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THE EFFECT OF DISPLACED MAGNETIC PULSATIONS ON THE HYSTERESIS LOSS OF SHEET STEEL

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ABSTRACT OF PAPER

Most modern revolving electrical apparatus has teeth on the rotor or stator, or both, which are subjected to constantly varying reluctance. This variation of reluctance causes high frequency changes of flux superimposed on the working flux. The result is a series of displaced hysteresis loops. This investigation was undertaken to determine the magnitude and, if possible, some of the laws governing the change in hysteresis loss due to displacing a loop from its symmetrical position.

An account is given of some early tests which, within the limits of induction studied, resulted in certain definite conclusions.

It is pointed out that the data from these displaced hysteresis loops limit the applicability of the Steinmetz hysteresis formula to symmetrical loops.

Recent tests are then described, giving the details of a new apparatus for obtaining hysteresis loops and showing an improved method of making displaced a-c. watt-loss tests.

Numerous loops and curves are included, showing the effect of displacement on the shape and area of the hysteresis loop.

No definite laws could be formulated from the data, but some general conclusions are given.

INTRODUCTION

IN THE early work of Steinmetz the following law for the relation between magnetic induction and hysteresis loss was given:

$$W_h = \eta \left(\frac{\Delta B}{2}\right)^{1.6}$$

where W_h = hysteresis loss
η = a constant
B = amplitude of induction.

This law is reasonably accurate for ordinary ranges of induction and for hysteresis loops which are symmetrical. It has been found, however, by several investigators* that if a hysteresis loop is displaced from its normal symmetrical position,

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*F. Holme, *Zeitschrift des Vereins Deutscher Ingenieur*, Oct. 1912.

there will result not only a change of shape but of area as well. Such an effect occurs in most modern rotating electrical ap. paratus. The rotor and stator teeth are subjected to a constantly varying reluctance which produces a high-frequency change of flux superimposed on the working flux. The high-frequency pulsations produce hysteresis losses which we believe cannot be accurately calculated from a knowledge of the ordinary symmetrical-loss characteristics of the steel.

The present investigation was undertaken to determine the magnitude of this effect, and, if impossible, some of the laws governing it.

Early Tests

Our first attempts were made in June, 1911. The following method of attack was used. Two laminated sheet-steel-ring samples were prepared, one of open-hearth steel and the other

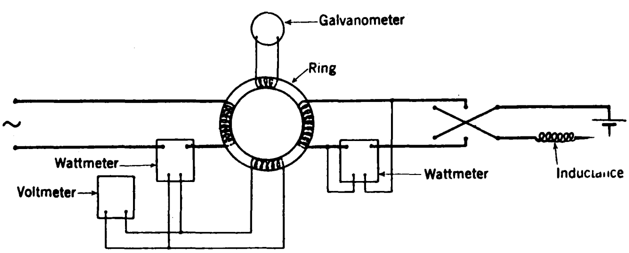


Fig. 1

of silicon steel. These samples were each wound with four uniformly distributed coils of wire, which were connected as in Fig. 1.

A d-c. magnetizing force was supplied to the d-c. winding through a high reactance in order to limit the a-c. current in the d-c. circuit. An a-c. wattmeter was placed in the d-c. circuit to measure the small amount of a-c. power that was lost in this circuit, and corrections made accordingly. The amount of displacement of the hysteresis loop was measured by reversing the d-c. supply and noting the deflection of a ballistic gals vanometer. The amplitude of pulsation of the a-c. flux wa- determined by means of an a-c. voltmeter, assuming the voltage to have a sine wave form-factor (1.11). This assumption was correct within 2 per cent except at the highest inductions. The total a-c. loss was measured by means of a precision wattmeter of the Kelvin type.

The curve of Fig. 2 gives some of the results of these tests. Also curves were plotted between different cyclic inductions and loss for two different mean displacements (*i.e.* 2000 and 5000 gausses). The Steinmetz exponent was determined by plotting the logarithm of induction against the logarithm of the loss. These latter curves are not shown as they are not as reliable as some more recent data shown below. Some ballistic loops were taken at this time and Fig. 3 illustrates a specimen which shows the increase of area with displacement from the symmetrical position.

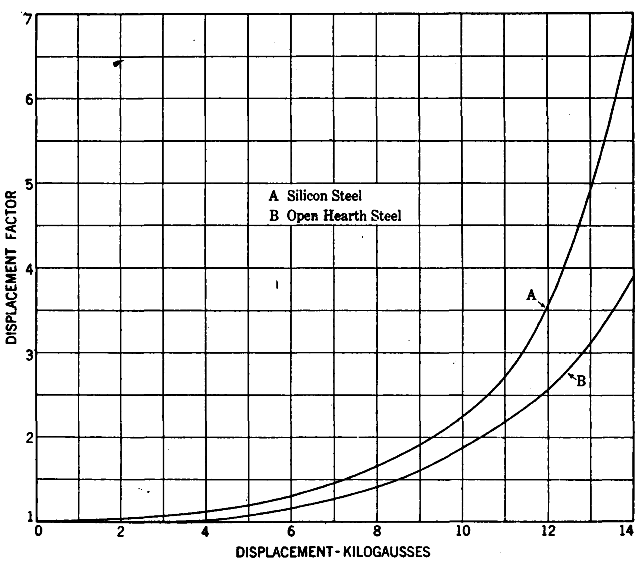


FIG. 2

At that time we called the ratio of the area of a displaced loop to the area of the symmetrical loop of equal amplitude the *displacement factor*. Various steel samples were from time to time tested for displacement factor to find out whether or not the material was suitable for specific applications. The routine tests at a mean displacement of 10 kilogausses and total pulsation of 2.5 kilogausses, and the previous investigation work, enabled us to draw the following general conclusions within the limits of induction used.

(*a*) With a given pulsation the hysteresis loss increases very considerably with the displacement.

(*b*) Silicon steel has a higher percentage increase of hysteresis loss with a given displacement of the loops than open-hearth or soft steel.

(*c*) The Steinmetz exponent for the relation between pulsation and hysteresis loss decreases as the displacement increases.

Recent Tests

Recently, with superior testing methods, additional data have been obtained on this subject.

