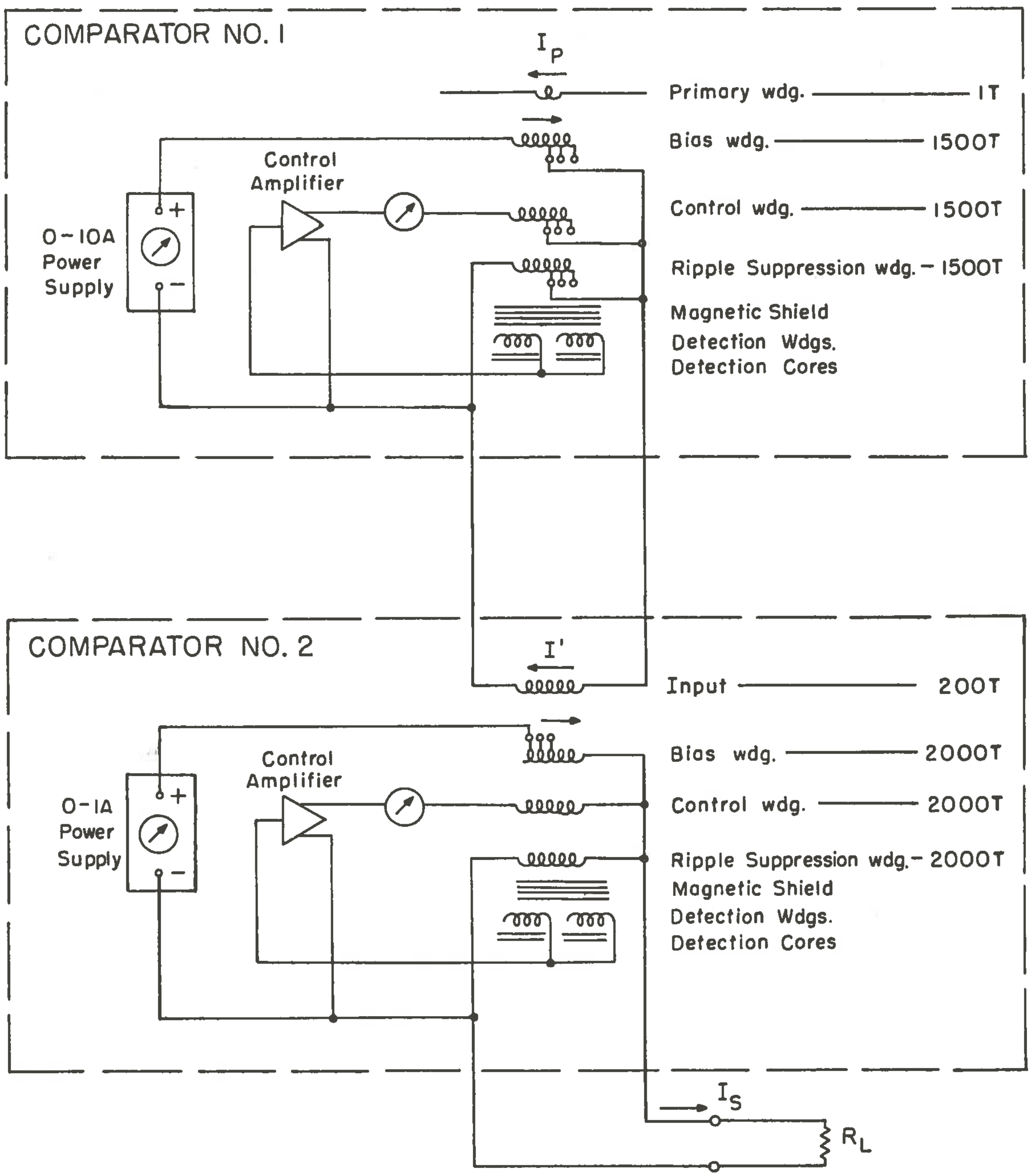
The NRC system is based on the current comparator, a ratio-measuring device which operates on the principle that when the ampere-turns imposed on a magnetic core by currents in two windings of opposite polarity are equal, the flux in that core will be zero. For direct-current applications, two cores are required to permit the use of second-harmonic magnetic-modulation techniques for flux detection. Electronic equipment is used to force a current of appropriate magnitude and polarity through one of the windings on the comparator to balance the ampere-turns imposed by the unknown current and so to maintain the flux in the core automatically at zero. This current, when multiplied by the turns ratio, yields an accurate and convenient measure of the unknown current. The effects of leakage fluxes and ambient magnetic fields are eliminated by surrounding the detection cores with a heavy magnetic shield.

The nominal ratio of the NRC system was designed to be the same as that of the CBA system; that is, 15,000/1. In addition, ratios of 17,500/1 and 20,000/1 were incorporated for increased versatility. In order to avoid a winding with a large number of turns, two comparators were used. The first comparator, no. 1, has ratios of 1500/1, 1750/1, and 2000/1, while the second, no. 2, has a ratio of 10/1 only. The primary busbar current is thus reduced in two stages, first to a level of about 10 amperes, and from there, by a ratio of 10/1, to a level of about one ampere.

The NRC system is shown schematically in Fig. 1, for a ratio of 15,000/1. The ampere-turns imposed by the primary busbar current I_p through one turn are opposed for the most part by a bias current supplied from a regulated d.c. power supply through 1500 turns. The flux in the detection cores caused by the residual ampere-turns is determined by the second-harmonic detector, and this is used to control the flow of additional current in a second winding of 1500 turns in such a way that this flux is reduced toward zero. Since the frequency response of this control is limited, an additional 1500-turn winding, the ripple suppression winding, is included, in which currents are induced by current transformer action (with the magnetic shield as its core) to oppose transient and ripple components in the primary busbar current.

These three currents are summed and passed through the primary winding of the second stage comparator, no. 2, which operates in the same way as comparator no. 1. The result is a current whose magnitude, to a high degree of accuracy, is 15,000 times smaller than the original busbar current.

