OVEREXCITED OPERATION

of

DISTRIBUTION TRANSFORMERS

Oregon State College

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By

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INTRODUCTION

This paper is the result of extensive experiments, investigating the effect on typical distribution transformers when operated overexcited as much as 117% of their rated voltage. Inasmuch as transformers are designed to provide the customer with 120/240 volts, or perhaps 240/480 volts, the question immediately arises as to the reason for 17% overexcitation; the answer follows:

The Portland General Electric Company employs, along with several three-phase primary systems, a 12,000 volt "wye" feeder network, which utilizes 12 KV transformers possessing four $2\frac{1}{2}$% taps below 12 KV and 7,200 volt transformers that have their taps set corresponding to the line-to-neutral 6,930 volts (taps set to 6,840 volts). This Company has found, for various and sundry reasons, it economically advantageous to increase its line voltage up to 12,900 volts which results in a line-to-neutral voltage slightly less than $3\frac{1}{2}$% above 7,200 volts. The problem, is what shall be done with the 12 KV transformers? These machines could still be used in three-phase banks by wye connecting their secondaries, setting taps to $92\frac{1}{2}$%, and impressing 12.9 KV upon them which results in 242/484 volts line to line -- an ideal power voltage, but requiring 16.2% overexcitation.[1]

1. In the event that the line voltage is raised to 12.6 KV, the taps may be set to 90% and the same power voltage obtained with 16.7% overexcitation.

PRELIMINARY CONSIDERATIONS

Three typical distribution transformers were loaned to Oregon State College, for the purpose of investigating overexcitation characteristics, by The Portland General Electric Company. These machines were made by three different manufacturers and all have the same ratings: 10 KVA, 12 KV with 4-$2\frac{1}{2}$% taps below 12 KV. Nameplate data appears in the Appendix. The manufacturers are General Electric (abbreviated G.E.), Westinghouse Electric (W.E.), and Allis-Chalmers (A.C.). This study was not conducted on a comparative basis, but instead to obtain an overall picture of the situation.

These transformers are modern; they possess grain-oriented silicon-steel cores; the G.E. machine is a "spirakore" speciman, the W.E. machine a "hypersil" make, and the A.C. transformer has a "curvacore" core. The "per unit" or "percentage" method of presenting test information is used freely in this paper, thus giving a more or less representative picture of a conglomeration of various transformers operating simultaneously on the three-phase system. The base volt-amperes (one per unit or 100%) is 10 KVA and one per unit voltage is that voltage corresponding to the specific tap setting. Precise instruments were utilized throughout all tests made and, where feasible, the same instruments were used in making identical tests on each transformer. Instruments and instrument corrections have been applied and appear in the Appendix.

Manufacturers of these machines were reluctant to divulge certain so-called confidential information regarding their transformer's construction and operation. Therefore, in the interest of curiosity and future reference, the following data was obtained by simple tests:

Polarity: These transformers exhibit standard subtractive polarity as stated on their nameplates and checked by the "inductive kick" method of test using a three volt battery and a d-c voltmeter.

Turns Ratio: A check was made against the turns ratios specified by the nameplates at individual tap settings, and the results (see Appendix) show that these ratios are exact to within the 0.5% guaranteed accuracy of the voltmeters and laboratory potential transformer used.

D-C Resistance: The resistancesof the 12 KV coils in each transformer were measured by the ordinary Wheatstone bridge method, and the resistances of the 240 volt coils were obtained by use of the Kelvin bridge. All measurements have been corrected in the Appendix for 100% tap settings and 75° C. obtaining the following values:

A. C. Transformer:	(12 KV coil resistance equals	137.21 ohms
	(240 volt coil resistance equals	0.04637 ohm
G. E. Transformer:	(12 KV coil resistance equals	133.81 ohms
	(240 volt coil resistance equals	0.05854 ohm
W. E. Transformer:	(12 KV coil resistance equals	147.34 ohms
	(240 volt coil resistance equals	0.04741 ohm

Weights: A platform scale, having a 0-500 pound range and estimated accuracy of 2%, was used in weighing each transformer complete with oil.

A. C. Transformer weight complete, is 272.0 pounds.

W. E. Transformer weight complete, is 262.4 pounds.

G. E. Transformer weight complete, is 268.0 pounds.

It is well to note that these weights are gross contradictions to the same quantities given by Portland General Electric Company on their transformer slip, which appears in the Appendix.

