# HYSTERESIS AND EDDY CURRENT LOSSES IN A REPEATING COIL BOTH WHEN MAGNETIZED AND UNMAGNETIZED

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## PREFACE

This thesis is a study of the change in equivalent resistance of a repeating coil, due to hysteresis and eddy currents. When a current flows in an inductive circuit, it is opposed both by the resistance and the reactance of the circuit. Any power losses due to hysteresis and eddy currents will produce the same effect as a resistance of an amount $\frac{P_h + P_e}{I^2} = R_{1}$. This quantity, $P_h + P_e + R$ is spoken of, in this thesis as the "equivalent resistance" of the circuit. In a repeating coil there is a flux set up by the flow of a direct current through the coil, superimposed on this is a variable, talking, current. To find the losses due to hysteresis and eddy currents for this variable current is my objective.

## GENERAL SURVEY OF THE FIELD

A large amount of experimental work has been carried on by the leading manufacturers of telephone equipment but it is not known to the writer, how extensively the subject of repeating coils has been treated. It is highly probable that closer and more accurate investigations have been made using other methods than the one followed in this thesis.

## STATEMENT OF PURPOSE

In this study it is proposed to make a series of tests by varying the magnetizing current from zero to a point well beyond that of saturation, having superimposed on this a fairly constant high frequency current. The current in a repeating coil in ordinary use, is a pulsating current made up of a direct current on which is superimposed an alternating current of voice frequency (200 -2000 cycles). To imitate this, in its effect on the core a direct durrent was sent through the primary of the repeating coil and an alternating current of 900 cycles was sent through the secondary. A 27-a repeating coil, manufactured by the Western Electric Company, was used in making this investigation.

## GENERAL THEORY

There are several methods which could be used in making this investigation. One method is by means of a voltmeter, an ammeter, and a wattmeter, using meters suitable for this frequency and small current. In the present case these quantities are too small to be measured this way. Another method is to obtain by experiment a hysteresis loop of the coil both with and without a direct current magnetizing the core. The difference in areas of the hysteresis loops would be the losses due to hysteresis and eddy currents. This is open to the same objection, that the quantities are too small for measurement. A third method, and the one followed in this thesis, is the bridge method. A wheatstone bridge gives us one of the most accurate means of measuring a resistance, reactance, or impedence.

## METHOD AND APPARATUS

By balancing a standard reactance with the reactance of the coil and the resistance of the coil with a known resistance in a wheatstone bridge the change of resistance over that of the unmagnetized coil can be found. Fig. 1 shows a schematic of the circuit used for balancing and measuring the resistance and reactance of the coil.

First, the coil was balanced for resistance only. Leaving the bridge balanced a small current of 900 cycles frequency was applied. Alternating current resistance is higher than direct current resistance due to hysteresis and eddy currents; consequently, the bridge was unbalanced and an audible tone was heard in the telephone receiver. The reactance and resistance standards were then adjusted until a minimum sound was heard in the phones. This was accomplished by moving the two across a point where the weakest sound was heard swinging from a tone of given loudness to weaker and on to the same amount of loudness. Each time the amount of swing was reduced until the mid point of weakest sound was heard. It was not possible to vary the standards so as to eliminate the sound entirely for the core of the coil was made up of turns of soft iron wire. The presence of iron distorted the alternating current from a true sine wave. The impurity of the wave due to the iron prevented the silence which would have been obtained had the core been of some non-magnetic substance.

The next step was to apply a small magnetizing direct current. This was done on the primary side, the secondary side being attached to the bridge. Thus we had a flux set up by a direct current and superimposed on this was the alternating current, variable talking current. Again the bridge was balanced as before. The d.c. magnetizing current was increased and the bridge balanced again. For every magnetizing current the bridge was balanced a number of times before the values of the resistance and reactance were noted. One great source for error was due to the difficulty in finding the point of weakest sound. The tuning was reasonably sharp up to 17 milli-amperes but beyond that it was not so marked and greater care was exercised.

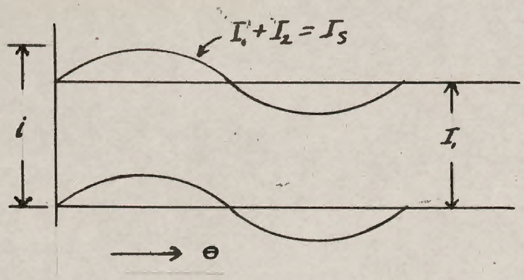
The observance of the varying reactance simultaneously with the changing resistance was a secondary matter; however, it furnished some interesting information which can be seen from the curves in Fig. 2. The peak of the resistance curve comes about 17 milli-amperes while that of the reactance comes at about 10 milli-amperes. Both curves begin to flatten out so that beyond a point a large change in magnetizing current produces very little change in resistance and reactance.

