A METHOD OF MEASURING NEGATIVE-PHASE-SEQUENCE CURRENTS IN A THREE-PHASE SYSTEM

by

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I INTRODUCTION

The solutions of unbalanced three-phase circuits can be greatly simplified through the use of the method of symmetrical components. In a three-phase system the presence of negative-phase-sequence current is an indication of unbalance in the circuit. Since most three-phase machines have balanced circuits, the presence of a negative-phase-sequence current is usually an indication of an abnormal condition in the circuit. The magnitude of the negative-phase-sequence current is an indication of the amount of unbalance.

At the present time various protective devices are in use which operate due to the presence of negative-phase-sequence currents, but very little is being done toward direct, accurate measurements of negative-sequence currents.

II THE REVIEW OF LITERATURE

The method of symmetrical components as applied to the solution of unbalanced polyphase networks was first introduced by C. L. Fortescue (3) in 1918. At this time no mention was made of methods for actually measuring the components in a circuit. In 1923 Fortescue (4) presented a paper to The American Institute of Electrical Engineers entitled, "Measurement of Power in Polyphase Circuits". Mr. Fortescue stated that the existing power rates were not equitable under unbalanced conditions and suggested that a new method of measuring power, based on the method of symmetrical components be used. Mr. Fortescue's paper also suggested networks which would be capable of measuring positive- and negative- sequence voltages and currents.

Also in 1923 an article was published by Mr. R. D. Evans (2) outlining methods of metering power in unbalanced polyphase systems. Mr. Evans stated some of the advantages of sequence metering and gave circuit diagrams of networks capable of metering positive- and negative-sequence components of voltage and current. After the positive- and negative-sequence components of voltage and current are separated, it was shown that it was possible to combine them to measure power, reactive power, and power factor.

Other writers such as Hayward (5), Shuck (6), and Borden and Behar (1) have presented discussions of the subject, but very little was added to the work of Fortescue and Evans.

III THE INVESTIGATION

Object of the Investigation

This study was set up with the following objectives in mind: (1) To construct a summing current transformer and connecting network which would give an output current proportional to, and in phase with, the negative-sequence current in an unbalanced three-phase network; and (2) To test this method of measuring negative-sequence currents in the laboratory.

Method of Procedure

It was decided to use a method similar to that given by Wagner and Evans (7). The method given by Wagner and Evans utilizes a three-winding ammeter as a summing device. A four-winding current transformer was used instead of the ammeter because the current transformer could perform essentially the same operation and at the same time was simpler to construct. The circuit used for measuring negative-sequence current is shown in figure 1.

The negative-sequence current can be calculated using the three line currents of a three-phase circuit when both magnitudes and time-phase relationships are known. When the magnitudes have been obtained by direct measurement, the phase relationships can be easily determined for a three-wire circuit since the vector sum of the three line currents must be zero and a simple graphical construction will give the phase angles between the currents (8). After the above information is determined the negative-phase-sequence current can be found using the equation,

$$I_2 = 1/3(I_a + a^2I_b + aI_c),$$

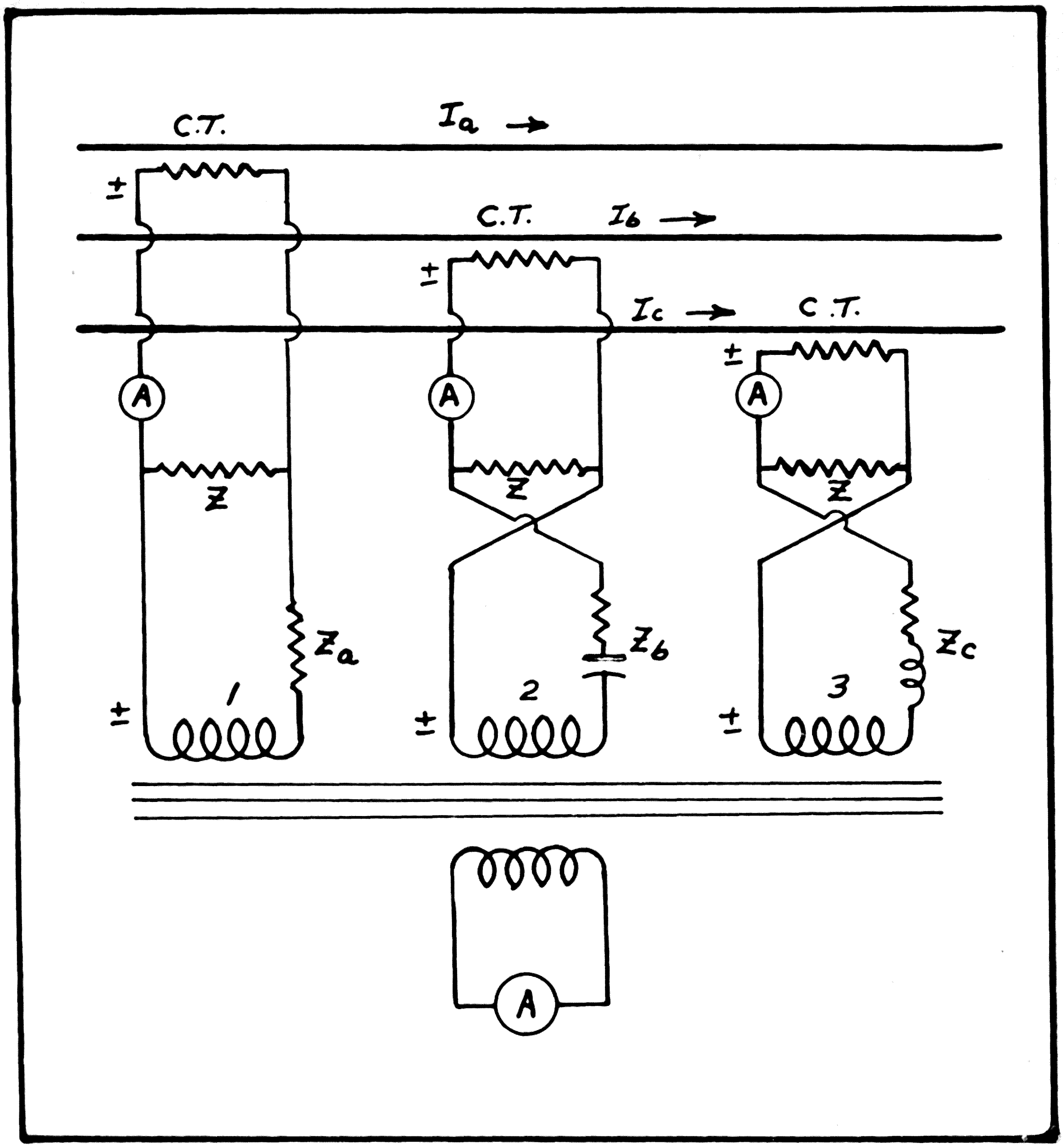

Figure 1
CIRCUIT FOR MEASURING NEGATIVE PHASE SEQUENCE CURRENTS

where (a) is the complex operator, $1\underline{/120^\circ}$. Referring to figure 1, if all windings of the current transformer have the same number of turns, the ammeter will read the correct value of negative-sequence current when the following conditions are satisfied:

1. The current in winding one is one-third of I_a and is in phase with I_a.
2. The current in winding two is one-third of I_b and is shifted in phase by an angle of 240 degrees with respect to I_b.
3. The current in winding three is one-third of I_c and is shifted in phase by an angle of 120 degrees with respect to I_c.

If the impedance of the summing current transformer windings and ammeter are neglected, a relatively simple method can be used to calculate the impedances Z, Z_a, Z_b, and Z_c. The size of the impedance of the loads to be placed on the main current transformers depends on the volt-ampere capacity of the current transformers used. In this investigation the impedances were chosen so that the volt-ampere burden on current transformer A was 15 volt-amperes at a secondary current of 5 amperes, and the remaining impedances were calculated such that the ammeter would read the negative-sequence current directly. The calculations are shown below.

In order to have a burden of 15 volt-amperes on transformer A, the following equation had to be satisfied.

$$(1)\quad \frac{Z_a\ Z}{Z_a + Z} = 0.6\underline{/0^\circ} \quad \text{ohms}$$

If the current through winding one is to be one-third of I_a, then

$$(2) \qquad \frac{Z}{Z_a + Z} = 0.333 \angle 0^\circ \quad \text{ohms;}$$

therefore from equation (1)

$$0.333 \angle 0^\circ \, Z_a = 0.6 \angle 0^\circ$$

and $Z_a = 1.8 \angle 0^\circ$ ohms.