During the course of the experiments, the G.E. machine was dismantled and the core and coil assembly weighed at 138 pounds. With the core extracted, the oil depth was measured at 14 3/8" and the inside diameter of the circular case is 14.0"; thus, the volume of oil was calculated: 9.6 gallons. With the aid of two graduated 1,000 milliliter cylinders and a balance obtained from the Chemistry department, the specific gravity of the transformer oil in the G. E. machine was measured by comparing it to tap water; specific gravity equals 0.864. The weight of oil can then be calculated to be 69.0 pounds. This leaves 61.0 pounds for the weight of the case, cover and bushings.

Actual Number of Turns on the G. E. Transformer:

A forty-turn winding of #26 wire was wound directly on the core of the G. E. transformer for the purpose of obtaining the actual number of turns in the primary and secondary windings. With approximately 900 volts impressed on the 12 KV coil and held constant, a vacuum-tube voltmeter having a 0-10 volt range was used to measure 4.10 volts on the forty-turn coil, 8.90 volts and 9.00 volts respectively, on each of the 120 volt coils. Since a vacuum-tube voltmeter does not impose a load on the small #26 wire coil, the actual number of turns on the secondary, 240 volt coil can be determined to be 175 turns. The 12 KV coil must then be composed of at least 8,750 turns, and perhaps a few less to account for resistance and leakage-reactance voltage drops. In general, we may assume that there are approximately 0.73 turns per volt for transformers of this type.

There are 186 laminations of continuous spiral core 4.00" wide and 0.015" thick comprising this core of the G. E. machine. From the previous data, the rated maximum flux density in the core of the transformer might be approximated by using the familiar equation,

$$(1) \qquad E_{rms} = 4.44\ fNAB_{max}$$

$$240 = (4.44)\ (60)(175)(7.2 \times 10^{-3}\ \text{meter}^{2})B_{max})$$

$$\text{Rated} \quad B_{max} = 0.715\ \text{weber/square meter}$$

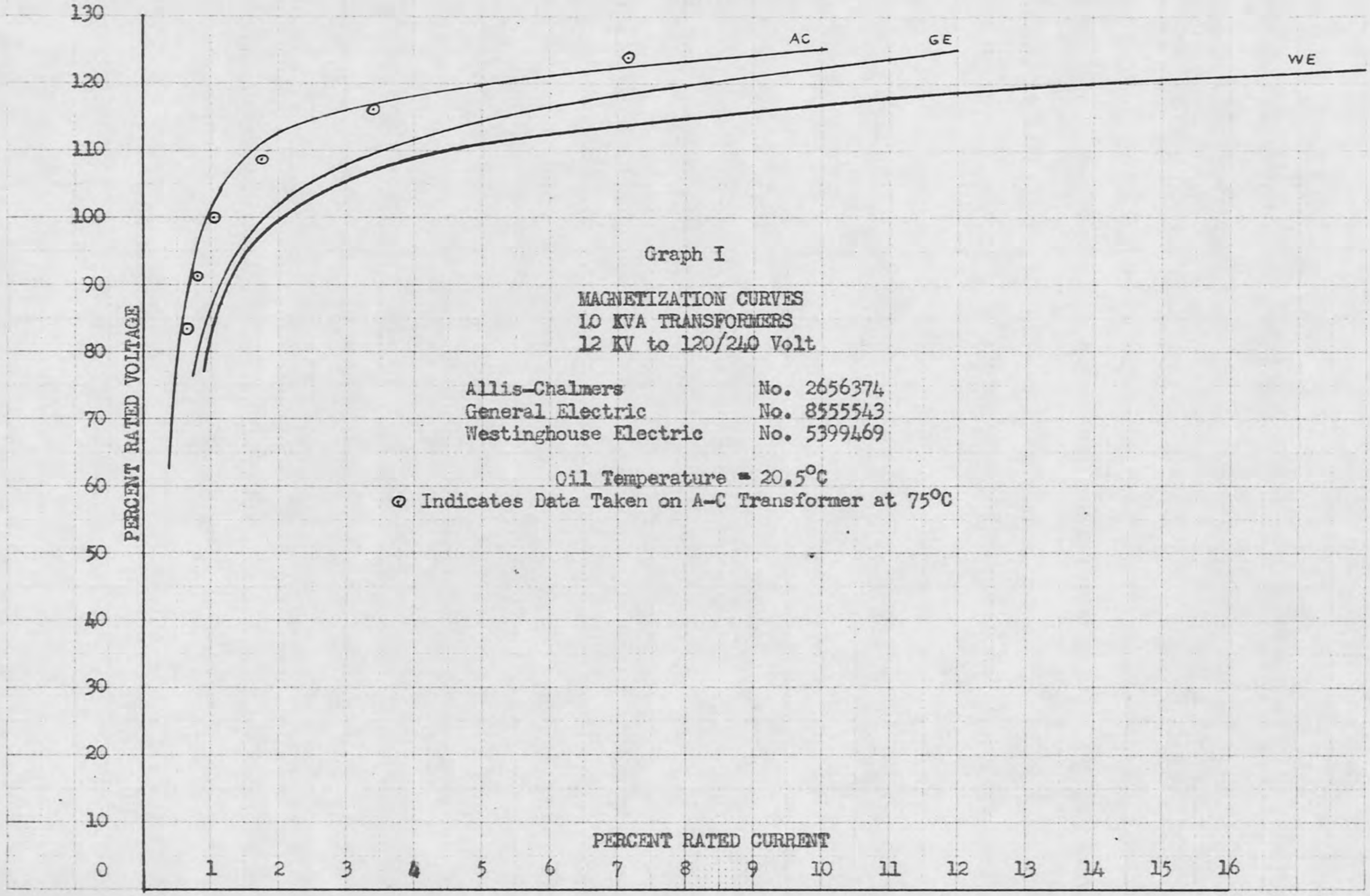
$$= 46{,}200\ \text{lines/square inch}$$