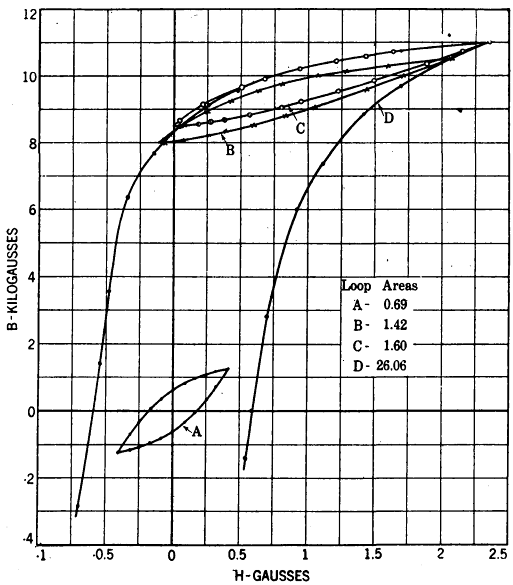


Fig. 3

TEST METHODS

Volt-Second Meter Method. About two years ago, one of the authors devised an apparatus for obtaining magnetization curves and hysteresis loops on completed electrical apparatus, particularly transformers.

The change of flux in a magnetic core surrounded by a winding is equal to

$$K \int e \, dt$$

where K = constant

e = voltage induced in winding

If a meter which will integrate the induced voltage is connected to a transformer winding, its reading will be proportional to the change of flux in the core. The method consists in passing direct current from a storage battery through the primary winding of a transformer and connecting to the secondary an integrating voltmeter or volt-second-meter which when properly adjusted makes one revolution for each change of one kilogauss in the magnetic induction of the transformer core. The procedure for testing consists in varying the impressed voltage and, at the end of each revolution of the volt-second-meter, reading the ammeter in the primary circuit. From this ammeter reading the value of H may be calculated. This

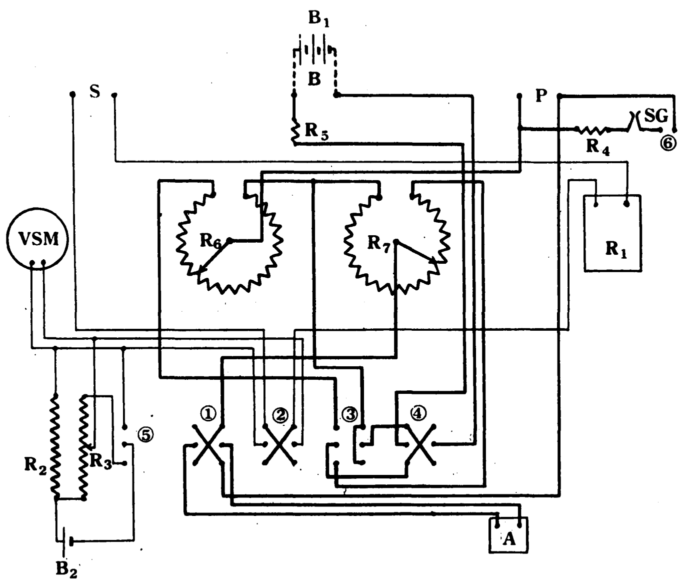


FIG. 4

gives the data for a magnetization curve or hysteresis loop, depending on the conditions.

A diagram of connections of this apparatus is shown in Fig. 4 and the apparatus is illustrated in Fig. 5. The primary of the transformer to be tested is connected to terminals P and the secondary to S. B_1 is the source of d-c. supply. $V.S.M$ is the volt-second-meter and R_1 is a resistance in series with it. B_2 is a dry cell which supplies sufficient current to the volt-second-meter through the high resistances R_2 and R_3 to compensate for friction when switch 5 is down. When switch 5 is up the volt-second-meter may be backed up to its zero point. Switch 1 reverses the ammeter A, switch 2 reverses the volt-second-meter, switch 3 gives R_6 a potentiometer connection and makes R_7 a series resistance or the opposite, depending on its position. This is for convenience in testing different sizes of transformers as R_6 and R_7 have resistances of 5 to 1 and sometimes one connection is more desirable than the other. Switch 4 reverses the main battery current. *S.G.* is a safety gap to limit the rise in voltage in case the primary circuit is accidentally opened.

In order to calibrate the volt-second-meter, terminals *P.* and *S* are connected together and a voltmeter is connected across *S*. R_1 is made some convenient value and the voltage is adjusted by R_6 and R_7 to give approximately 20 revolutions per minute of the volt-second-meter. The time for 10 revolutions (or more if desired) is then recorded by a stop watch and the voltage noted. The constant of the apparatus is then determined from the formula:

$$C = \frac{10\,R_T}{E\,T}$$

where R_T = total resistance of circuit inside of terminal S

E = voltage

T = time in seconds

Next R_1 is to be adjusted as follows:

$$R_T' = A\,N\,C\,10^{-5}$$

where R_T' = total resistance of circuit including transformer winding, *V.S.M.* resistance, etc.

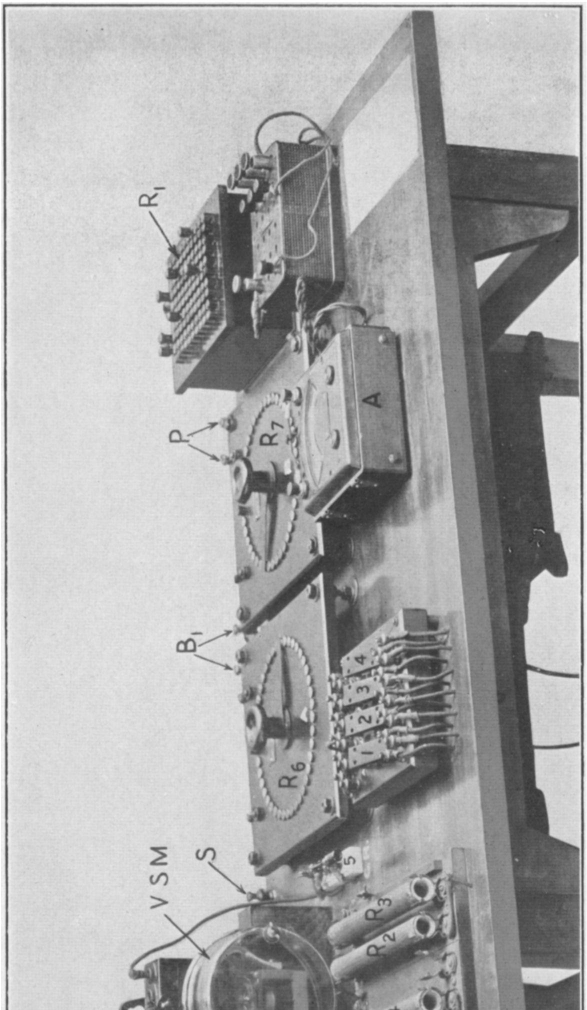
$R_1 = R_T'$ — all other resistance of circuit.