Solving for Z:

$$\frac{Z}{Z_a + Z} = 0.333 \angle 0^\circ \; .$$

Using the value calculated for Z_a the above equation can be solved for Z, which is found to be $0.9 \angle 0^\circ$ ohms.

The current through winding two is to be one-third of I_b and is to be shifted in phase by 240 degrees with respect to I_b. The phase shift of 240 degrees can be obtained by getting a current that leads the line current by an angle of 60 degrees and then reversing the connections to the current transformer winding. This gives the same effect as a 240-degree phase shift. The calculations are as follow:

$$\frac{Z}{Z_b + Z} = 0.333 \angle 60^\circ$$

Substituting the value of Z previously found yields

$$\frac{.9 \angle 0^\circ}{Z_b + .9 \angle 0^\circ} = 0.333 \angle 60^\circ \quad \text{ohms,}$$

from which $Z_b = 2.38 \angle -79.1^\circ$ or $0.45 - j2.34$ ohms.

The current through winding three must be one-third of I_c and must have a 120-degree phase shift. This may be obtained in a manner similar to the previous case except that a minus 60° phase shift must be used. In this manner Z_c was found to be $2.38 \underline{/79.1^\circ}$ or $0.45 + j2.34$ ohms.

Equipment

The summing current transformer was constructed using the core of a Westinghouse Type PC 135 current transformer rated at two and one-half volt-amperes. Four windings were placed on the core, each winding consisting of two sections connected in parallel. The sections consisted of 50 turns of number 17 B & S gauge enameled copper wire.

In the phase-shift network the resistances were constructed from number 22 advance metal wire, a copper-nickel-chromium alloy. This wire was chosen because of its low temperature coefficient of resistance.

The capacitance for the phase-shift network was obtained by connecting a number of capacitors in parallel and adjusting the combination of capacitances for the proper impedance. As was shown previously, the calculated capacitive reactance required was 2.34 ohms. At a frequency of 60 cycles per second the capacitance required would be 1134 microfarads. This is a rather large capacitance, but it should be remembered that if the system were designed for a primary current transformer having a higher volt-ampere rating, the capacitance required could be reduced. Another method of reducing the required capacitance would be to design the circuit so that the current through the summing transformer could be less than one-third of the line current.

An attempt was made to wind an air core inductance coil to be used in the inductive part of the circuit, but difficulty was experienced in keeping the resistance low enough to satisfy the circuit requirements and still have enough inductance.

The possibility of using an induction voltage regulator connected as a variable inductance was investigated, and it was found that the correct value of resistance and reactance could be obtained in this manner. The next step was to determine if the presence of iron in the inductance would cause any objectionable distortion in the current wave form. It was found through use of a cathode-ray oscillograph that the current wave form did not deviate appreciably from a sine wave, and, it was therefore concluded that under the range of currents used, the distortion present in the current wave was not large enough to appreciably affect the accuracy of the network.

Calibration

It was found that the impedance of the summing transformer windings and the reflected impedance of the ammeter could not be neglected, and, therefore, that the impedances Z_a, Z_b, and Z_c in the circuit of figure 1 were not exactly those calculated. It then became necessary to calibrate the network with the current transformer and I_2 ammeter connected. The calibration was carried out by making the assumption that the effect of mutual coupling between the three circuits connected to the summing current transformer was negligible and then making necessary adjustments to obtain the impedances Z_a, Z_b, and Z_c which now represent, respectively, the total impedance of each branch of the network. The shunt impedance, Z, which was placed in each line was left at 0.9 ohms as was calculated. Impedance measurements were made using the voltmeter-ammeter-wattmeter method. This method, although not extremely accurate because of the low values of current, voltage, and power that had to be read, was chosen because it was felt that the impedance should be measured under conditions as near as possible to the operating conditions. The network was then connected as shown in figure 2 in order to check the calibration.

Referring to figure 2, with a current I flowing in the circuit and with either of the switches closed, the ammeter should read I/3 amperes. With S_1 and S_2 closed and S_3 open, the current in the ammeter should be the vector sum of $I/3 \underline{/ 0^\circ}$ and $I/3 \underline{/240^\circ}$ also I/3 in magnitude. Similarily with any two of the three switches closed the ammeter should read I/3 amperes. With all three switches closed the current in the ammeter should be the vector sum of $I/3 \underline{/ 0^\circ}$, $I/3 \underline{/240^\circ}$, and $I/3 \underline{/120^\circ}$, which is equal to zero. When each of these checks was made the impedances were adjusted to eliminate as far as possible any error noticed.

Results

With the network thus calibrated it was then connected so as to measure the negative-sequence current in an unbalanced three-wire resistive load. Readings were taken of I_a, I_b, I_c, and I_2, and the value of I_2 calculated using I_a, I_b, and I_c was compared with the value of I_2 read on the meter. The results are shown in tables 1 and 2, and curves of I_2 (measured) versus I_2 (calculated) are plotted in figures 3 and 4. Figures 5 and 6 are plots of the difference between

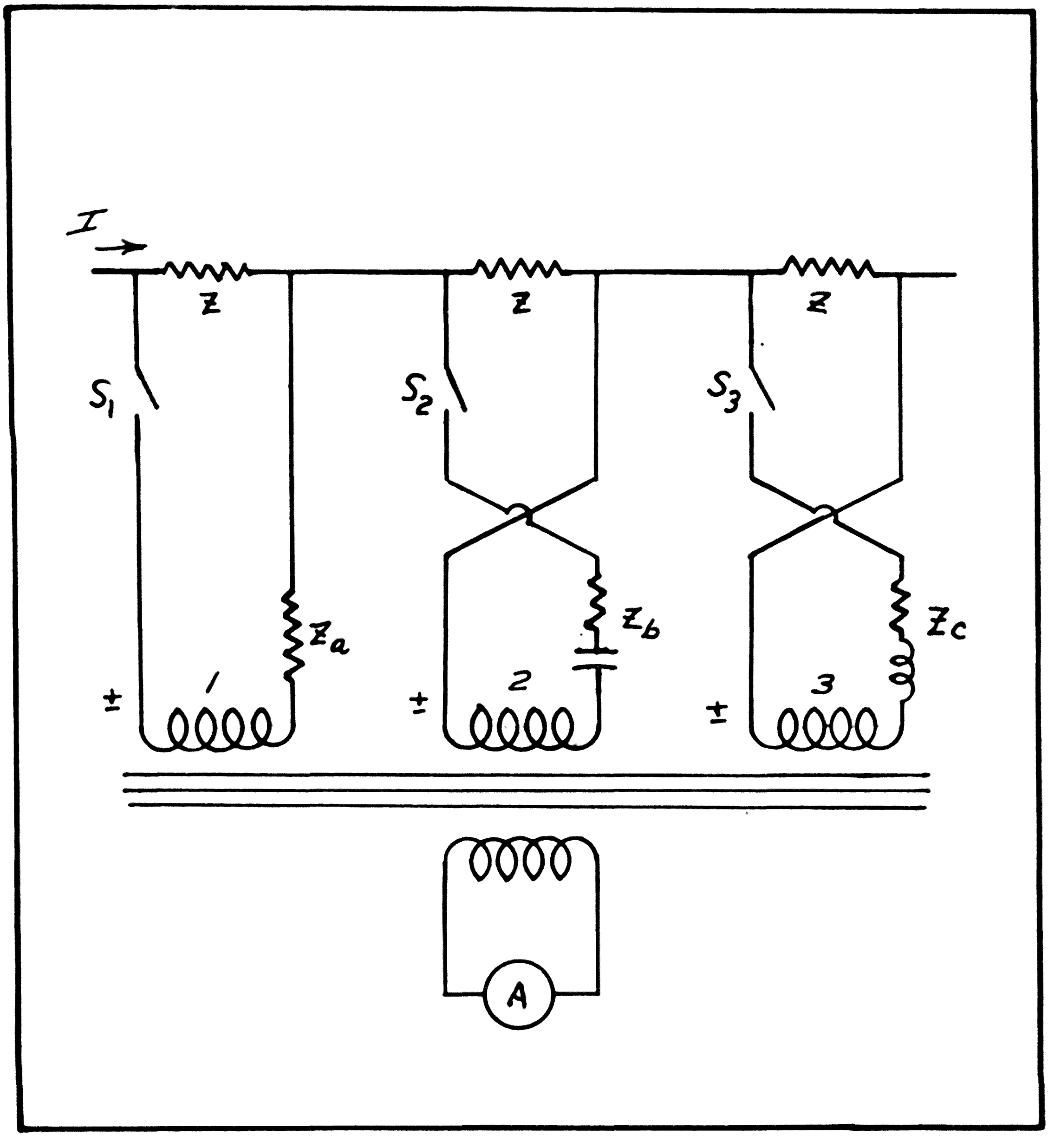

Figure 2
CALIBRATION CIRCUIT

the calculated and measured values of I_2 expressed as percentages of the measured values.