Discrepancies in the NRC system arise from ambient fields and because a finite error is required to operate the control circuits. The range of the controlled balance current in comparator no. 1 is ±1 ampere, and the control amplification is such that, to attain this, an input equivalent to approximately 0.15 ampere-turns error is required. For the 1500/1 ratio, this means that an error component of some 100 microamperes may be present in the intermediate current I' (or 10 microamperes in the output current). A similar error may also arise in the control of comparator no. 2, so that the output current of the system may contain a total error component of up to 20 microamperes. It is to be noted, however, that this error is present only if both control circuits are delivering full output current of such polarity that the two errors are cumulative.



$$\frac{I_P}{I_S} = \frac{1500}{1} \times \frac{2000}{200} = 15{,}000$$

Fig. 1 NRC measuring system

The effectiveness of the magnetic shield may be judged by the fact that the error due to the field resulting from two 12,500 ampere-turn windings of opposite polarity, concentrated at two diametrically opposed sectors of the comparator, results in an error current of about 4 microamperes.

The NRC equipment is shown in Plate I.

2) CBA Measuring System

The CBA system for metering the d.c. busbar current is based on a magnetic current-ratio device known as the "transductor" or "d.c. current transformer". The circuit is shown in Fig. 2. The transductor has a nominal ratio of 3000/1, and is supplied from an a.c. power source through a tapped autotransformer. An additional 5/1 in ratio is obtained with an a.c. current transformer, yielding an over-all ratio of 15,000/1. Fine adjustment in ratio is achieved by changing the current transformer connections.

3) Comparison Method

Measurement of the error of the CBA system was made by installing both that system and the NRC system on the same busbar and comparing the two secondary currents. Since these two currents are nominally equal, a differential technique was used.

The comparison circuit is shown in Fig. 3. The two systems were connected in such a way that only the difference between the two currents flowed through the common resistor R_c. The value of this difference or error current was determined with respect to the nominal secondary current by comparing the voltage across the common resistor R_c with the voltage across a series resistor R_s. If the relationship between the two secondary currents is expressed as

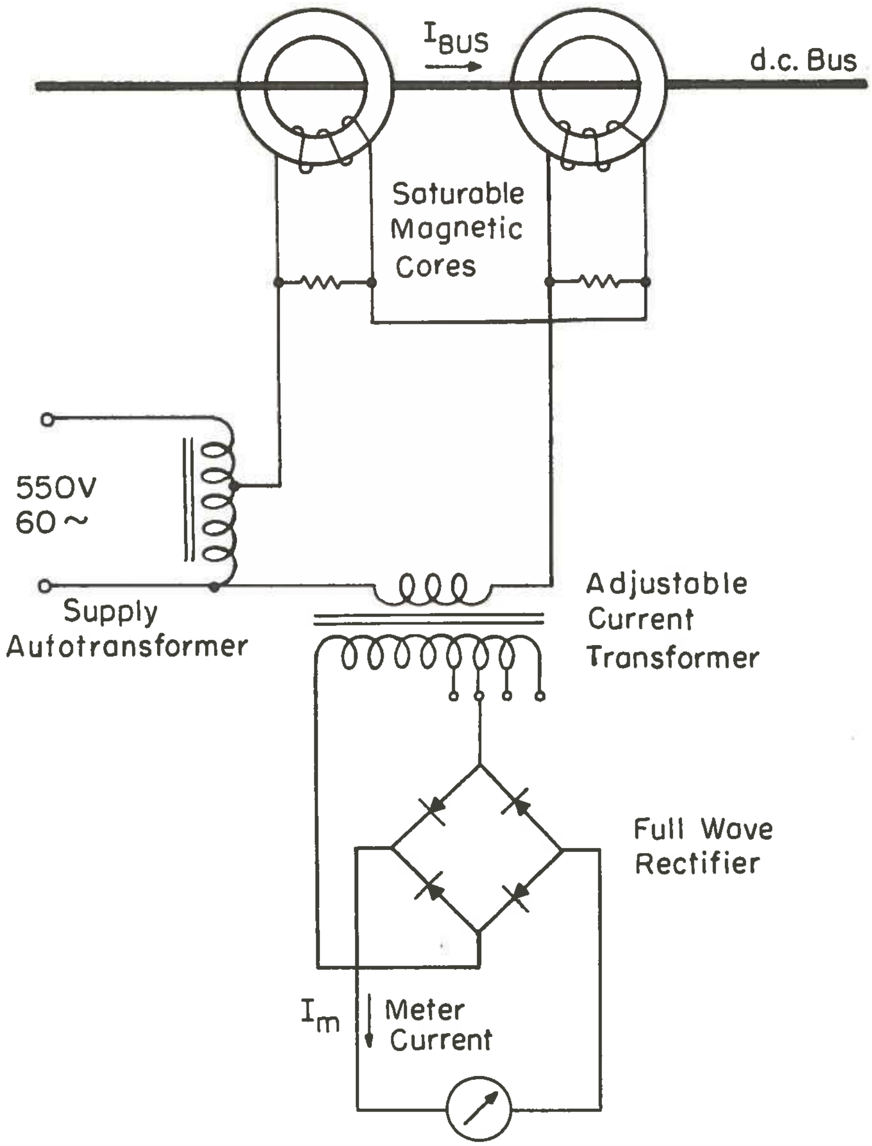
$$I_{CBA} = I_{NRC}(1 + \epsilon),$$

then, at detector null,

$$\epsilon = \frac{KR_s}{R_c},$$

where K is the setting of the resistive voltage divider connected across R_s.