$$= 7.15\ \text{kilogauss.}$$

This calculated amplitude of the rated flux density appears much too low to this author; a B_{max} ranging somewhere between 11 and 14 kilogauss would be more reasonable. Two reasons may be given for the discrepancy: 1. In any continuous spiral core, each single line of flux must necessarily cross an air gap between the laminations. This fact would necessitate the flux to crowd into that portion of the core having the largest stacking factor which, incidentally, for a spirakore make, is inherently small. 2. Upon examining the core, it was noticed that the so-called continuous spiral was not continuous but possessed many (20 or 30) breaks, as if it were wound from 20 or 30 separate sheets of metal. This fact, coupled with the previous one, would obviously require the effective area of the core to be much less than that which was measured, resulting in a more reasonable maximum flux density.

NO-LOAD SATURATION CHARACTERISTICS

Perhaps the most important and prominent change incurred when operating a distribution transformer overexcited is the increase in exciting current. Graph I, page 6, illustrates the magnetization current for all three transformers taken as a function of terminal voltage up to 125% excitation. This data was obtained by exciting the machines from the 240 volt coils and leaving the 12 KV coils open-circuited with one bushing, the case, and the center tap solidly grounded.



AC
GE
WE
130
120
110
100
90
80
70
60
50
40
30
20
10
0
PERCENT RATED VOLTAGE
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
PERCENT RATED CURRENT
Graph I
MAGNETIZATION CURVES
10 KVA TRANSFORMERS
12 KV to 120/240 Volt
Allis-Chalmers No. 2656374
General Electric No. 8555543
Westinghouse Electric No. 5399469
Oil Temperature = 20.5°C
⊙ Indicates Data Taken on A-C Transformer at 75°C

From Graph I, Table 1 was prepared showing the percentage increase in rms exciting current with 116.7% voltage applied. Later in this

Table I

Transformer	Percent Exciting Current 100% Voltage	Percent Exciting Current 116.7% Voltage	Percent Increase of Exciting Current
A. C.	0.99%	3.56%	260%
G. E.	1.85%	6.10%	230%
W. E.	2.08%	9.90%	376%

paper, it will be shown that the change in phase angles of each machine between rated and overexcited voltage is such that the data of Table 1 cannot be averaged--directly. Taking phase angles into account, the actual average increase in exciting current is 300%. Five points are given on Graph I illustrating the excitation current of the AC transformer operating at 75° C. These points show the temperature effect on magnetizing current to be negligible.

TELEPHONE INTERFERENCE

The curves of Graph I illustrate a typical characteristic of grain-oriented silicon steel; they exhibit sharp "knees", and since each transformer's core is shown to operate on the knee of the saturation curve, then overexcitation is bound to result in extremely non-sinusoidal exciting current giving rise to inductive interference on communication circuits that parallel the 12 KV feeder lines.