The circuit was next used to measure the negative-sequence current drawn by a three-phase induction motor. In this case unbalance was caused by placing a variable resistance in series with one of the line conductors connected to the motor. The degree of unbalance was varied from zero unbalance to the extreme condition where one conductor was open. Readings were taken at various degrees of load on the motor from zero to approximately full load. The results of this test are shown in tables 3 and 4. Curves of I_2 (measured) versus I_2 (calculated) are plotted in figures 7 and 8. Figures 9 and 10 are plots of the difference between the calculated and measured values of I_2 expressed as percentages of the measured values.

Table 1

Measurement of Negative-Sequence Currents for Unbalanced Three-Phase-Resistive Loads Using a Weston Model 433 Zero-to-Five-Ampere Ammeter for Measuring I_2.

I_A	I_B	I_C	I_2	I_2(calculated)	Difference	Per Cent Difference
4.54	1.40	4.78	1.97	1.97	0	0
1.30	3.32	3.31	1.20	1.22	-0.02	-1.64
4.02	7.18	8.48	2.64	2.56	+0.08	3.03
2.28	8.92	9.38	4.20	4.02	+0.18	4.30
2.32	9.34	9.92	4.50	4.42	+0.08	1.80
6.36	16.48	17.48	6.68	6.56	+0.12	1.80
6.40	19.52	19.76	8.16	7.96	+0.20	2.50
0	19.16	19.16	11.20	11.08	+0.14	1.25
31.00	31.00	12.50	11.90	11.30	+0.60	5.04
30.40	30.40	0	17.40	17.50	-0.10	-0.057

Table 2

Measurement of Negative-Sequence Currents for Unbalanced Three-Phase-Resistive Loads Using a Weston Model 433 Zero-to-One-Ampere Ammeter for Measuring I_2.

I_A	I_B	I_C	I_2	I_2(calculated)	Difference	Per Cent Difference
3.70	3.74	3.65	Deflection	---	---	---
4.06	4.13	4.95	0.452	0.570	-0.118	-26.1
3.81	3.96	4.44	0.265	0.379	-0.114	-43.0
2.03	3.76	3.96	0.850	1.150	-0.300	-35.3
2.08	3.95	4.27	0.960	1.410	-0.450	-47.0
1.96	2.93	3.32	0.545	0.840	-0.295	-54.0

Corrected Values of I_2 Using Correction Factor of 1.43.

I_2(corrected) (I_2 x 1.45)	I_2(calculated)	Difference	Per Cent Difference
0.648	0.570	0.078	12.0
0.379	0.379	0	0
1.220	1.150	0.070	5.7
1.370	1.410	-0.040	- 2.8
0.780	0.840	-0.060	- 7.7