The detector used with this circuit was a Hewlett-Packard Model 425A, D.C. Micro Volt-Ammeter. The output current was measured using a Model 2745 Honeywell Potentiometer across a 0.01 ohm shunt.



$$\frac{I_{BUS}}{I_{METER}} = 15{,}000$$

Fig. 2 CBA measuring system

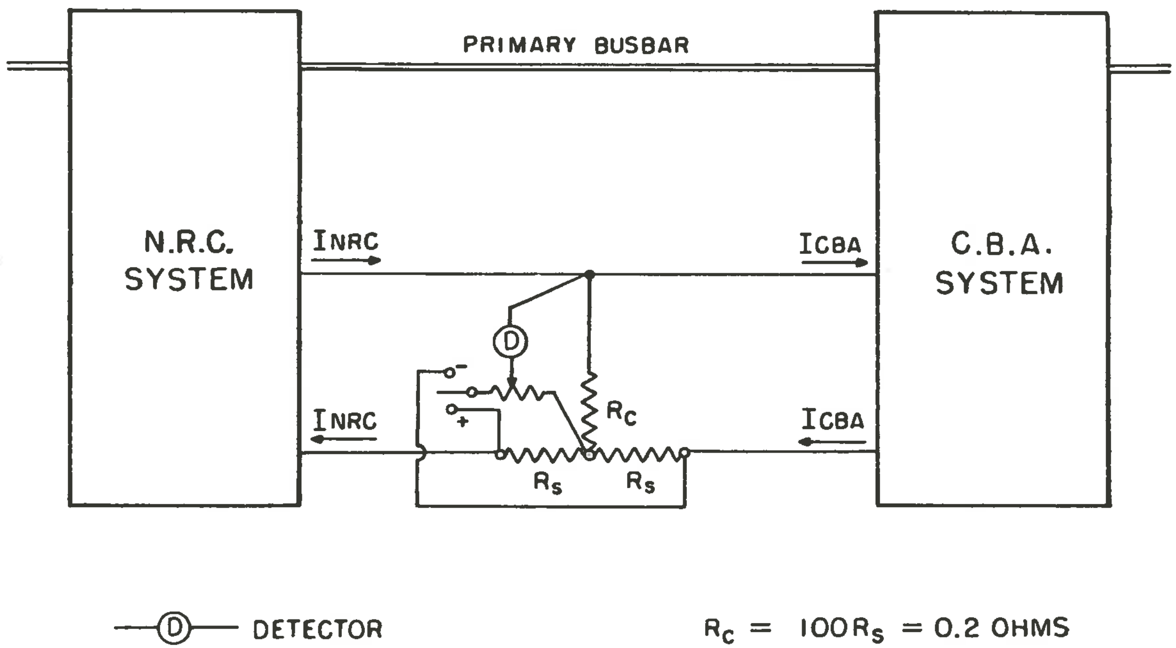


Fig. 3 Comparison method

MEASUREMENT AND TEST RESULTS

1) Ambient Field Measurements

The magnetic environment in an aluminum plant, owing to the large direct currents which are used, is considerably different from those experienced in the NRC laboratories. To obtain some idea of the magnitude of the magnetic field in the area where the tests were to take place, various magnetic field measurements were made.

In the Rectifier Control Room, where the control equipment and comparator no. 2 were located, the amplitude of the magnetic field was of the order of 2 oersteds. In the Busbar Room where comparator no. 1 and the CBA transductors were installed, the following field measurements were made:

a)	4 inches from busbar, horizontally toward return bus:	185 oersteds
b)	1 foot " " , " " " ":	85 "
c)	2 feet " " , " " " ":	50 "
d)	6 feet " " , " " " ":	30 "
e)	16 inches from busbar, directly below:	55 "

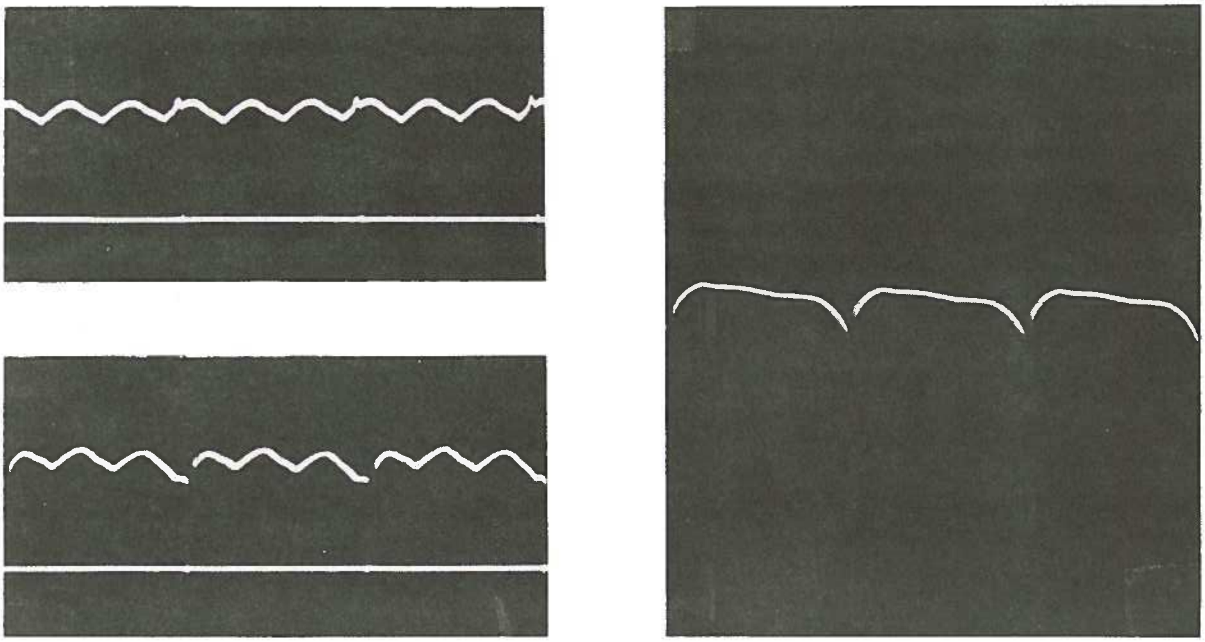
All measurements indicated a more or less circular field centered on the busbar. Measurement (d) was made about halfway between outgoing and return current circuits, but as the latter had several branches leading off from it, the field pattern there was more complex.