A milli-ammeter was used to measure the direct current but the amount of alternating current was found in the following manner. Fig. 3 is a schematic of the circuit used. The thermo-couple was connected in one side and a known amount of direct current in the other side. With both the d.c. and the a.c. flowing the deflections of the galvanometer, connected to the other side of the thermo-couple, was noted. The source of a.c. was discontinued without interrupting the flow of d.c. by stopping the alternator which furnished the a.c. and the deflections of the galvanometer were then noted. The deflections of the galvanometer are in proportion to the squares of the direct current and the combined current.

The field of the alternator was kept constant at all times. The exciting current was 0.4 amperes direct current.

## CALCULATIONS AND OBSERVATIONS

Proof that the square of the effective combined currents is the same as the sum of the squares of the effective current:




$I_s$ - Sum of d.c. and a.c.

$I_1$ - Value of direct current

$I_2$ - Effective value of a.c.

$i_m$ - Maximum value of a.c.

$i_2$ - Instantaneous a.c.

$i_1$ - Instantaneous d.c.

Equation: $i_2 = im \sin \theta$

Equation: $i_1 = I_1$

Equation: $I_s = im \sin \theta + I_1$

$$I_s^2 = i_m^2 \sin^2 \theta + I_1 i_m \sin \theta + I_1^2$$

$$\text{Av. } I_s^2 = \frac{\int_0^{2\pi} i_m^2 \sin^2 \theta \, d\theta + I_1 i_m \sin \theta \, d\theta + I_1^2 d\theta}{2\pi}$$

$$= \left[ \frac{\frac{i_m^2}{2} \theta - \frac{i_m^2}{4} \sin 2\theta - I_1 i_m \cos \theta + I_1^2 \theta}{2\pi} \right]_0^{2\pi}$$

$$= \frac{(i_m^2 \pi - I_1 i_m + 2\pi I_1^2) + I_1 i_m}{2\pi}$$

$$= \frac{i_m^2 \pi + 2\pi I_1^2}{2\pi} = \frac{i_m^2}{2} + I_1^2$$

$$i_m = I_2 \sqrt{2}$$

$$\text{Av. } I_s^2 = 2/2 \; I_2^2 + I_1^2$$

$$\text{Eff. } I_s = \sqrt{2/2 \; I_2^2 + I_1^2}$$

## Measurement of a.c.

$I_1^2 : I_1^2 + I_2^2 : : d_1 : d_2$

$I_1$ = Value of direct current

$I_2$ = Effective value of alternating current

$I_s = I_1 + I_2$

$I_1^2 : I_s^2 : : d_1 : d_2$

$d_1$ - Deflection due to direct current

$d_2$ - Deflection due to combined current

$I_1$ - 7 Milli-amperes

$I_2$ - ? milli-amperes

$d_1$ - 1.09 c.m.

$d_2$ - 1.21 c.m.

Deflections of Galvanometer

| | d.c. | a.c. and d.c. | No current |
|---|---|---|---|
| | 11.58 | 11.63 | 10.40 |
| | 11.53 | 11.65 | |
| | 11.55 | 11.72 | 10.52 |
| mean deflections | 11.55 | 11.67 | 10.46 |

$$\begin{array}{r} 11.55 \\ \underline{10.46} \\ d_1 = 1.09 \end{array} \qquad \begin{array}{r} 11.67 \\ \underline{10.46} \\ d_2 = 1.21 \end{array}$$

substituting:-

49: 49 - I : : 1.09 : 1.21

$I_2$ - 3.3 Milli-amperes

It was not observed until later that the a.c. could have been measured as well, by itself.

Observations and calculations for equivalent resistance and inductance.

| Obs. | Mag. Current Mil-amps | Mil-Henry's | Equivalent Ohms Res. | Watts loss |
|---|---|---|---|---|
| 1 | 0 | 10.0 | 114 | 1.231 |
| 2 | 1.0 | 10.3 | 114 | 1.231 |
| 3 | 2.5 | 11.3 | 129 | 1.395 |
| 4 | 5.0 | 18.5 | 164 | 1.772 |
| 5 | 7.0 | 23.0 | 259 | 2.800 |
| 6 | 10.0 | 24.0 | 308 | 3.330 |
| 7 | 17.0 | 19.0 | 335 | 3.620 |
| 8 | 25.0 | 15.0 | 315 | 3.415 |

| Obs. | Mag.Current Mil-amps | Mil-Henry's | Equivalent Ohms Res. | Watts loss |
|---|---|---|---|---|
| 9 | 38.0 | 14.0 | 249 | 2.690 |
| 10 | 47.5 | 13.5 | 234 | 2.528 |
| 11 | 70.0 | 12.0 | 169 | 1.828 |
| 12 | 100.0 | 11.5 | 114 | 1.231 |

The field of the alternator was magnetized at all times by a direct current of 0.4 amperes.