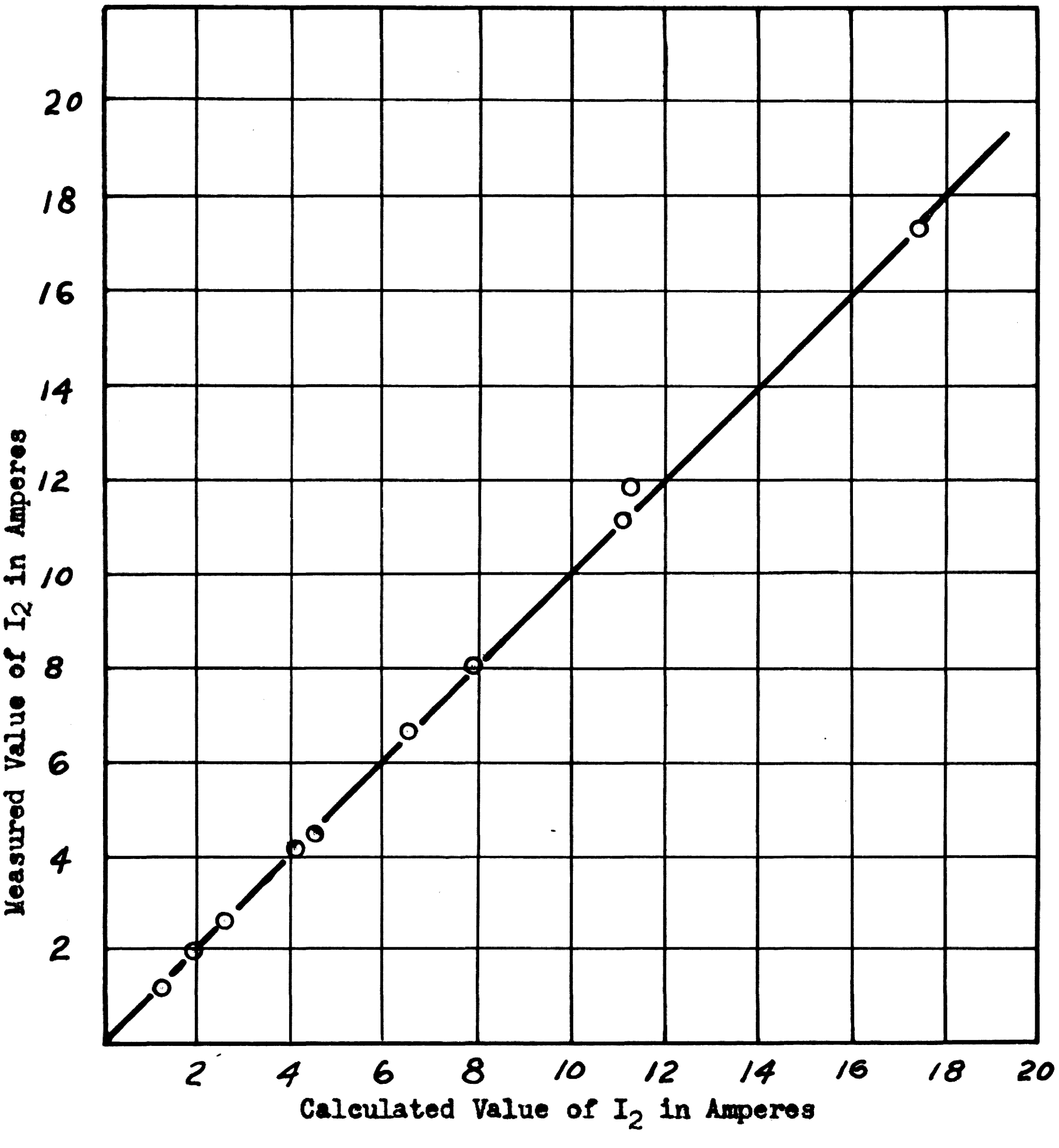

Figure 3
MEASURED VALUES VERSUS CALCULATED VALUES FOR A THREE-PHASE RESISTIVE LOAD

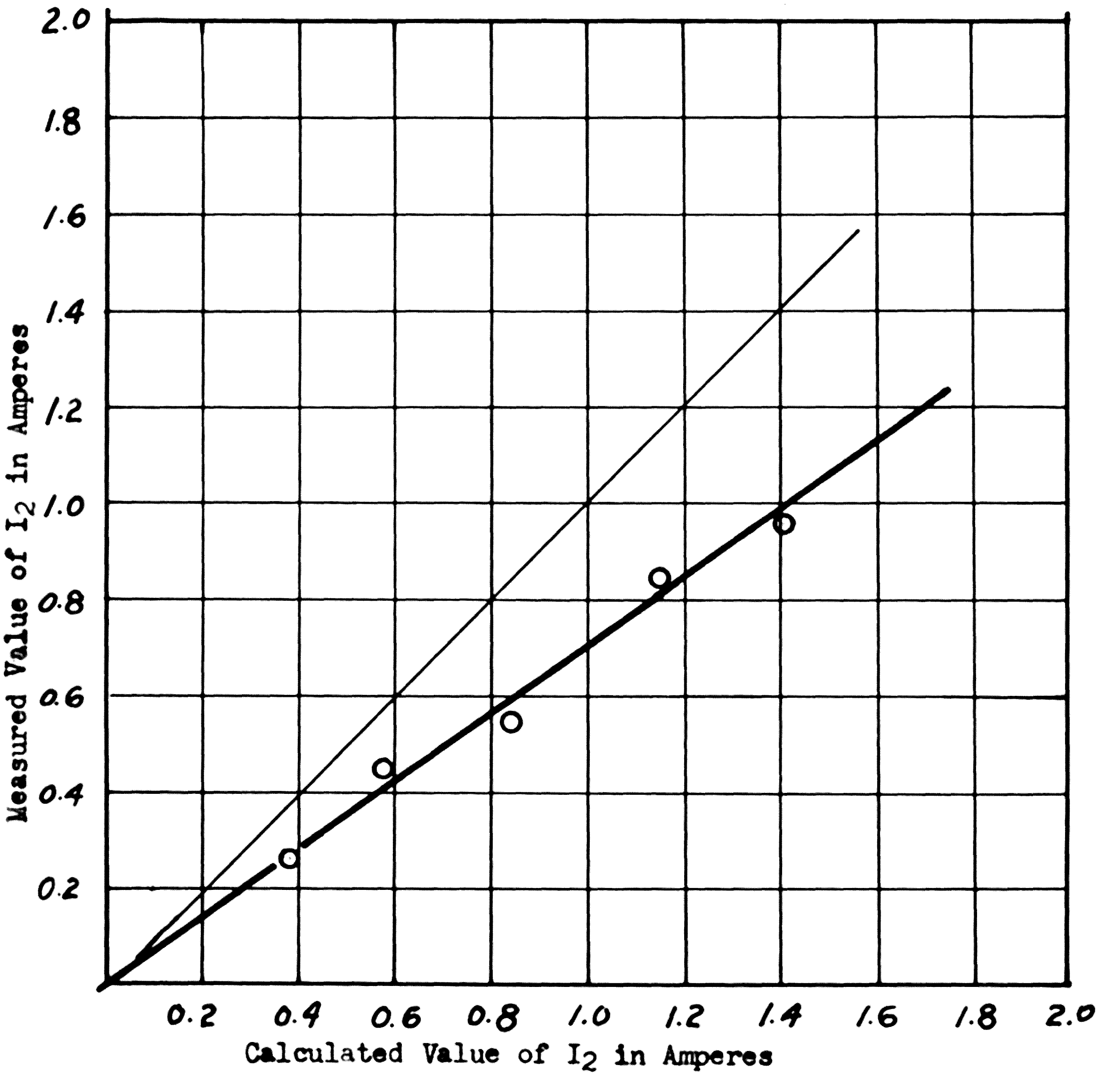

Figure 4
MEASURED VALUES VERSUS CALCULATED VALUES FOR A THREE-PHASE RESISTIVE LOAD

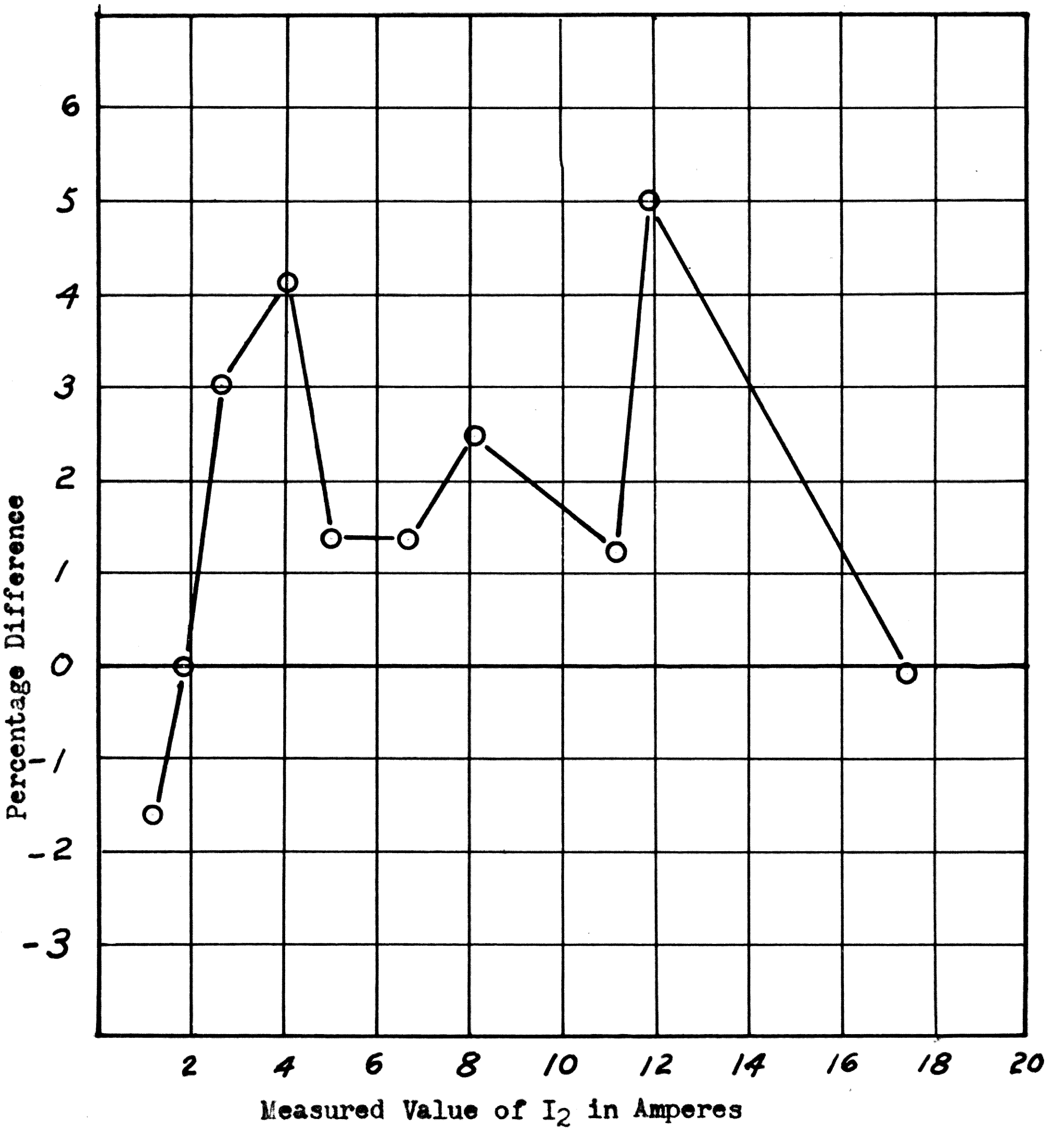

Figure 5
DIFFERENCE BETWEEN MEASURED AND CALCULATED VALUES FOR THREE-PHASE RESISTIVE LOAD

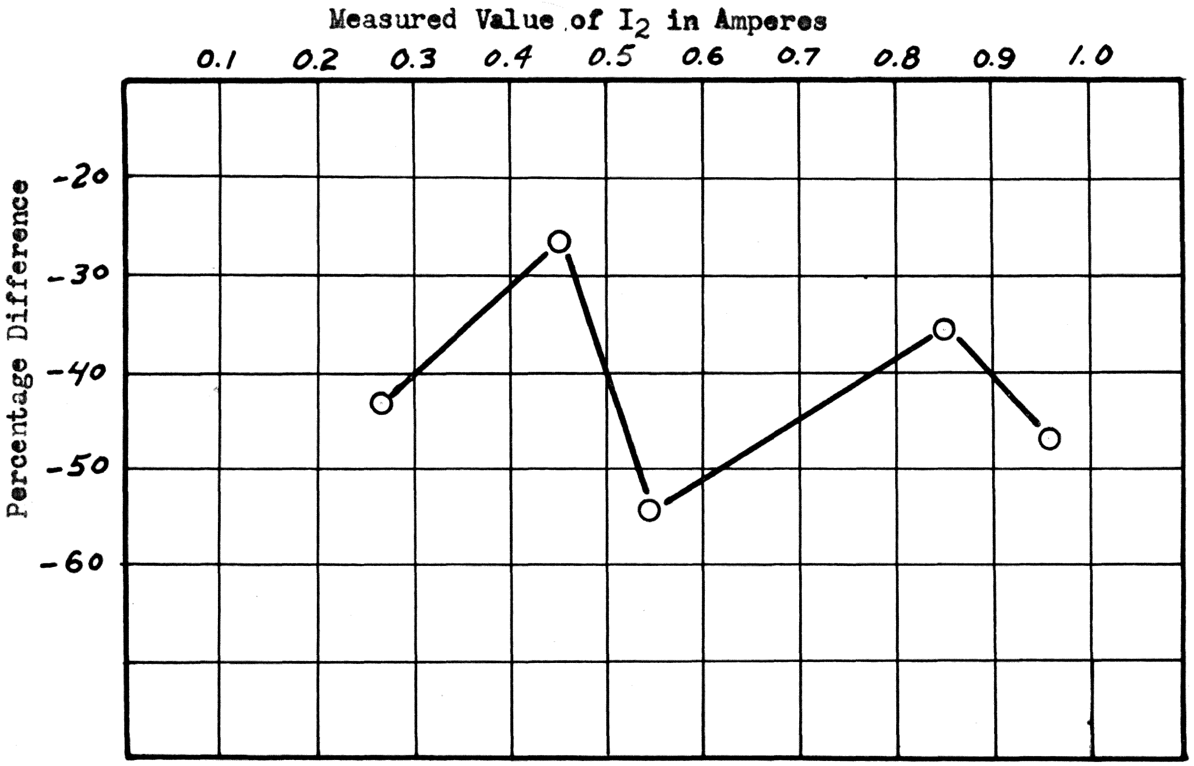

Figure 6
DIFFERENCE BETWEEN MEASURED AND CALCULATED VALUES FOR THREE-PHASE RESISTIVE LOAD

Table 3

Measurement of Negative-Sequence Currents for a Three-Phase Induction Motor Operating on Unbalanced Voltages With I_2 Read on Weston Model 433 Zero-to-Five-Ampere Ammeter.

I_A	I_B	I_C	I_2	I_2(calculated)	Difference	Per Cent Difference
0	10.76	10.76	6.24	6.20	0.04	0.64
0.5	14.08	12.08	7.00	7.16	-0.16	-2.28
0	14.40	14.40	8.40	8.32	0.08	0.95
5.20	18.48	14.52	6.60	7.20	-0.60	-9.1
6.56	19.20	12.72	8.16	8.80	-0.64	-7.84
0	20.40	20.40	11.50	11.80	-0.30	-2.6
14.00	19.00	13.76	5.76	5.76	0	0
0	31.00	31.00	18.00	17.9	0.10	0.55
10.00	28.00	20.80	10.50	11.50	-0.50	-4.85

Table 4