2) On-Site Tests of NRC System

Certain tests were made at the plant before comparator no. 1 was installed on the busbar to determine whether the NRC system was adversely affected by the magnetic environment. These consisted of moving the comparator about in areas of different magnetic field and noting whether any change occurred in the output of the detection circuit. No significant effect was noted between operation in the Rectifier Control Room and in the Busbar Room at distances varying from 2 to 6 feet from the primary busbar.

3) Waveform Measurements

Comparisons of the output current waveform of the two measurement systems were also made. These are shown in Fig. 4, along with the waveform of the difference current which flows in resistor R_c of Fig. 3.



(above) Current from NRC system
(below) Current from CBA system

Difference current
(vertical scale: × 2)

Fig. 4 Output current waveforms

4) Measurements on CBA Experimental Measuring System

In order to determine the operating characteristics of the CBA type of measuring system without interfering with the normal plant metering, an experimental system was assembled using spare components. This was installed on the Rectifier Unit No. 7 busbar, along with the existing CBA measuring system and the NRC measuring system. The arrangement of the two transductors and the comparator is shown in Plate II. The transductor of the experimental system is that shown in the foreground.

The components used in the experimental system were as follows:

Transductor	- No. 887110
Autotransformer	- No. 887117, Serial No. 204656-9, 5 KVA, 550/500, 480, 460, 440, 420 volts
Current Transformer	- No. 887111

The connection to the autotransformer is normally at the 480-volt tap. The current transformer connection was adjusted for minimum system ratio error by joining terminals L4 and L5, L1 and L6, and taking the output from terminals M and L2. It should be noted that the current transformer connections required for minimum error differed from one set of components to another, and that incorrect connections can yield errors up to 12%.

In measuring the variation of the error with busbar current, it was not possible to maintain constant voltage, nor in determining the effect of voltage on error was it possible to maintain constant current. The variations were sufficiently small, however, to permit adjustments to be made on the basis of the uncorrected characteristics.

a) Error vs. Excitation Voltage

The effect of supply voltage on the measuring system error was investigated by changing the tap connections of the autotransformer. This necessitated the removal of excitation to the transductors for each point measured. While a method of varying the voltage continuously without disconnection would perhaps have been more desirable, no practical means was available for doing this without introducing additional impedances in the circuit.

The results of two sets of measurements, taken at a busbar current of approximately 12.7 kilo-amperes (and adjusted to that value), are shown in Fig. 5. Lines depicting a relationship of 0.01% per volt are also shown for each set.

b) Error vs. Burden

The effect of burden on the error of the CBA measuring system was determined by adding resistance in the output circuit. The variation in error was determined over the range from zero to 2 ohms, and from 12 to 14 ohms. The autotransformer voltage was approximately 465 volts (480-volt tap) and the busbar current about 15.0 kilo-amperes. Unfortunately, the number of measurements was not sufficient to establish a definite characteristic. The adjusted results, such as they are, are shown in Fig. 6.

c) Error vs. Transductor Position

Some idea of the extent to which the CBA measuring system is dependent on the transductor being coaxial with the busbar was determined by displacing the axis of the transductor both vertically and horizontally. The following table gives the change in error arising from specific displacements from the normal position. These measurements, taken at a busbar current of approximately 13 kilo-amperes and an autotransformer voltage of 460 volts (480-volt tap), were adjusted for both current and voltage variation.