A = cross section of transformer core in sq. cm.

N = secondary turns of transformer.

With this adjustment, a change of induction of one kilogauss in the transformer core will cause the volt-second-meter to make one revolution.

To obtain a hysteresis loop the procedure is as follows: Set the primary current to some convenient value by means of the rheostats R_6 and R_7, back up the volt-second-meter to zero by throwing switch 5 up, reverse the primary current by means of switch 4 and note the total revolutions of the volt-second-meter. If this is not the value required, change the current, set the volt-second-meter to zero, reverse the volt-second-meter connections by means of switch 2, reverse switch 4 and



[CHUBB AND SPOONER]

FIG. 5—APPARATUS FOR OBTAINING MAGNETIZATION CURVES AND HYSTERESIS LOOPS

again note the total revolutions of the volt-second-meter. Repeat until the transformer is brought to the proper induction. When the current has been reversed a sufficient number of times to insure a cyclic condition for the core, the applied voltage is decreased to zero by the rheostats R_6 and R_7 at any rate desired, readings of the ammeter A being taken at each revolution (or fraction thereof) of the volt-second-meter. Switch 4 is then reversed and the applied voltage gradually increased to its original value, at the same time taking readings of the

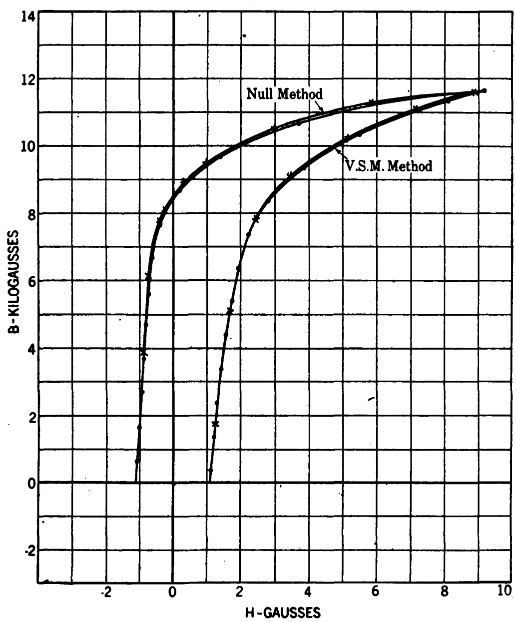


FIG. 6

ammeter as the volt-second-meter revolves. Switch 1 is, of course, to be reversed when the current passes through zero. With this apparatus, after the current has been adjusted to the proper value, it is possible to obtain the data for a complete loop in less than one minute.

As a check on the apparatus, loops were taken on a 250 kv-a., 30,000-volt transformer, both by the volt-second-meter method and by an independent null method, using a long-period ballistic galvanometer and mutual inductance. The two loops are shown in Fig. 6. The maximum magnetizing forces are slightly different due to small errors in determining the constants for one or both methods, but the areas of the two loops check within a small fraction of one percent.

A-C. Test Method. After obtaining considerable data with the volt-second-meter apparatus, a few 60-cycle tests were made on open-hearth and silicon-sheet-steel rings by methods superior to those used in the early tests.

A synchronous rectifier and d-c. voltmeter were used to determine the average value of the voltage and hence the maximum value of the flux. The rectifier could be adjusted to cut off at the zero points of the voltage wave, although the two zero points were not 180 degrees apart. This was necessary, as even harmonics were introduced into the voltage wave due

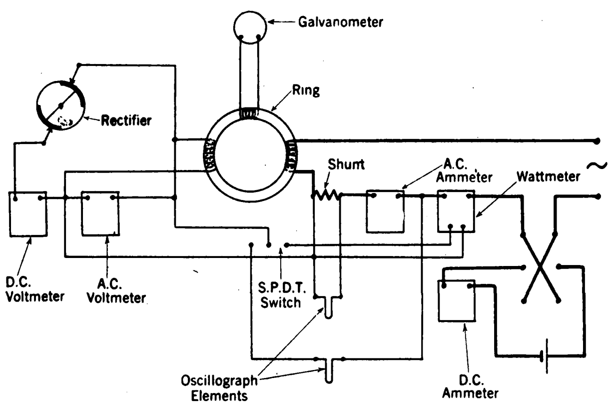


FIG. 7

to the unsymmetrical current passing through a certain unavoidable amount of inductance. The d-c. component of magnetizing force was introduced by inserting storage cells in series with the a-c. generator. The amount of displacement of the hysteresis loop was determined by a null method. To do this, the direct current was reversed and the mean change in flux was measured with a long-period ballistic galvanometer and variable mutual inductance. The secondary of the mutual inductance and the exploring coil on the ring were in series opposing. The primary of the inductance and the d-c. supply for the ring were reversed simultaneously and the mutual inductance adjusted for a balance. A diagram of connections is shown in Fig. 7. In the figure the galvanometer is supposed to represent the mutual inductance and other apparatus to measure the displacement of the hysteresis loop.

DATA

The volt-second-meter tests were made on a 3333 kv-a. 110,000 to 15,240-volt transformer. The core was of silicon steel. The data were obtained by first putting the transformer through the major hysteresis loop (which had a tip corresponding to that of the desired displaced loop) a sufficient number of times to insure a cyclic condition of the iron and then putting the core through the minor or displaced loop.

Figs. 8 to 23 inclusive show these loops plotted in various ways. The titles are self-explanatory. Table I shows the areas of these loops.

TABLE I.—SUMMARY OF AREAS.
SCALE OF CURVES: ORDINATES: 1″ = 2 KILOGAUSSES
ABSCISSAE: 1″ = 1 GAUSS
(The illustrations are reproduced to 1/3 of this scale.)
DISPLACEMENT—KILOGAUSSES

Minor loop kilogausses	0	2000	4000	6000	8000	10,000	12,00
			Area squ	are inches			
1,000	0.29	0.30	0.35	0.43	0.52	0.70	1.00
2,000	0.94†	1.18†	1.03	1.25	1.55	2.10	..
3,000	1.71	1.83	2.01	2.39	3.00	3.58	..
4,000	2.81	2.86	3.17	3.50	4.10	..	..
5,000	3.96	4.08	4.35	4.68	5.70	..	..
6,000	5.48	5.57	5.87	6.05	..	..	..
7,000	6.90*	7.09	7.44	8.16	..	..	..
8,000	8.60	8.92	9.40	..	..	..	..
9,000	10.61*	10.84	10.90	..	..	..	..
10,000	12.96	13.04	..	..	..	..	..
11,000	15.6*	15.28	..	..	..	..	..
12,000	19.36	..	..	..	..	..	..
13,000	21.76	..	..	..	..	..	..