Measurement of Negative-Sequence Currents for a Three-Phase Induction Motor Operating on Unbalanced Voltages With I_2 Read on Weston Model 904 Ammeter Zero-to-One-Ampere Range.

I_A	I_B	I_C	I_2	I_2(calculated)	Difference	Per Cent Difference
6.40	8.16	6.60	0.92	1.25	-0.33	-35.8
6.00	9.00	6.80	1.51	1.89	-0.38	-25.2
4.20	9.76	7.00	2.30	2.85	-0.55	-23.9
4.00	10.40	7.80	3.20	3.88	-0.68	-21.2
7.88	9.84	8.20	1.04	1.24	-0.20	-19.3
7.40	10.44	8.04	1.62	1.97	-0.35	-21.6
6.60	11.28	8.20	2.42	2.86	-0.44	-18.2
4.80	12.76	9.40	3.86	4.88	-1.02	-26.4
10.00	12.60	10.36	1.36	1.64	-0.28	-20.9
8.56	14.84	11.72	3.24	4.04	-0.80	-24.7
12.44	15.60	12.92	1.65	1.93	-0.28	-17.0
12.00	16.40	12.80	2.34	2.79	-0.45	-19.2
11.36	17.80	15.12	3.38	3.70	-0.32	- 9.5
14.60	18.12	15.08	1.92	2.26	-0.34	-17.7
13.88	19.44	15.16	2.88	3.57	-0.69	-23.9

Corrected Values of I_2 Using Correction Factor of 1.23.

I_2(corrected) (I_2 x 1.23)	I_2(calculated)	Difference	Per Cent Difference
1.13	1.25	-0.12	-10.60
1.86	1.89	-0.03	- 1.60
2.83	2.85	-0.02	- 0.70
3.94	3.88	0.06	1.53
1.28	1.24	0.04	3.13
1.98	1.97	0.01	0.51
2.98	2.86	0.12	4.05
4.75	4.88	-0.13	- 2.74
1.67	1.64	0.03	1.80
3.98	4.04	-0.06	- 1.51
2.03	1.93	0.10	4.94
2.88	2.79	0.09	3.12
4.16	3.70	0.46	11.00
2.36	2.26	0.10	4.24
3.54	3.57	-0.03	- 0.85