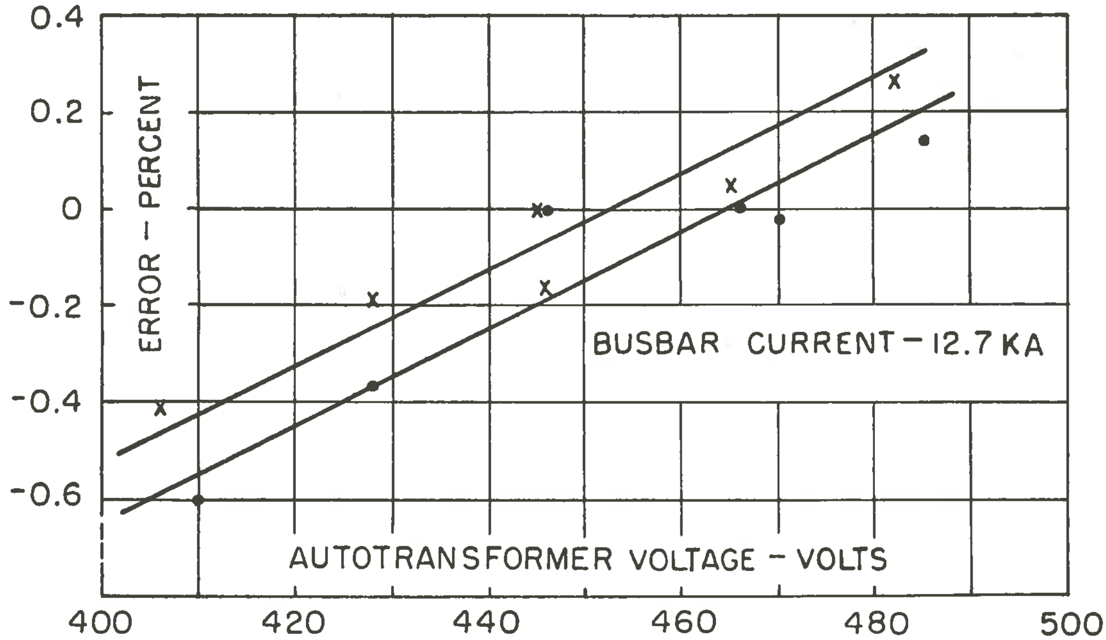


Fig. 5 Ratio error vs. excitation voltage — experimental measuring system

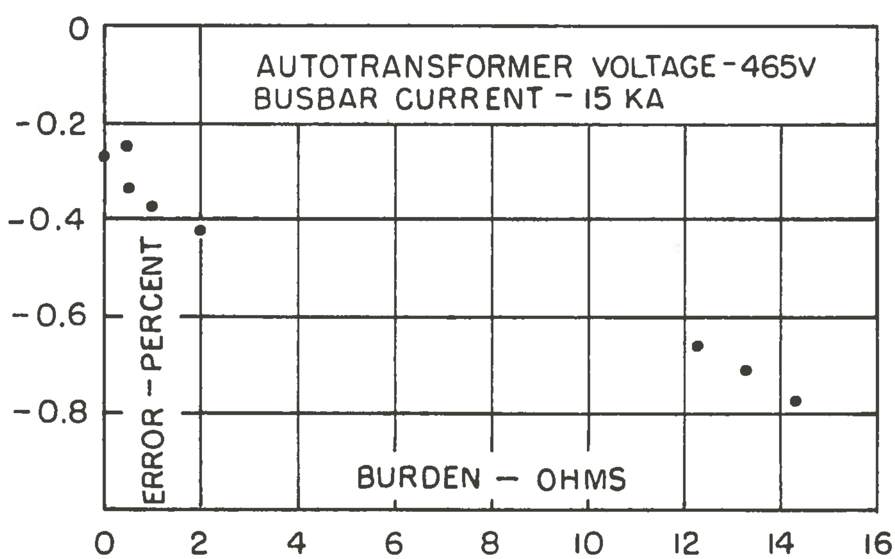


Fig. 6 Ratio error vs. burden — experimental system

Displacement (inches)	Change in Error (percent)
$\frac{5}{8}$ up	+ 1.1
$\frac{3}{8}$ up	+ 0.8
$\frac{1}{8}$ up	+ 0.5
$\frac{3}{8}$ down	- 0.5
$\frac{5}{8}$ down	- 1.8
$\frac{3}{4}$ horizontally, away from wall	- 0.1
$\frac{3}{4}$ horizontally, toward wall	- 0.3

No attempt was made to determine the effect of angular displacement.

d) Error vs. Busbar Current

The effect of busbar current amplitude on the CBA measuring system error is shown in Fig. 7. Four separate sets of measurements were made, three of which indicate possible variations due to the position of the transductor on the busbar. After both Tests 1 and 2, the blocks which positioned the transductor on the busbar were removed and then reinserted. The same positioning of the transductor was sought in each instance.

In Tests 1, 2, and 3, the excitation voltage was approximately 465 volts (480-volt tap), and each measurement was adjusted to 465 volts, according to the relation 0.01% per volt. Test 4 was made at an excitation voltage of approximately 445 volts (460-volt tap) and the results adjusted to 465 volts by the same relationship. The transductor position was unchanged between Test 3 and Test 4.

The burden in the output circuit during these tests was 2 ohms.

5) Measurements on CBA Rectifier Unit No. 7 Measuring System

Error vs. current measurements were also made on the Rectifier Unit No. 7 measuring system. The components of this system were as follows:

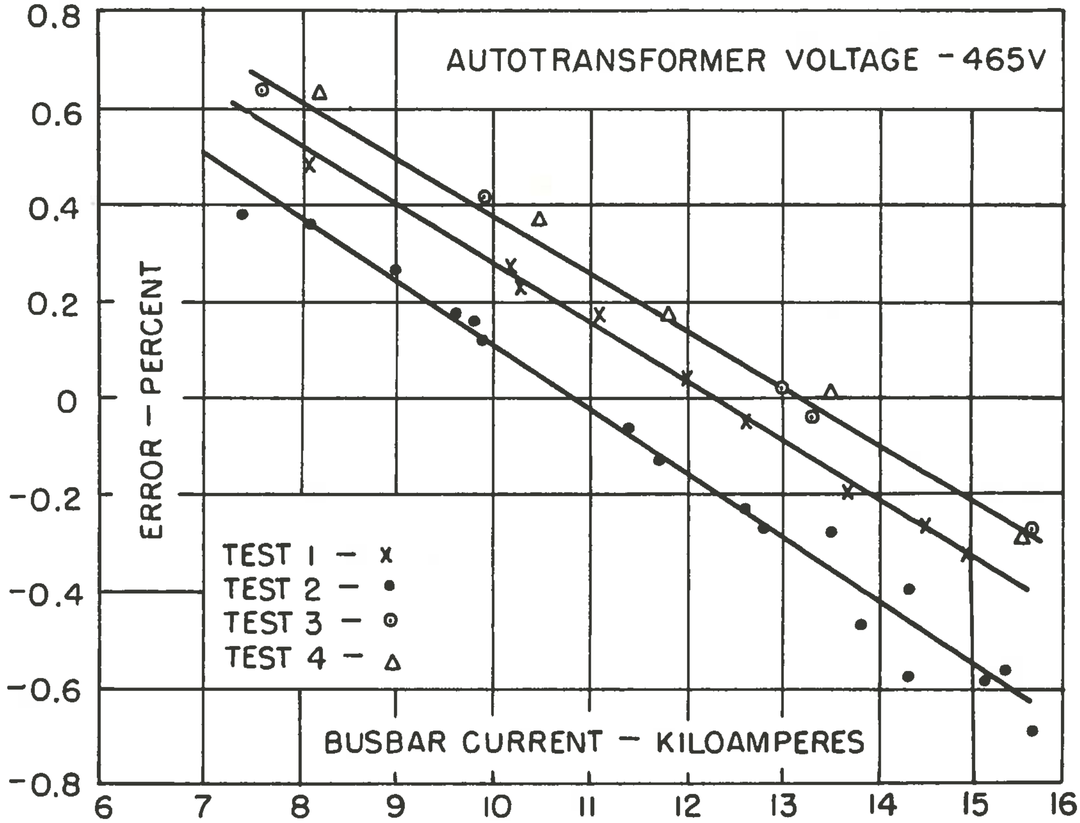


Fig. 7 Ratio error vs. busbar current — experimental measuring system

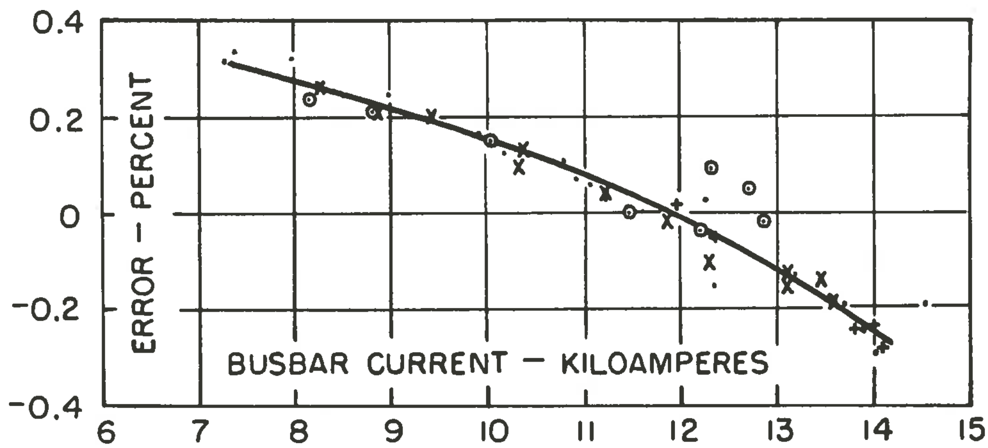


Fig. 8 Ratio error vs. busbar current — rectifier unit no. 7 measuring system

Transductor	-	No. 918791
Autotransformer	-	Serial No. 210840-7, 5KVA, 550/500, 480, 460, 440, 420 volts
Current Transformer	-	No. 899658 A, Type FX

The connection to the autotransformer was at the 480-volt tap. The current transformer had connections between terminals L1 and L7, and L4 and L5, with the output being taken from M and L6.

The results of four sets of measurements, made at intervals of about one-half hour, are shown in Fig. 8. No measurements were made of the corresponding autotransformer voltage, and consequently no adjustments for variation of this parameter were made.

Throughout these measurements, the system was connected in parallel with the metering systems of the seven other rectifier units.

MEASUREMENT ACCURACY

In making the comparison measurements presented in this report, it was relatively easy to distinguish a difference of 0.1%, but almost impossible to resolve 0.01%. This is not unreasonable, considering that the sensitivity of the CBA system to excitation voltage is 0.01% per volt and to busbar current 0.12% per kilo-ampere. Normal line voltage excursions and small changes in plant load can thus introduce random variations in the percentage error which are several times in excess of 0.01%. Under such conditions, a realistic estimate of the accuracy of individual ratio measurements would be 0.1%.

Measurements of magnetic field strength are intended to give a rough estimate of magnitude only. No estimate of accuracy is, therefore, given.

CONCLUSIONS

This report presents the results of on-site ratio measurements made on a 15,000-ampere direct-current measuring system in an aluminum plant, using a direct-current comparator as a reference. As such, it may be considered from three different aspects — as a test of the NRC direct-current comparator-based measuring system in an industrial environment; as a study of the CBA transductor-based measuring system; or as an experiment in on-site calibrations in industry.

The main environmental factor which might have affected the performance of the NRC system in these measurements was the presence of a relatively large ambient magnetic field. The magnetic field in the area where comparator no. 1 was located, however, was mainly that due to the current being measured. The influence of this field, even when applied under most unfavourable conditions (that is, with the comparator located next to the busbar, but not installed on it), was found to be insignificant.

Oscillograms of the output current waveforms of the two measuring systems indicate that the frequency response of the NRC system is at least as good as, and probably better than, that of the CBA system. Both reproduce the ripple components of the rectifier, but the response of the CBA system also contains components arising from the commutation transient in its own rectifier and the inability of its current transformer to sustain a square wave of current.

Direct measurements of the rate of change of error with respect to excitation voltage in the CBA experimental system yielded a relationship of 0.01% per volt. The inconsistency of the measured values does not warrant greater precision in defining this characteristic, nor is greater precision necessary to correct for normal variations in line voltage. Confirmation of this relationship is given by Test 4 of the error vs. busbar current measurements.

The results of measurements to determine the effect of burden were, in general, unsatisfactory. Although some indication of this effect is provided, more revealing measurements could have been made. In the CBA system variations in error due to burden in the output circuit arise from its effect not only on the transductor but also on the current transformer. The effect of burden on the transductor may be considered to be more or less equivalent to a change in excitation voltage, and this could have been studied by inserting a resistance in series with the transductor. Unfortunately this was not done.

Measurements of the effect of transductor position were also limited, but they did indicate that the alignment was fairly critical. Even when attempts were made to repeat the exact positioning of the transductor, variations up to 0.3% in error were shown to occur.

Measurements of error vs. busbar current in the experimental CBA system indicated a more or less linear relationship. This is in contrast to similar measurements on the CBA Rectifier Unit No. 7 system where a curved characteristic was obtained. A possible explanation for this is that the Unit No. 7 system was connected to the plant metering circuit which, under the conditions of measurement, represented an almost constant voltage load of 2.8 volts. Thus, over a busbar current range of 15 kilo-amperes to 7.5 kilo-amperes, the burden on that system was effectively doubled, from 2.8 ohms to 5.6 ohms. This effect would not be present, however, if the total plant load was reduced in the same proportion.

On the whole, the measurements indicate that, over a current range from 7 to

15 kilo-amperes, over-all accuracy of about 0.5% can probably be achieved with the CBA type system without correction. Careful installation of the transductor and calibrations in situ would, however, be necessary if such accuracy is to be realized. With good regulation of the excitation voltage, some additional benefit might be gained by correcting for current amplitude. The correction required would be to some extent a function of the current in the other rectifier units as well.