## CONCLUSIONS

From the above data and calculations it is apparent that the losses are higher at about 10 to 17 milli-amperes of magnetizing current and that the most economical range of operation is beyond that. The losses are of such magnitude that on the face of it they do not seem reasonable. The opinion is held that the chief source of error as outlined above is in getting the proper balance. A galvanometer sensitive to alternating currents would offer a much better means than the use of phones for determining when the bridge is properly balanced.

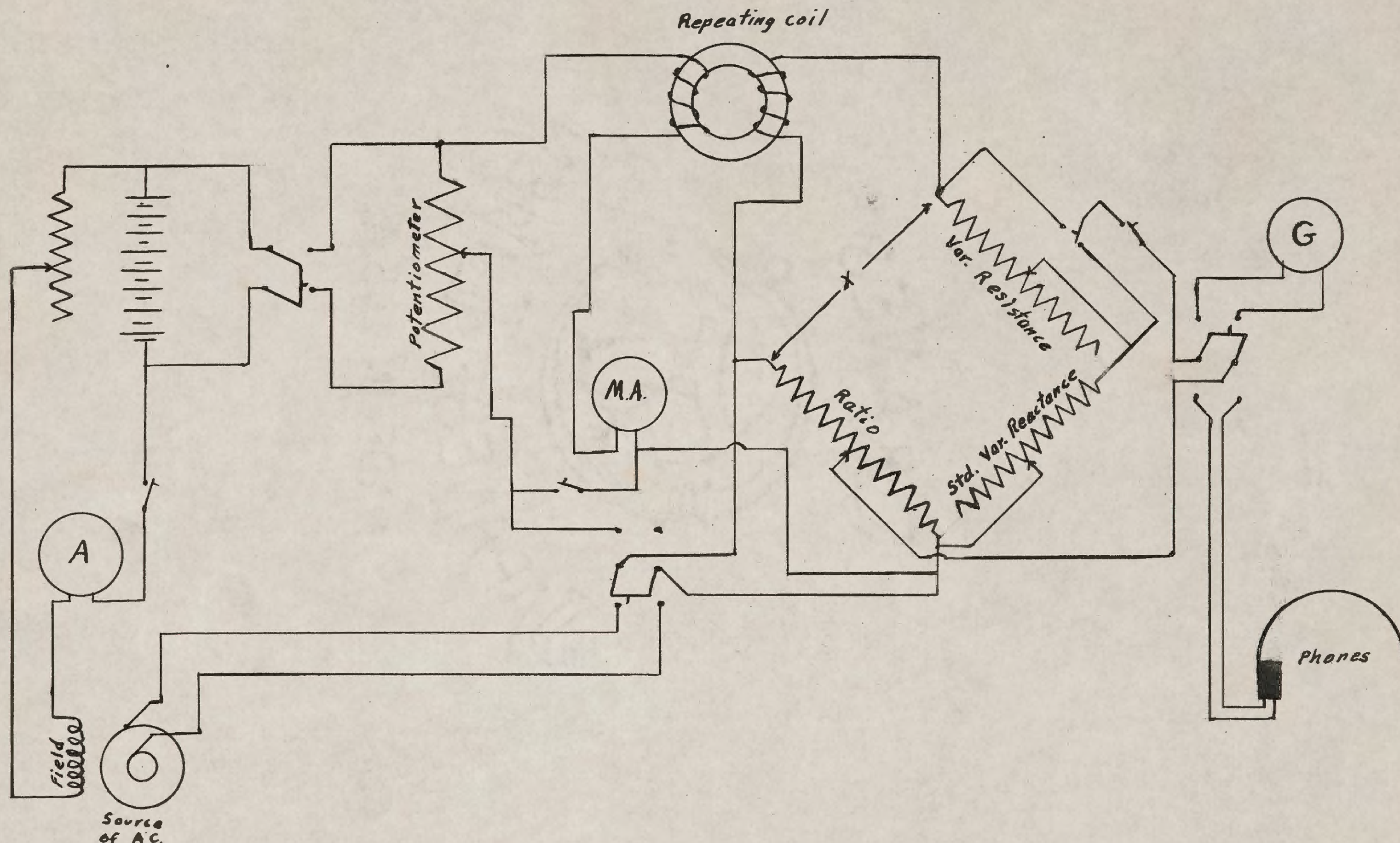



Fig. 1

Circuit for Measuring Resistance and Reactance of Coil


Resistance - ohms
Milli-Henry's
350
300
250 25
200 20
150 15
100 10
5
0 0
0 2.5 5 7.5 10 15 25 30 40 50 60 70 80 90 100
Resistance
Reactance
Milli-Amperes - D.C.