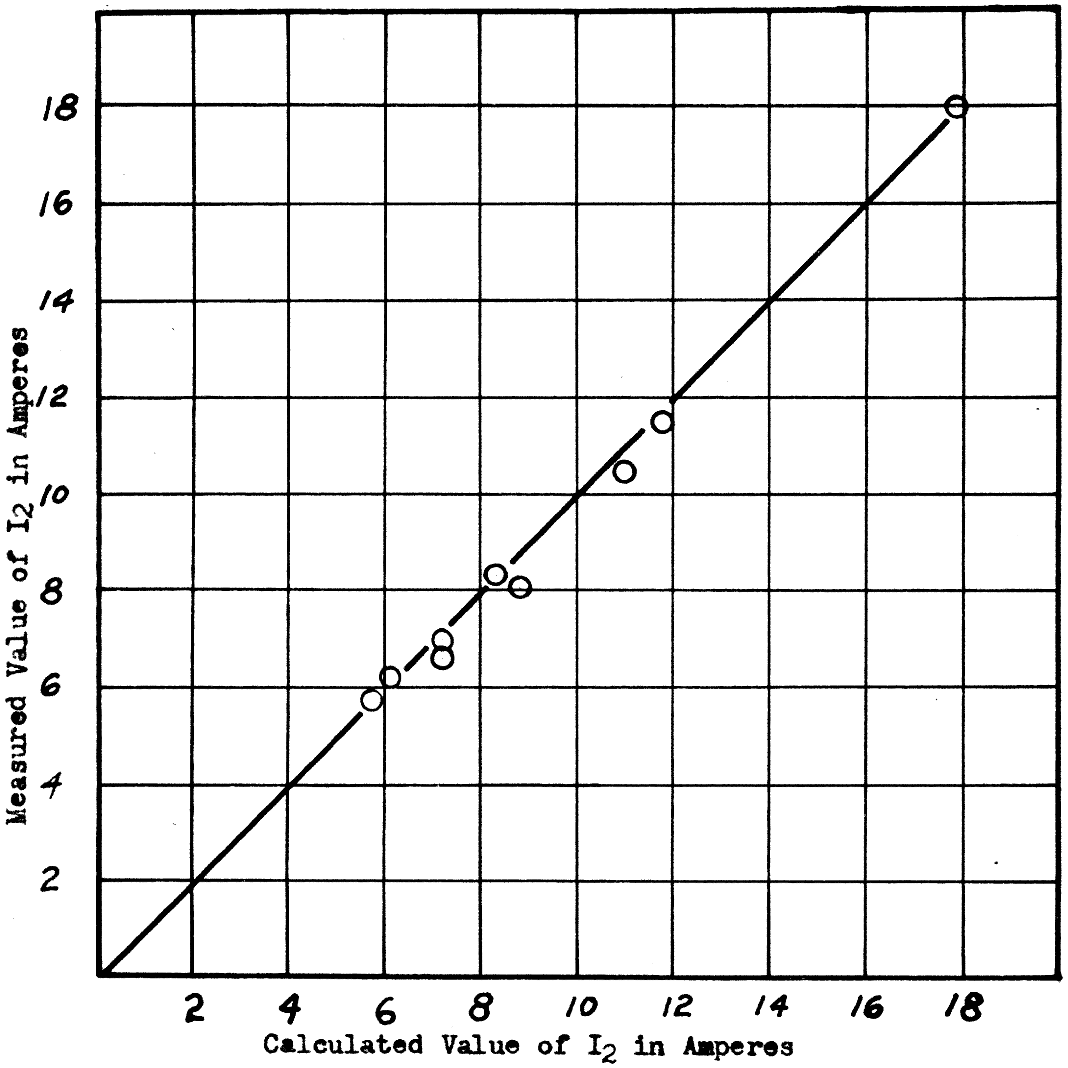

Figure 7
MEASURED VALUES VERSUS CALCULATED VALUES FOR A THREE-PHASE INDUCTION MOTOR OPERATING ON UNBALANCED VOLTAGES

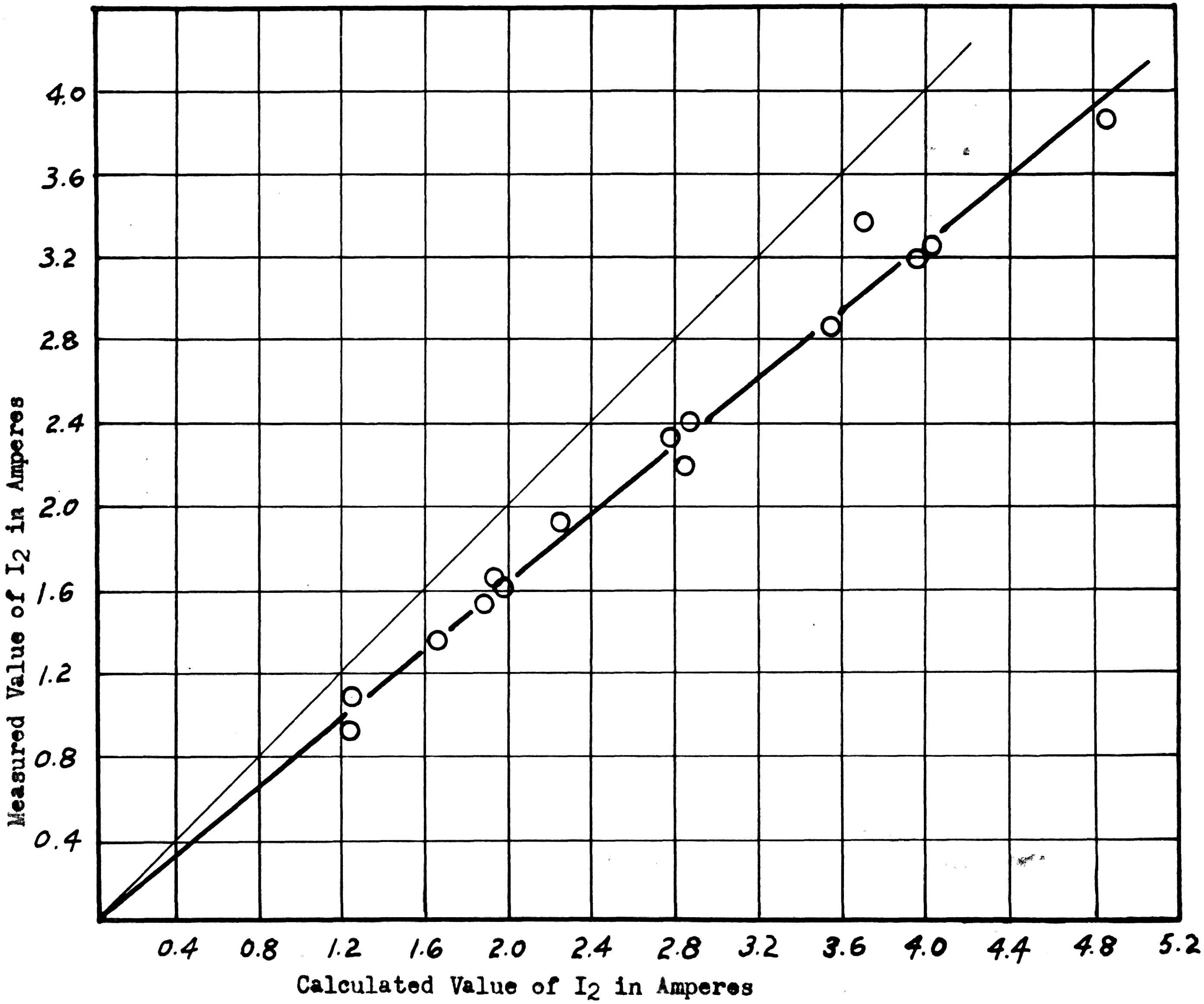

Figure 8
MEASURED VALUES VERSUS CALCULATED VALUES FOR A THREE-PHASE INDUCTION MOTOR OPERATING ON UNBALANCED VOLTAGES

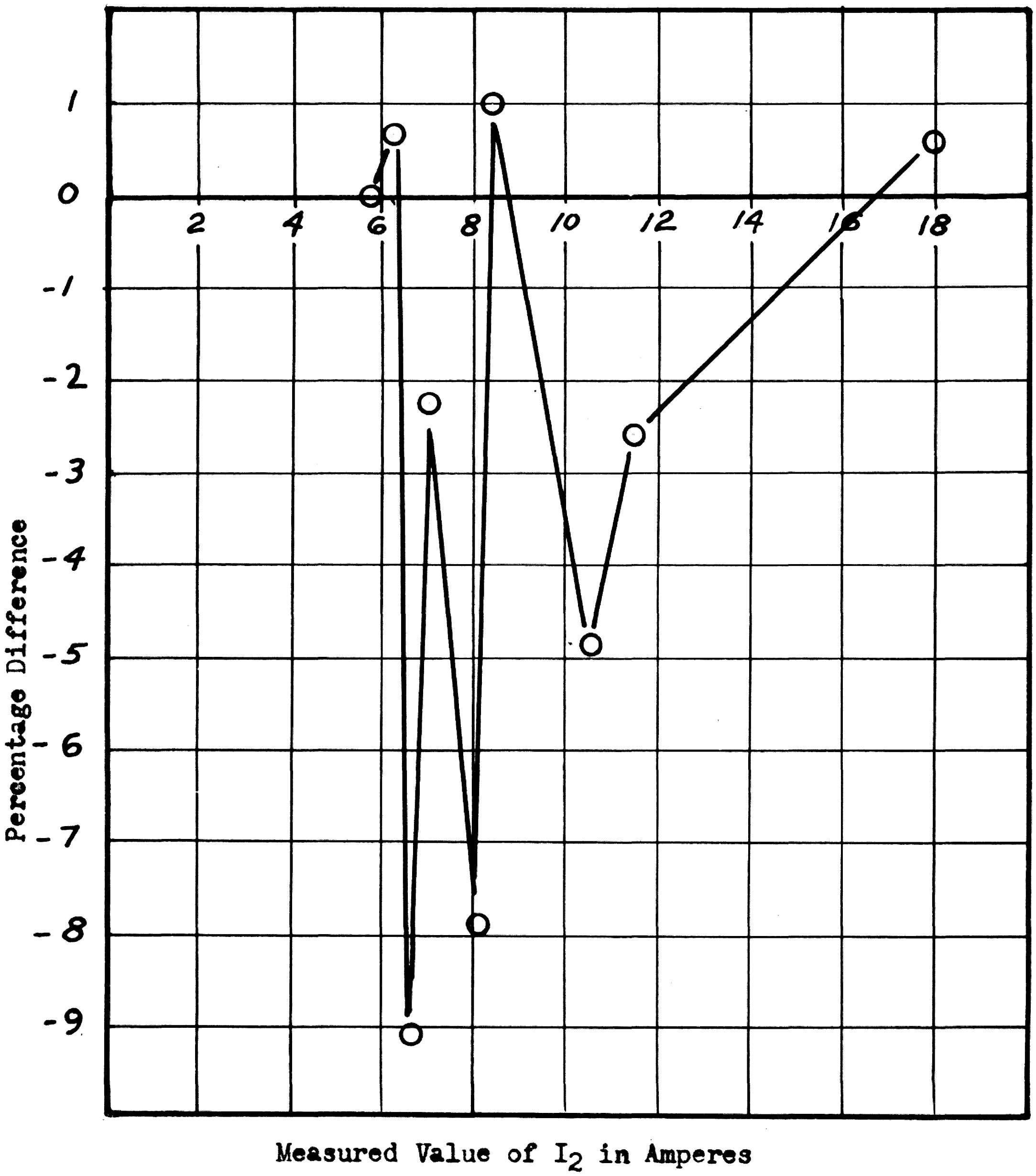

Figure 9
DIFFERENCE BETWEEN MEASURED AND CALCULATED VALUES FOR A THREE-PHASE INDUCTION MOTOR OPERATING ON UNBALANCED VOLTAGES