As an experiment in on-site calibrations in industry, this report provides an illustration of the type of measurements that can be performed on large direct-current measuring systems. Conditions, of course, are not as stable as in the NRC laboratory, but the accuracy attainable appears to be compatible with the over-all performance expected in industrial measuring systems.

REFERENCE

1. N.L. Kusters, W.J.M. Moore, and P.N. Miljanic. A Current Comparator for the Precision Measurement of D-C Ratios. Elec. Eng. 82: 204; 1963

APPENDIX

APPLICATION OF THE NRC MEASURING SYSTEM TO CONTINUOUS METERING

The feasibility of using the NRC measuring system, not just for calibration of other systems, but for continuous metering, has been considered. Some of the important factors are:

1) The accuracy attainable in the conversion of the busbar current to a current which can be easily measured directly, is much higher than is possible with any other available equipment. The accuracy of the actual current measurement depends on the quality of the reference. This reference may be either a calibrated meter, or a precise reference voltage, or a combination of both.

2) The accuracy of the comparator is not affected by external conditions, such as supply voltage, alignment on the busbar, ambient temperature, burden or magnetic fields.

3) Each comparator requires circuits and power supplies which probably make it more expensive than the transductor-based system.

4) Because of the greater number of components, it is possible that reliability may be less than that of a metering system which contains only transformers and rectifiers. However, defective operation is easily indicated and com-

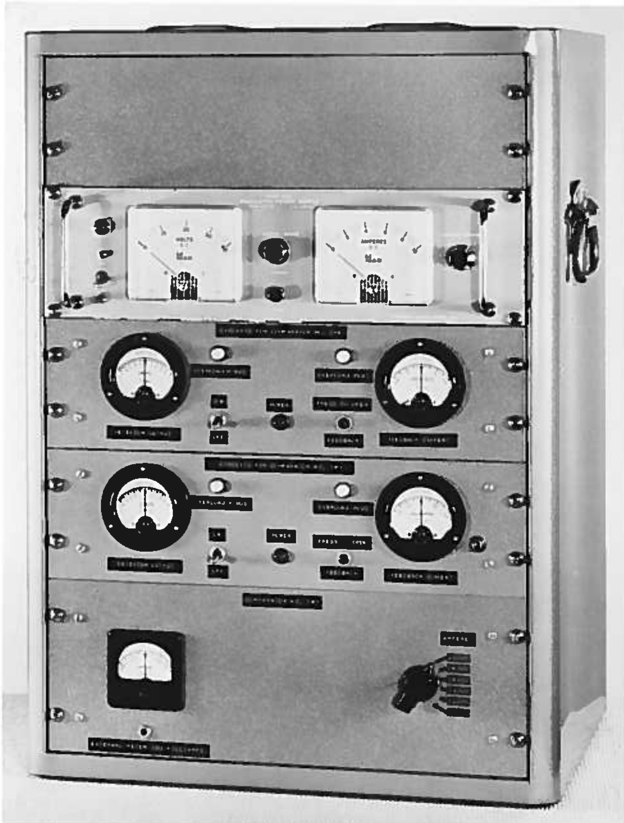
ponents can be made so that they are readily replaced.

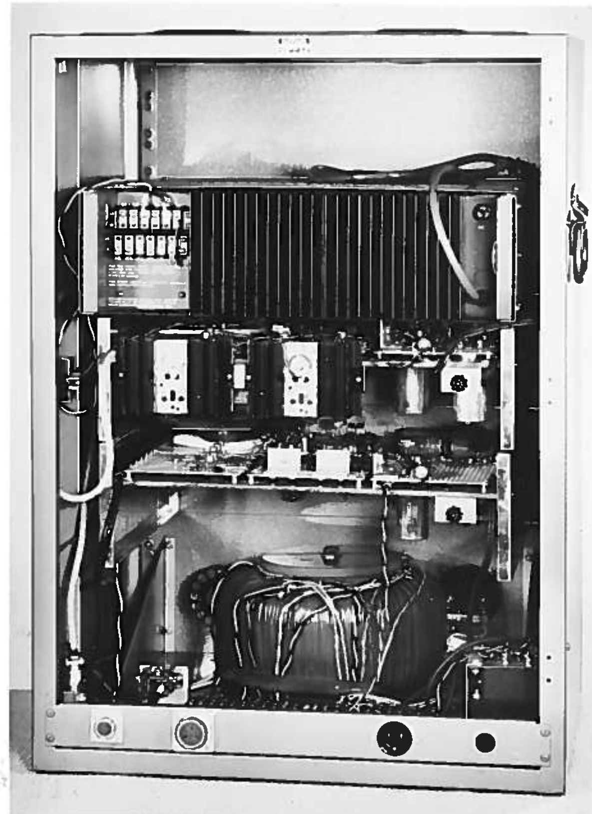
5) Two currents are combined to balance the busbar current: a steady current from the power supply through the bias winding, and a variable current from the amplifier through the control winding. The result is that the busbar current cannot be varied by more than that which can be compensated for by the amplifier. For example, if the bias is set at 13 KA-turns and the control amplifier can supply ±3 KA-turns, the range of the instrument, without adjustment, is from 10 KA to 16 KA. The centre of the range can easily be changed by adjustment of the bias current.

6) It is possible that the detection cores might become saturated if the busbar current exceeds the control range. However, this condition is detected automatically and is easily corrected.

7) If it is desirable to add the currents from a number of busbars, this can be done in a similar comparator, thus maintaining electrical isolation between all circuits.

From a consideration of these factors it is concluded that the NRC ratio-measuring equipment may be used for continuous metering of large direct currents in installations where its very high accuracy would be deemed sufficiently important to offset the fact that it is more complicated than the less accurate transductor-based system.