* Interpolated values.
†Values too high.

Relative Area of Hysteresis Loops for Various Displacements and Pulsating Inductions (½ Amplitude) Obtained with the Volt-Second-Meter Apparatus on a 3333-kv-a., Single-Phase, 50-Cycle, 110,000 to 15,240-Volt Transformer.

After the first minor loop was completed, the transformer core was put through the same minor nine times, keeping the maximum value of H and the amplitude of B constant. Complete readings were taken on the tenth minor loop. In general, the area of the tenth minor loop was slightly decreased from that of the first minor. The mean displacement changed only slightly. Fig. 24 shows an example. This is plotted on the assumption that the B displacement did not change at all.

The curves of Fig. 25 show the relation between area (hysteresis loss) and B ($\frac{1}{2}$ amplitude of pulsation) for various mean displacements.

The curves of Fig. 26 show the relation between the logarithm of the area (hysteresis loss) and the logarithm of B ($\frac{1}{2}$ amplitude of pulsation) of the minor loop for various displacements.

Fig. 27 shows the relation between the area of the loops

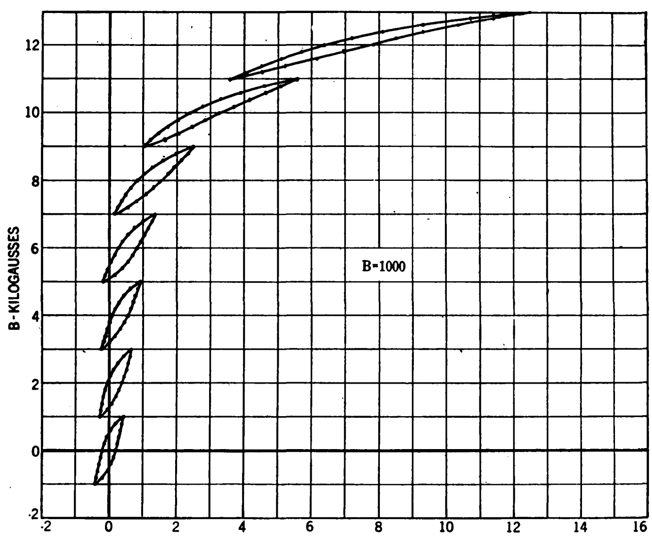


FIG. 8

(hysteresis loss) and displacement for various values of B ($\frac{1}{2}$ amplitude of pulsation).

Referring to the a-c. tests, the curves of Fig. 28 show the relation between displacement and 60-cycle displacement factor where $B = 1000$ ($\frac{1}{2}$ amplitude) and $B = 2000$ respectively for silicon and open-hearth sheet steel rings.

Discussion

The curves of Fig. 25 and Fig. 26 show that for each mean displacement the Steinmetz law expressing the relation between the induction and the hysteresis loss requires a different co-

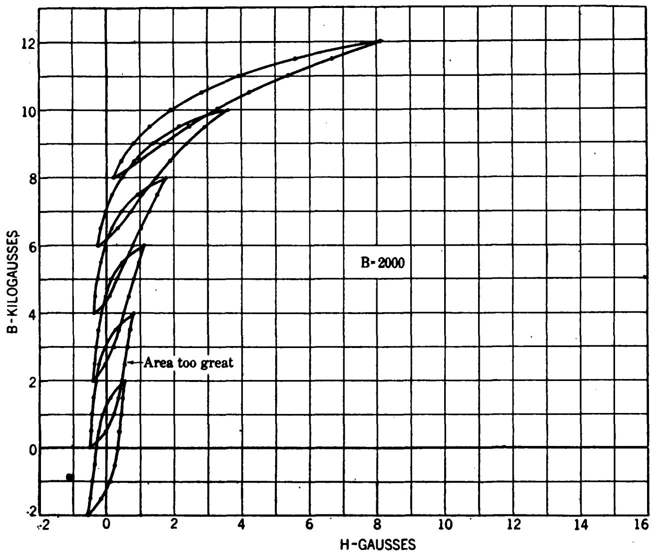

B-KILOGAUSSES
H-GAUSSES
B-2000
Area too great
12
10
8
6
4
2
0
-2
-2
0
2
4
6
8
10
12
14
16