Current telephone influence factor (TIF) is a measure of the tendency of a current wave to produce interference or "noise" in a paralleled telephone line; TIF of a current wave is defined as the ratio of the square root of the sum of the squares of the weighted effective values of each sine wave component (including both fundamental and harmonic) to the effective value of the wave. The TIF of a single harmonic depends upon its frequency and is "weighted" accordingly, a harmonic whose frequency is in the middle of the voice range being given a much heavier weighting than a 60 cycle or 180 cycle harmonic. Thus, while TIF is a function of frequency only, the actual interference is proportional to the product of TIF and the rms magnitude of each harmonic current in amperes comprising a current wave. Suffice it to say here that the prime interest in this study is the actual relative amounts of interference, between 100% voltage excitation and 116.7% excitation, due to the non-sinusoidal current flowing in a primary line feeding a single transformer, while the telephone influence factor itself is of secondary importance.

The overall interference of a current wave is proportional to the product of rms current (measured with a simple ammeter) and the effective TIF of the whole wave. In other words,

(2) $$\text{Interference} \sim (I)(TIF)$$

The Pacific Telephone and Telegraph Company loaned to O. S. C. a 2-B Noise Measuring Set equipped with a Current Coupler which they use to measure TIF or interference directly. This set is equipped with two frequency-weighting networks, one which corresponds to the 1935 TIF-frequency curve which is available in the Westinghouse Transmission and Distribution Reference Book, page 757. The other weighting network corresponds to the 1941 weighting curve which is applicable to more modern telephone equipment. This curve is available from P. T. and T.

From the operating instructions provided with the instrument, the following two equations are applicable to the tests made.

(3) $$(I)(TIF_{35}) = 10^{\left[\frac{R_{35} - 13.3}{20}\right]}$$

(4) $$(I)(TIF_{41}) = 10^{\left[\frac{R_{41} - 6.6}{20}\right]}$$

(Exponents)

where I = rms exciting current in amperes.

TIF_{35} = telephone influence factor corresponding to the 1935 frequency-weighting curve.

R_{35} = instrument reading in decibels with the 1935 weighting network in use.

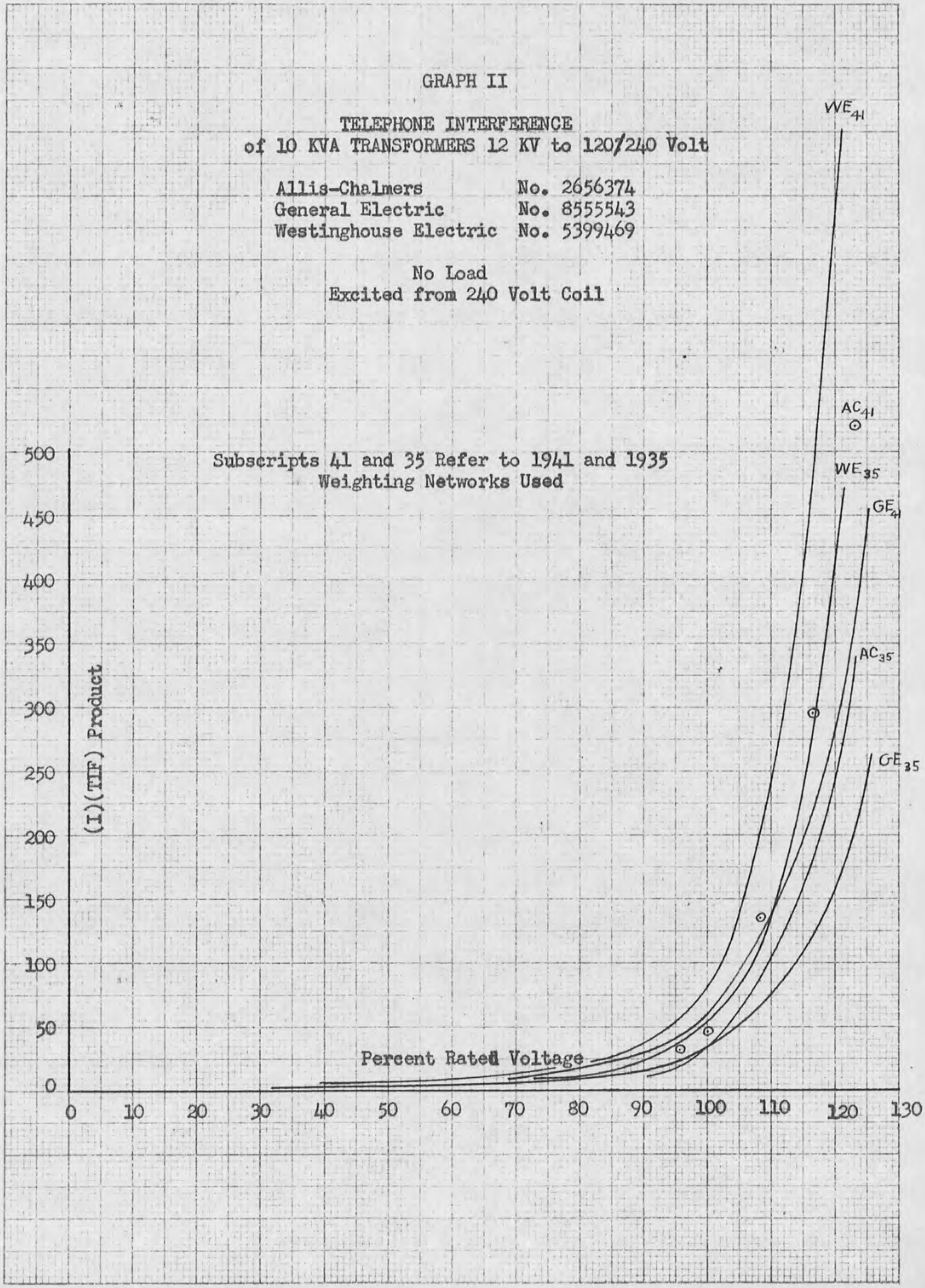
TIF_{41} = telephone influence factor corresponding to the 1941 frequency-weighting curve.