Fig. 2

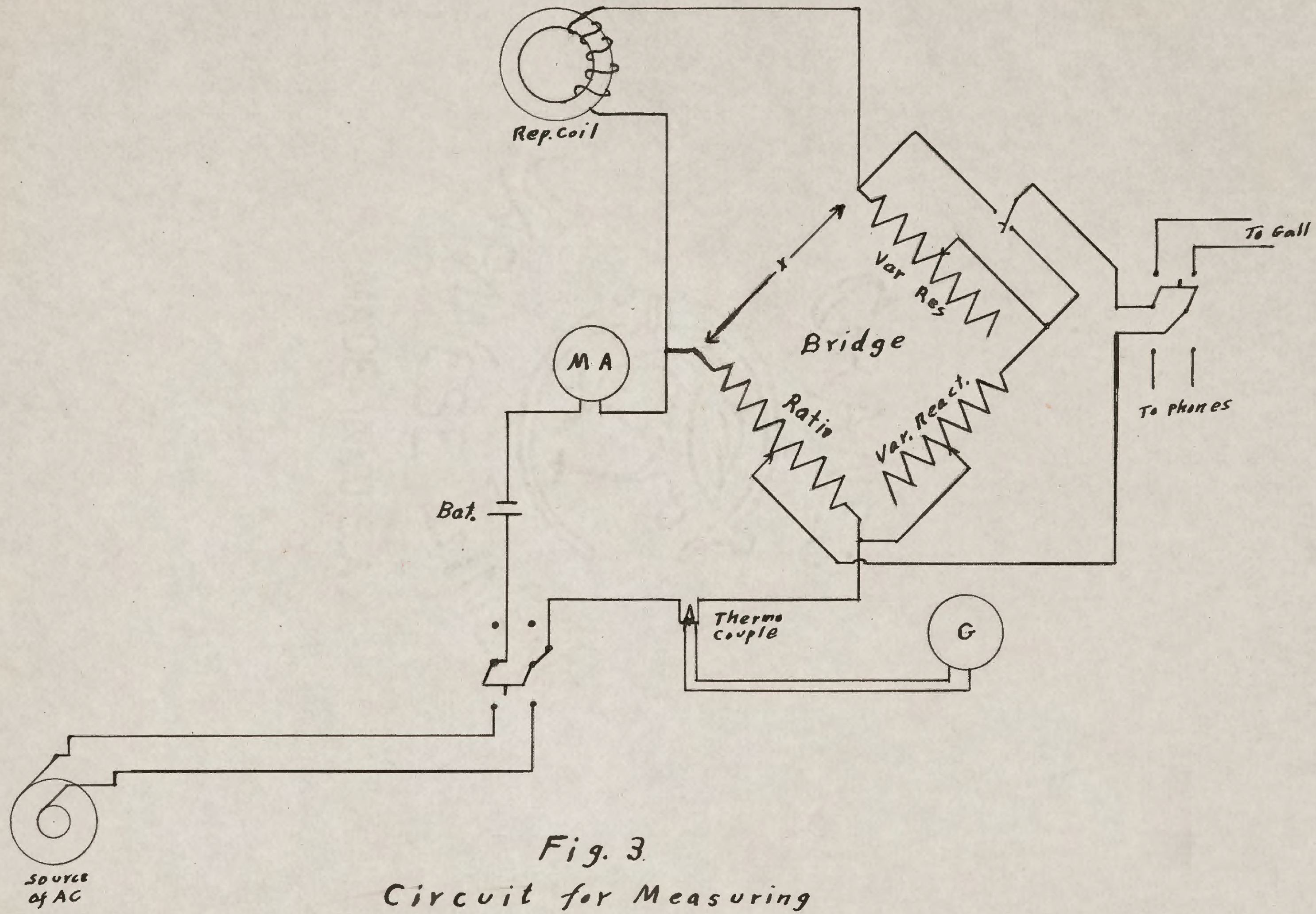



Fig. 3
Circuit for Measuring
High Frequency A.C.

APPROVAL

The foregoing thesis is hereby approved as a creditable study of an engineering subject, carried out and presented in a manner sufficiently satisfactory to warrant its acceptance as a prerequisite to the degree for which it has been submitted. It is to be understood that by this approval the undersigned does not necessarily endorse or approve any statement made, opinions expressed, or conclusions drawn therein, but approves the thesis only for the purpose for which it is submitted.

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