FIG. 9

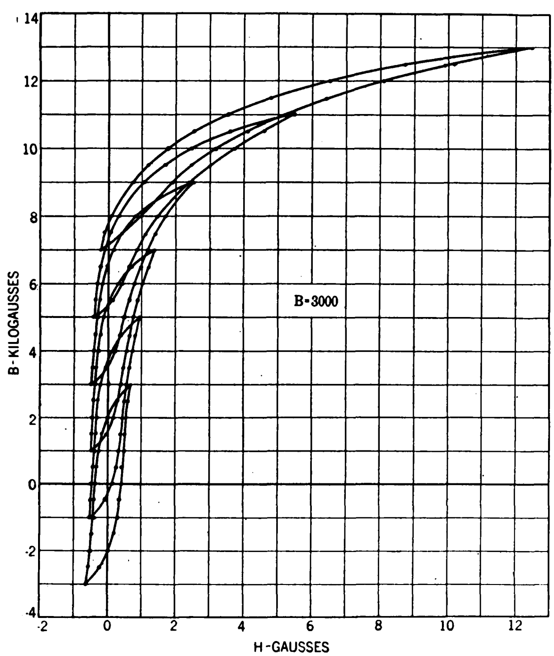

B-KILOGAUSSES
H-GAUSSES
B-3000
14
12
10
8
6
4
2
0
-2
-4
-2
0
2
4
6
8
10
12

FIG. 10

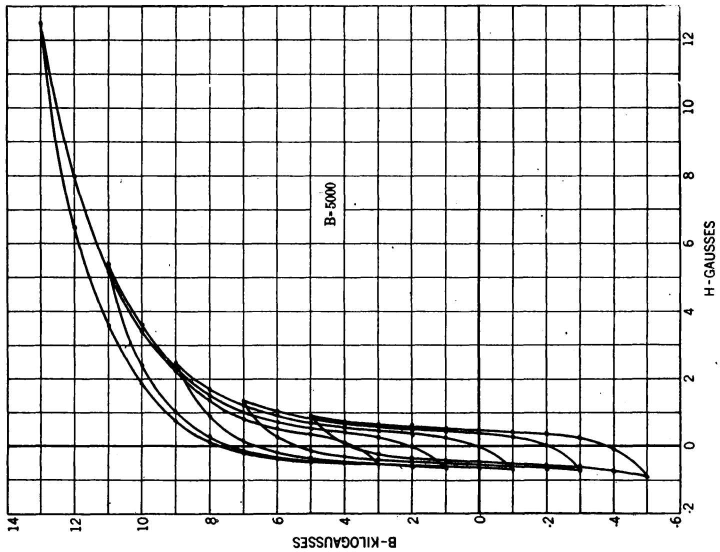

B=5000
B-KILOGAUSSES
H-GAUSSES

FIG. 12

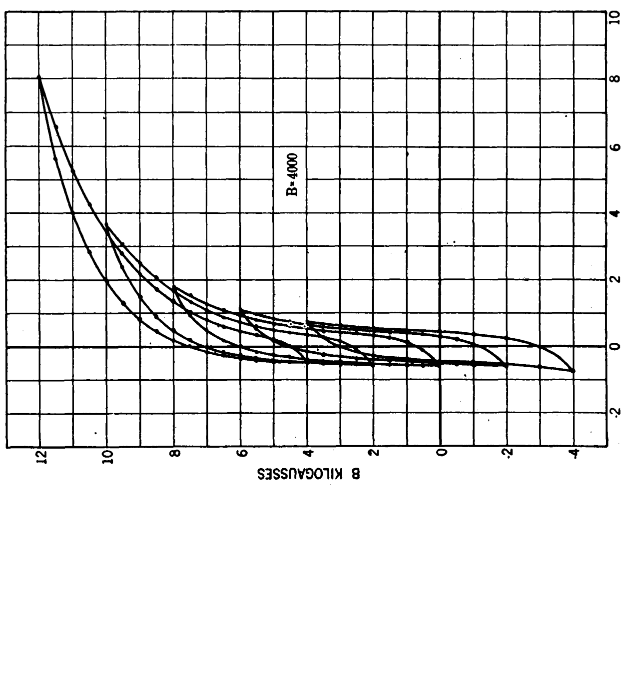

B=4000
B KILOGAUSSES
H-GAUSSES

FIG. 11

efficient and a different exponent. The coefficient increases very greatly with the displacement. The exponent, for a time, decreases and then later, apparently, slightly increases with increasing displacement. The points are so few for the high displacements, however, that this latter assumption is not at all certain. This condition of decreasing exponent with increasing displacement was noted from the early a-c. tests.

The curves of Fig. 27 indicate that at very high amplitude

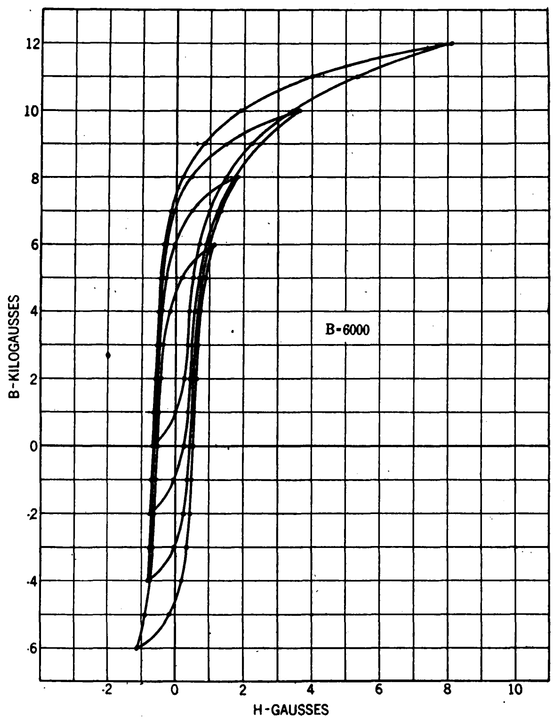


FIG. 13

the hysteresis loss decreases slightly with the displacement Holme* shows this same thing from his a-c. tests.

The curves of Fig. 28 for the a-c. tests show the interesting condition that at high displacements the loss increases less rapidly and in one case actually decreases. This effect would seem to be analogous to the decreased hysteresis loss at high inductions due to a rotating field and harmonizes somewhat

*F. Holme, *Zeitschrift des Vereines Deutscher Ingenieur*, Oct. 1912.