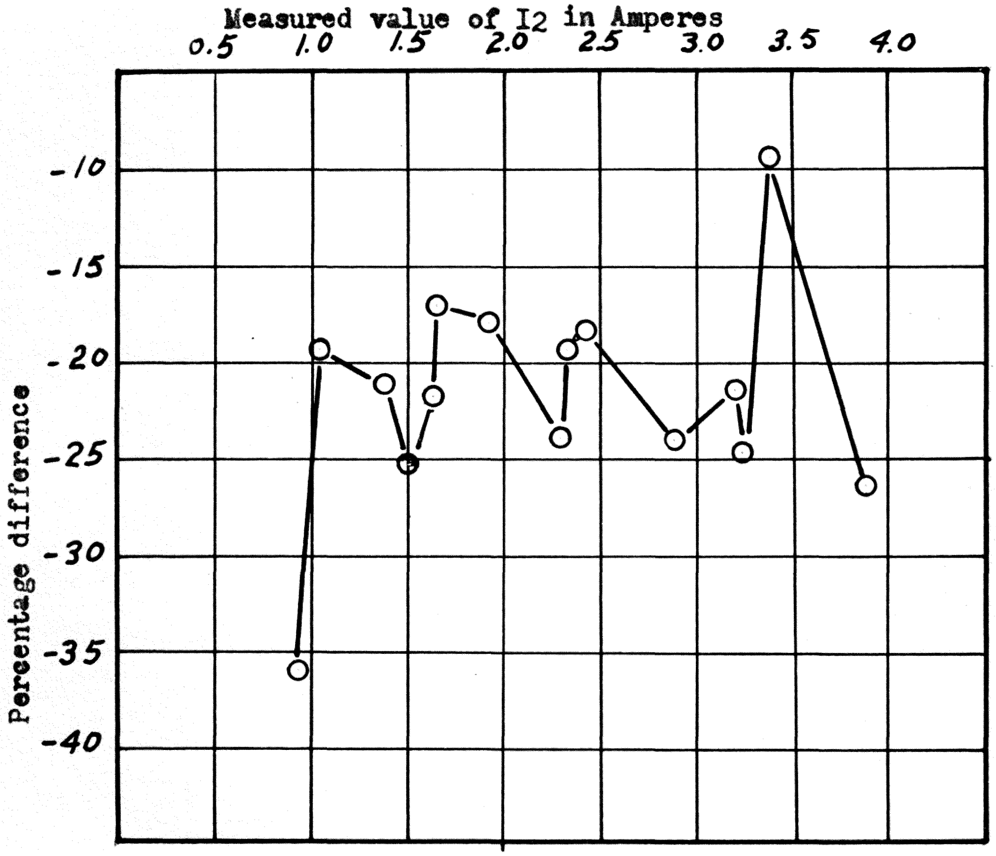

Figure 10

DIFFERENCE BETWEEN MEASURED AND CALCULATED VALUES FOR A THREE-PHASE INDUCTION MOTOR OPERATING ON UNBALANCED VOLTAGES

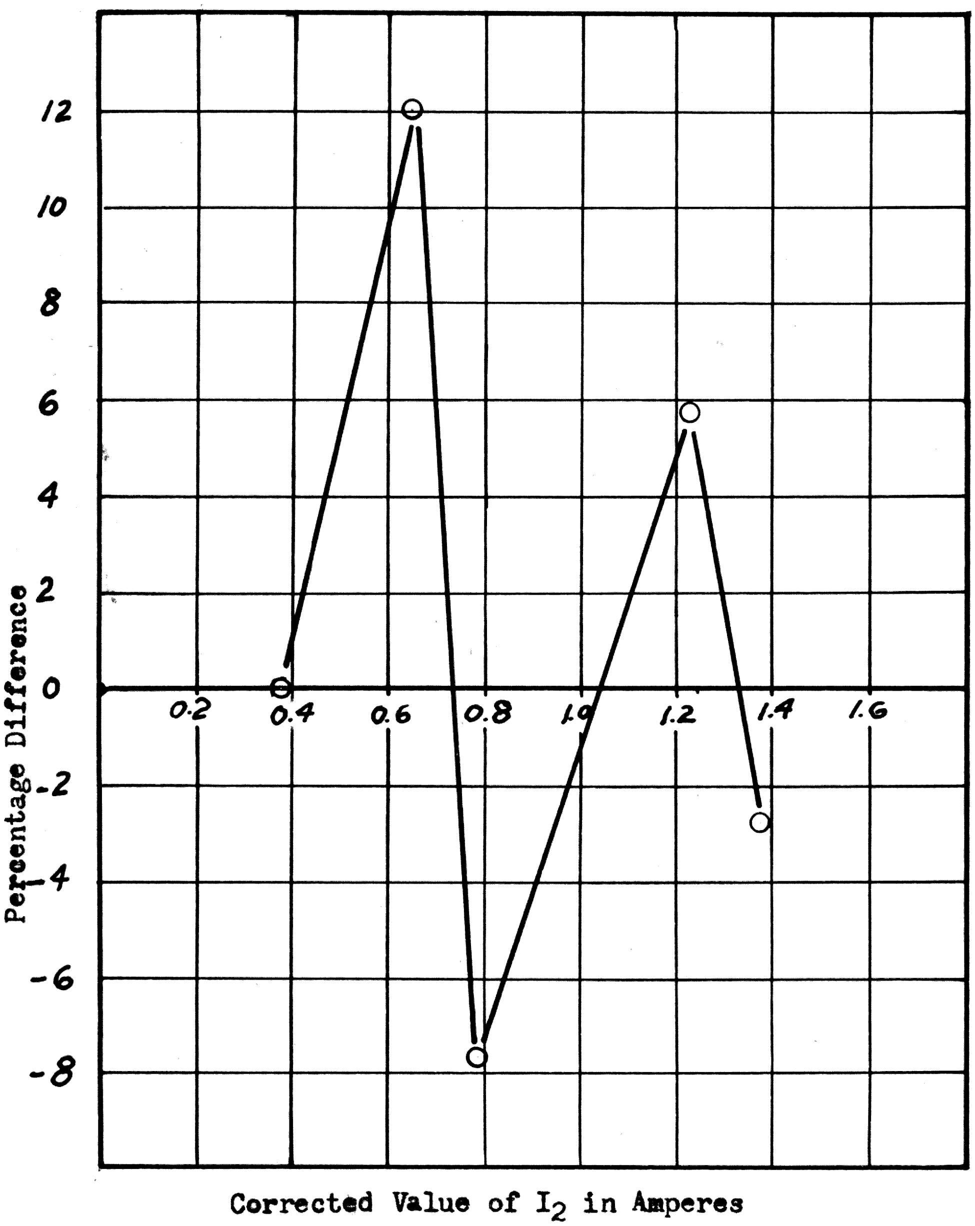

Figure 11
DIFFERENCE BETWEEN CORRECTED AND CALCULATED VALUES
FOR A THREE-PHASE RESISTIVE LOAD

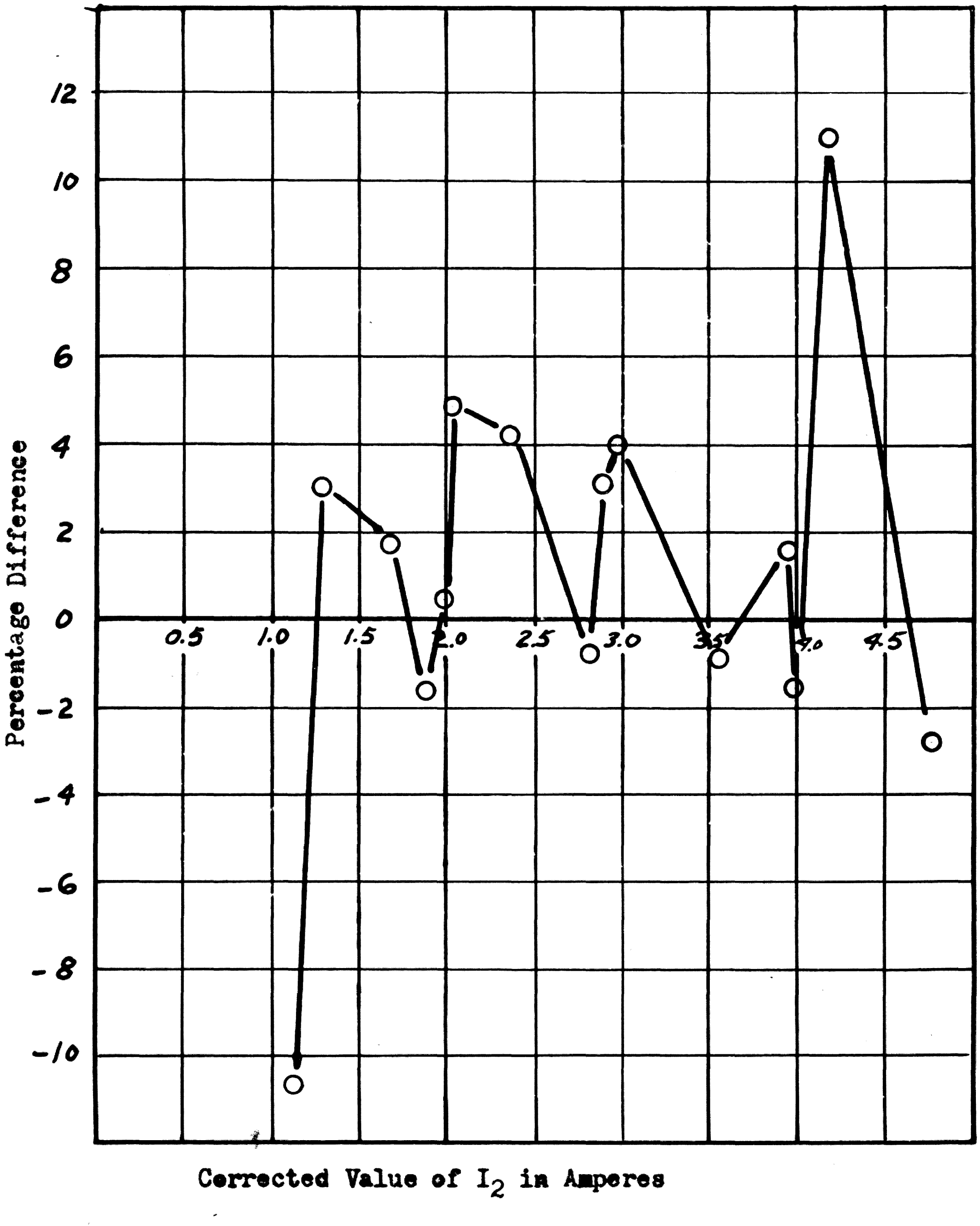

Figure 12
DIFFERENCE BETWEEN CORRECTED AND CALCULATED VALUES FOR A THREE-PHASE INDUCTION MOTOR OPERATING ON UNBALANCED VOLTAGES

IV DISCUSSION OF RESULTS

The results of this investigation show that it is possible to build a negative-phase-sequence ammeter for accurate measurements of negative-sequence currents. The results also point out some of the difficulties and limitations of this method.

The network was calibrated for use with a Weston Model 433, zero-to-five-ampere ammeter, and readings taken with this meter were found to be reasonably accurate. In most cases the difference between the calculated value of I_2 and the value read from the I_2 meter, expressed as a percentage of the I_2 meter reading, was well under five per-cent.

Since the network was designed for operation with primary current transformers whose current rating was five amperes, a rather serious unbalance had to be present before accurate readings of I_2 could be taken. This was true because readings from zero to one ampere could not be accurately taken with the meter used. Thus for the less serious cases of unbalance where the I_2 meter current became less than one ampere, the recording meter had to be changed in order to obtain a reading. The effect of changing the meter was to introduce errors into the readings since the network was calibrated for the zero-to-five-ampere ammeter. With a zero-to-one-ampere ammeter connected, the per cent difference between the calculated and measured values of I_2 was in some cases as much as 35 or 40 per-cent of the measured value. In all cases the measured value of I_2 was lower than the calculated value. This error meant that the particular circuit arrangement used in this investigation could not be used to obtain accurate readings of I_2 for slightly unbalanced loads.

An attempt was made to recalibrate the circuit for use with a zero-to-one-ampere meter but due to the fact that the smaller ammeter had a much higher resistance than the original meter it was impossible to recalibrate the circuit without changing the circuit entirely. In other words, the proper resistance-to-reactance ratio could not be obtained. This could perhaps be remedied by increasing the volt-ampere burden on the primary current transformers in order to allow a higher impedance to be used in the phase-shift network. In this way it might be possible to obtain the proper resistance-to-reactance ratio in the phase-shift network.

In all cases the readings taken with the zero-to-one-ampere ammeter were low and, as shown in figures 4 and 8, the value of I_2 read from the I_2 meter varied linearly with the calculated value, but was consistantly low. This variation suggested that it might be possible to use a correction factor to obtain values reasonably close to the correct value of I_2. For Run one with a Weston model 433, zero-to-one-ampere ammeter, a correction factor of 1.43 was used; for Run two, with a Weston model 904, zero-to-one-ampere ammeter a correction factor of 1.23 was used. The results incorporating the correction factors are shown in tables 2 and 4 and figures 11 and 12. In most cases the use of these correction factors gave values close to the calculated value of I_2.