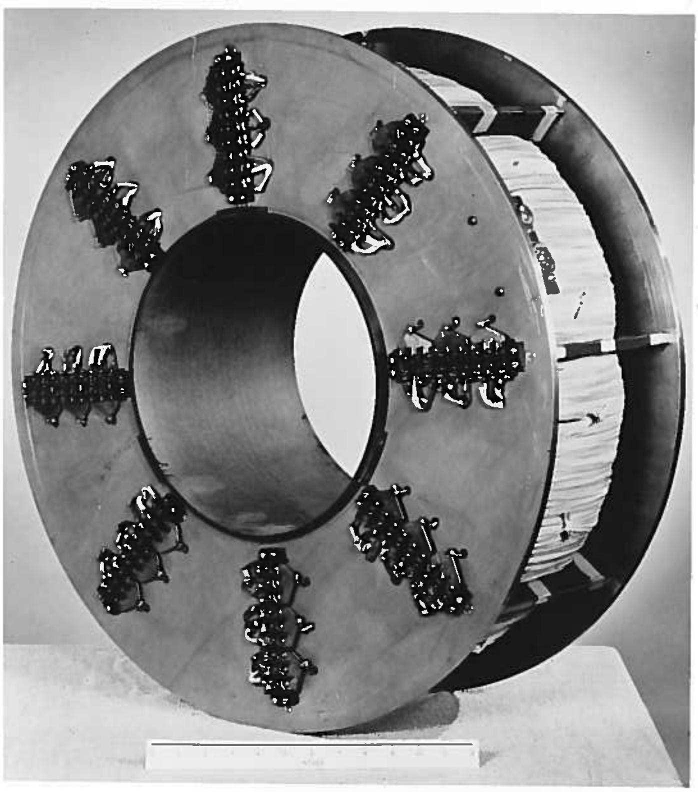


Plate I — NRC equipment

(top, left) Control Cabinet, front view

(top, right) Control Cabinet, rear view showing comparator no. 2

(at left) Comparator no. 1

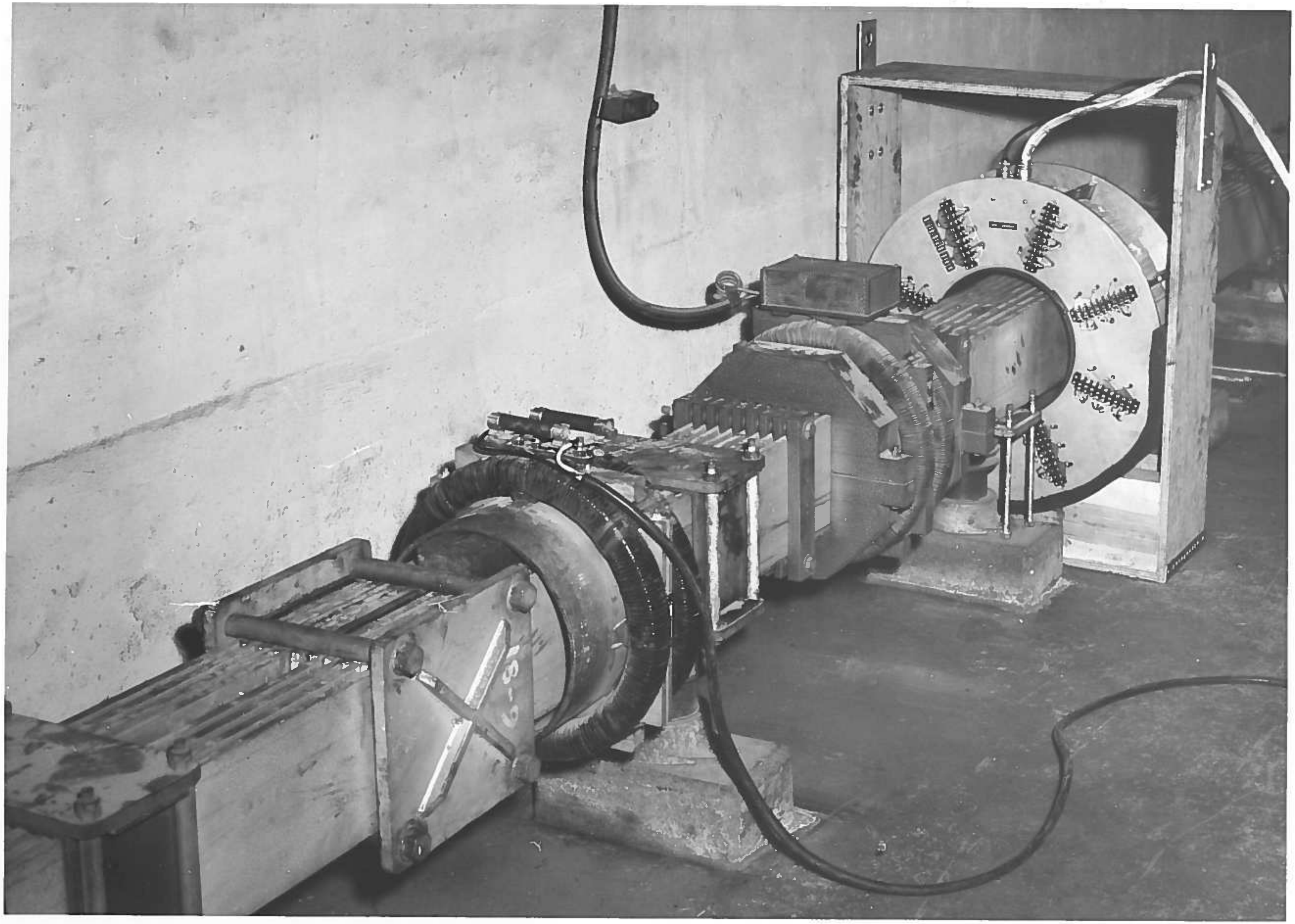


Plate II — Arrangement of comparator and transductors on busbar