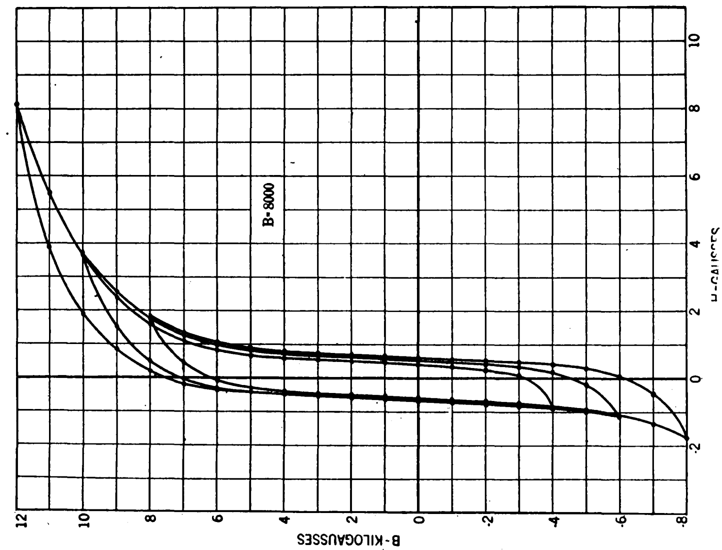

B=8000
B-KILOGAUSSES

FIG. 15

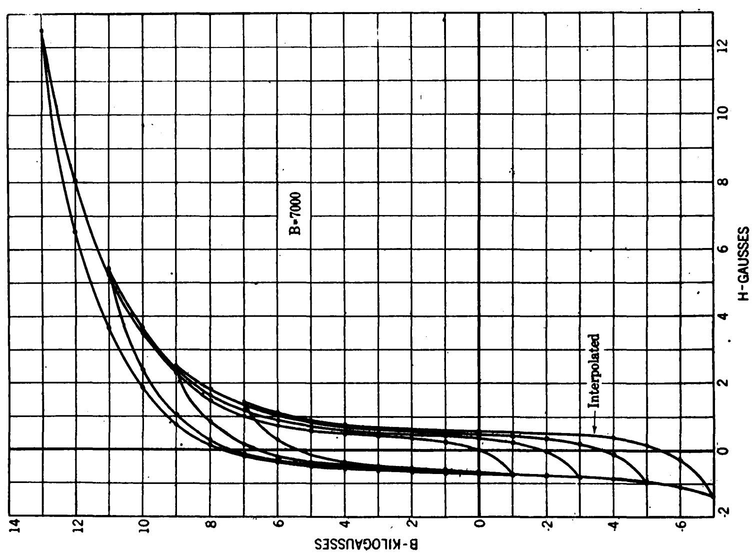

B=7000
Interpolated
H-GAUSSES
B-KILOGAUSSES

FIG. 14

with the commonly accepted theory of hysteresis loss. It is, unfortunately, not known whether or not the volt-second-meter data would have checked with the a-c. data in this respect, as the former tests were not carried to sufficiently high displacements at these amplitudes. This point could not be checked later, as the transformer was no longer available. A simialr effect is shown, however, in the case of the small displacement and the higher amplitudes. (See Fig. 27).

These a-c. curves do not show as high displacement factors at the high inductions as have been found in other tests. However, all known sources of error have been eliminated and we

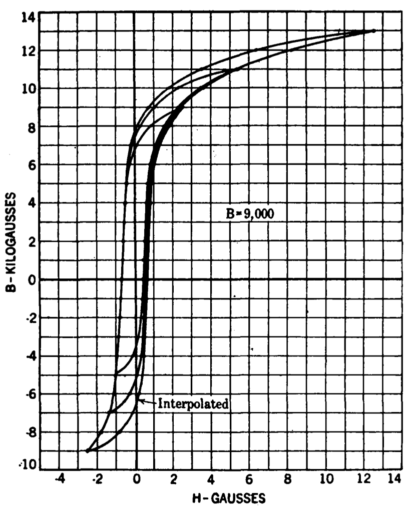


FIG. 16

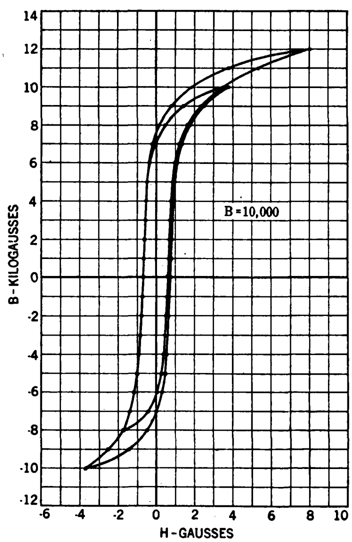


FIG. 17

see no reason to believe that the data are not correct for these particular samples. In addition to the hysteresis loss, there is present in these a-c. tests a small amount of eddy-current loss. This was found by test to be so small that no account has been taken of it in calculating the data for the curves of Fig. 28.

At the time the a-c. tests were made, oscillograms were taken. Due to lack of time, the data from these have not been included, but may be presented at a later date.

An attempt was made some months ago to determine, if possible, a relation between permeability and hysteresis loss for various displacements. Samples of widely different per-

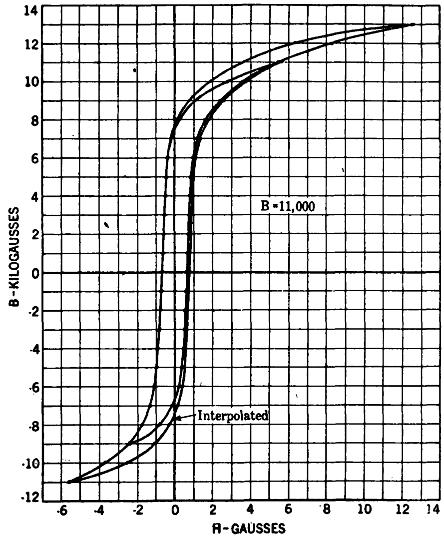

B-KILOGAUSSES
H-GAUSSES
B=11,000
Interpolated
14
12
10
8
6
4
2
0
-2
-4
-6
-8
-10
-12
-6
-4
-2
0
2
4
6
8
10
12
14