V CONCLUSIONS

From the information gathered in this study it can be concluded that measurement of negative-phase-sequence currents with accuracy consistent with commercial requirements is possible. The most difficult problem in the design of a circuit for measuring negative-sequence currents using this method is that of keeping the volt-ampere burden on the primary current transformers low yet still having a network whose impedances are in a range that can be easily constructed and calibrated.

Although no measurements were taken of negative-phase-sequence currents in a three-phase, four-wire circuit, it can be seen that the method used in this investigation would be just as applicable for the four-wire circuit since the definition of the negative-sequence current remains the same no matter whether the three- or four-wire circuit is used.

The system must be calibrated for the particular meter that is going to be used, much the same as the shunt for a direct-current ammeter must be calibrated for use with a particular meter. Thus if a change in scale reading is desired, the circuit must be recalibrated in order for the readings to be correct.

VI SUMMARY

This investigation was set up for the purpose of perfecting a method of measuring the negative-sequence current in an unbalanced three-phase circuit. A four-winding current transformer, in conjunction with a phase shift network and an alternating current ammeter, was used for obtaining a current proportional to, and in phase with, the negative-phase-sequence current.

After calibration of the circuit, readings were taken of the three line currents in a three-phase three-wire circuit and of the current in the ammeter used for measuring the negative-sequence current. The value of the negative-sequence current was calculated from the line currents and was compared with the ammeter reading. The difference between the two readings in most cases was less than five per cent of the ammeter reading. When an attempt was made to change the range of readings by changing the meter used for measuring the negative-sequence current, it was found to affect the calibration. Thus it would be necessary to calibrate the circuit for each type of ammeter used.

It was concluded that direct readings of negative-sequence currents can be made with accuracy consistent with commercial requirements.

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A METHOD OF MEASURING NEGATIVE-PHASE-SEQUENCE CURRENTS IN A THREE-PHASE SYSTEM

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A method of measuring the negative-sequence current in an unbalanced three-phase circuit. A four-winding current transformer, in conjuction with a phase shift network and an alternating current ammeter, was used for obtaining a current proportional to, and in phase with, the negative-sequence current.

After calibration, readings were taken of the three line currents in a three-phase three-wire circuit and of the current in the negative-sequence ammeter. The negative-sequence current was calculated from the line currents and compared with the ammeter reading. The difference between the two values, in most cases, was less than five per cent of the ammeter reading. It was found that the circuit had to be calibrated for each type of ammeter used.

It was concluded that direct readings of negative-sequence currents can be made with accuracy consistent with commercial requirements.