FIG. 18

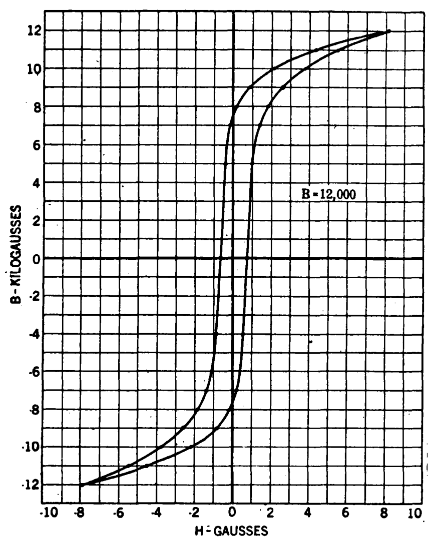

B-KILOGAUSSES
H-GAUSSES
B=12,000
12
10
8
6
4
2
0
-2
-4
-6
-8
-10
-12
-10
-8
-6
-4
-2
0
2
4
6
8
10

FIG. 19

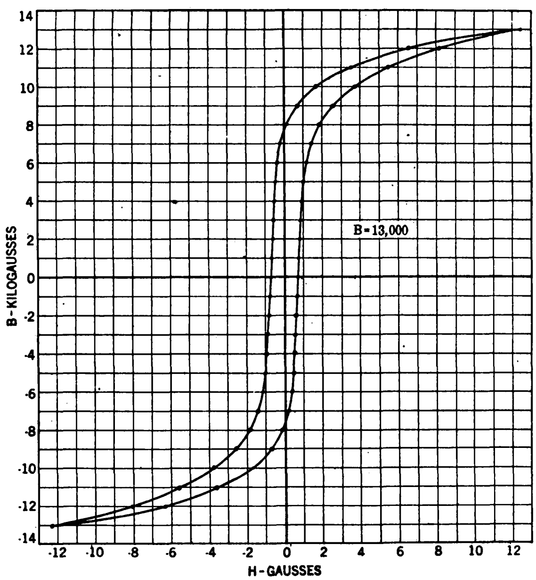


FIG. 20

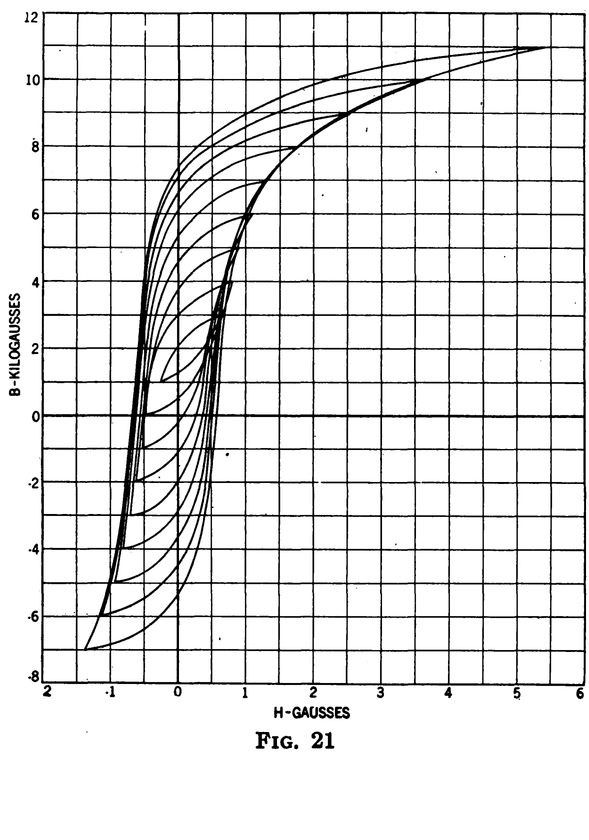


FIG. 21

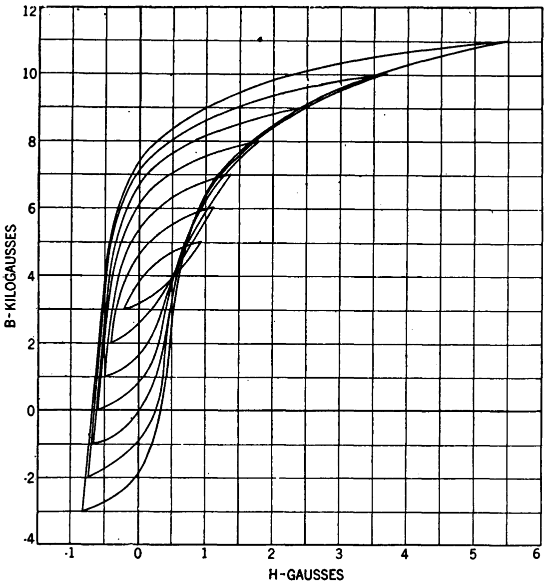

B-KILOGAUSSES
12
10
8
6
4
2
0
-2
-4
-1
0
1
2
3
4
5
6
H-GAUSSES

FIG. 22

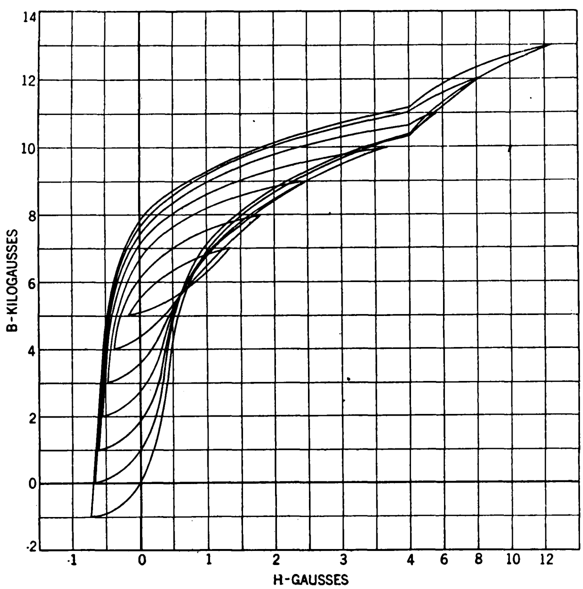

B-KILOGAUSSES
14
12
10
8
6
4
2
0
-2
-1
0
1
2
3
4
6
8
10
12
H-GAUSSES

FIG. 23

meabilities were obtained for this purpose, the resulting data for four of which are shown in Table II.

These data were obtained in an ordinary Epstein set with

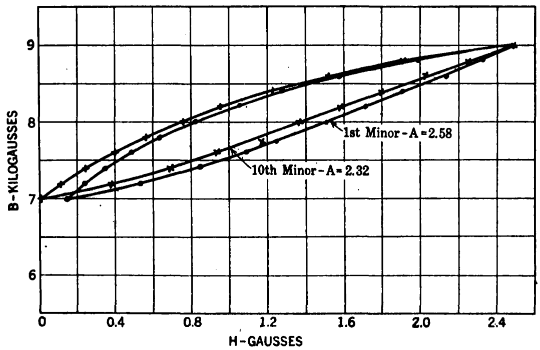


FIG. 24

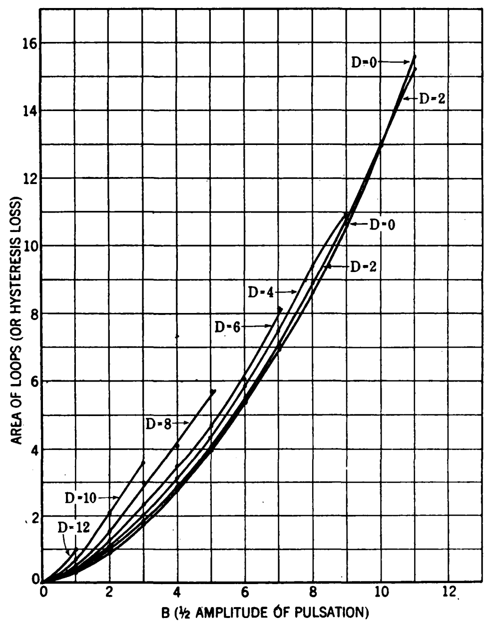


FIG. 25

Epstein samples cut with the grain lengthwise of the strips. The samples were silicon steel.

These data are not altogether consistent but there is a good indication that, with the high inductions, at least, the lower permeability steel gives the higher percentage increase of loss.

TABLE II.

Sample	Permeability		W_1	W_2	W_3	$D\ \frac{2}{10}$	$D\ \frac{2}{15}$
	$B = 10$	$B = 15$					
A	5490	674	100	188	830	1.88	8.30
D	5460	560	86	198	768	2.30	8.94
B	4880	405	90	190	926	2.11	10.30
C	4770	372	90	202	872	2.24	9.69

Where W_1 = undisplaced loss factor at $B = 2000$ and 180 cycles
W_2 = ditto with mean induction displaced 10,000 gausses.
W_3 = ditto with mean induction displaced 15,000 gausses.

$$D\frac{2}{10} = \frac{W_2}{W_1}$$

$$D\frac{2}{15} = \frac{W_3}{W_1}$$

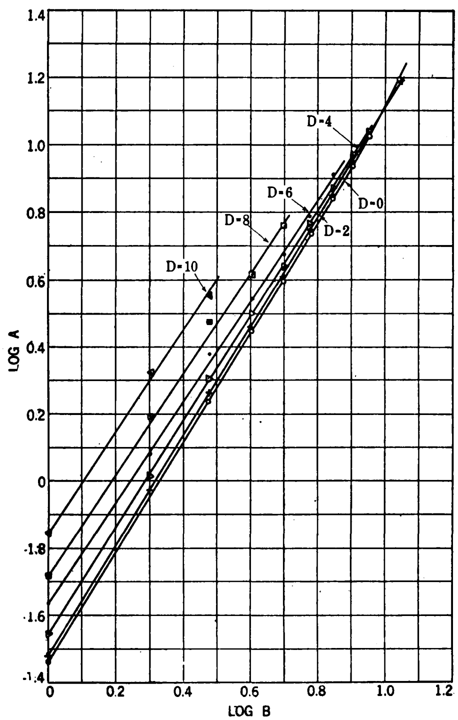


FIG. 26

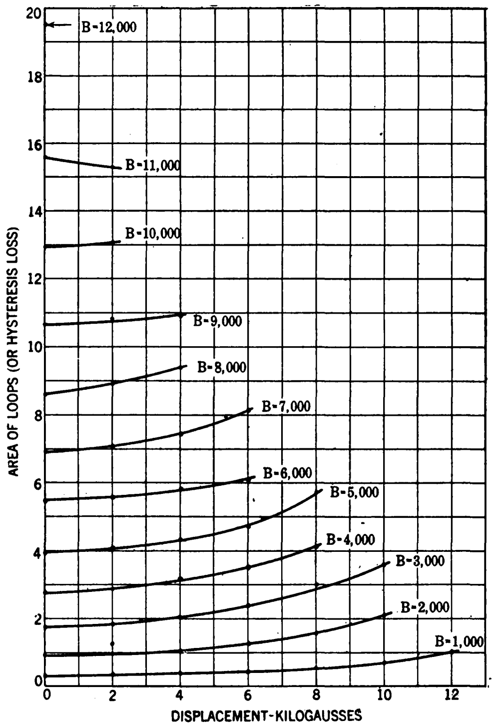

B-12,000
B-11,000
B-10,000
B-9,000
B-8,000
B-7,000
B-6,000
B-5,000
B-4,000
B-3,000
B-2,000
B-1,000
AREA OF LOOPS (OR HYSTERESIS LOSS)
DISPLACEMENT-KILOGAUSSES

FIG. 27

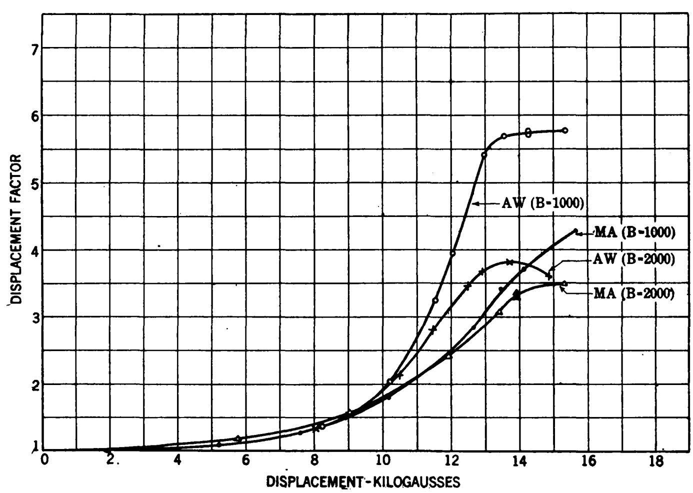

AW (B-1000)
MA (B-1000)
AW (B-2000)
MA (B-2000)
DISPLACEMENT FACTOR
DISPLACEMENT-KILOGAUSSES

FIG. 28

It should be noted that these displacement factors at $B = 15$ are higher than for the 60-cycle tests on the ring samples. This may be due to a variety of causes, such as frequency, direction of grain, phase displacements of wattmeter currents, and form factor for which no corrections were made in these 180-cycle tests. There is opportuntiy for considerable more investigation along this line, as the pulsation losses in electromagnetic machines are of great importance in some cases and their reduction depends upon a knowledge of their variation with frequency, displacement, permeability, direction of grain, heat treatment, and possibly other factors.

General Conclusions

1. The hysteresis loss in sheet steel does not follow the Steinmetz law when the material is unsymmetrically magnetized, since both the coefficient and exponent of the familiar equation $W = \eta \left(\frac{\Delta B}{2}\right)^{1 \cdot 6}$ are found to change with displacement.

2. The coefficient of the Steinmetz equation is increased by displacement.

3. The exponent of the Steinmetz equation is, in general, decreased with increase of displacement.

4. The displacement factor for silicon steel is greater than for open-hearth steel at moderate displacements.

5. The displacement factor for different samples varies greatly at the same values of pulsation and displacement, and the symmetrical loss alone is no indication of the displacement factor.

6. There is evidence that the displacement factor is a function of the permeability, at least at high displacements.

7. The great variations in the shape of the displacement-factor curves at and above saturation have made it impossible to derive satisfactory empirical equations from the data obtained.

8. A quick and accurate method of obtaining the data for hysteresis loops through any sequence of flux variation has been developed.

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