R_{41} = instrument reading in decibels with the 1941 weighting network in use.

Tests were conducted using the noise-measuring set and current coupler connected in series with an ammeter located in the lines feeding the low side of each transformer with the high-voltage coil open circuited. The excitation voltage was taken from a variable autotransformer fed by Mountain States Power Company. Thus, the voltage wave form used should be identical to that of Portland General Electric Company's. Results of these tests, corrected by equations 3 and 4, are illustrated on Graph II, page 10, and tabulated in Table 2.

Table 2

	(Current)(TIF) Products					
	1935 Weighting		1941 Weighting			
Transformer	100% Volts	116.7% Volts	100% Volts	116.7% Volts	Percent Increase 1935	Percent Increase 1941
G. E.	39	123	60	220	215%	267%
A. C.	40	183	47	295	265%	527%
W. E.	54	287	80	458	432%	507%


GRAPH II
TELEPHONE INTERFERENCE
of 10 KVA TRANSFORMERS 12 KV to 120/240 Volt
Allis-Chalmers No. 2656374
General Electric No. 8555543
Westinghouse Electric No. 5399469
No Load
Excited from 240 Volt Coil
Subscripts 41 and 35 Refer to 1941 and 1935
Weighting Networks Used
(I)(TIF) Product
Percent Rated Voltage
WE41
AC41
WE35
GE41
AC35
GE35
0
50
100
150
200
250
300
350
400
450
500
0
10
20
30
40
50
60
70
80
90
100
110
120
130

The percent increase in interference as given by Table 2 appears very serious. However, one should consider the multitude of factors that affect the interference produced by a system. For instance, the data taken was conducted on a single-phase basis, and these transformers must be installed in closed delta banks in order to achieve the proper secondary voltage. Thus the balanced third, ninth, fifteenth, etc. harmonics could not flow in the feeder lines. Residual currents will, unfortunately, be present. Other major considerations are, of course, the geometrical configuration of the distribution system, the specific location of the transformers, the relative number of over-excited machines compared with the 7,200 volt transformer, the KVA rating of each bank, etc, and the possibility that even if the interference increased five times, the resultant effect may still be insignificant. Apparently, the only practical method of determining the extent of telephone interference is to install the transformers and hope that there will be no objections.

POWER LOSSES

Obviously, a major consequence of overexciting transformers will be a boost in energy consumption and, owing to a transformer's inherent non-linearity, this power loss can be obtained accurately by direct measurement only. Graph III, page 12, illustrates this loss for each transformer, and comparisons are tabulated in Table 3. Notice the individual points given on the AC machine with its temperature raised to 75^{o} C and the resulting small reduction in power loss. This effect is attributed to an increase in the resistance to the flow of eddy currents; it is considered insignificant in this paper.

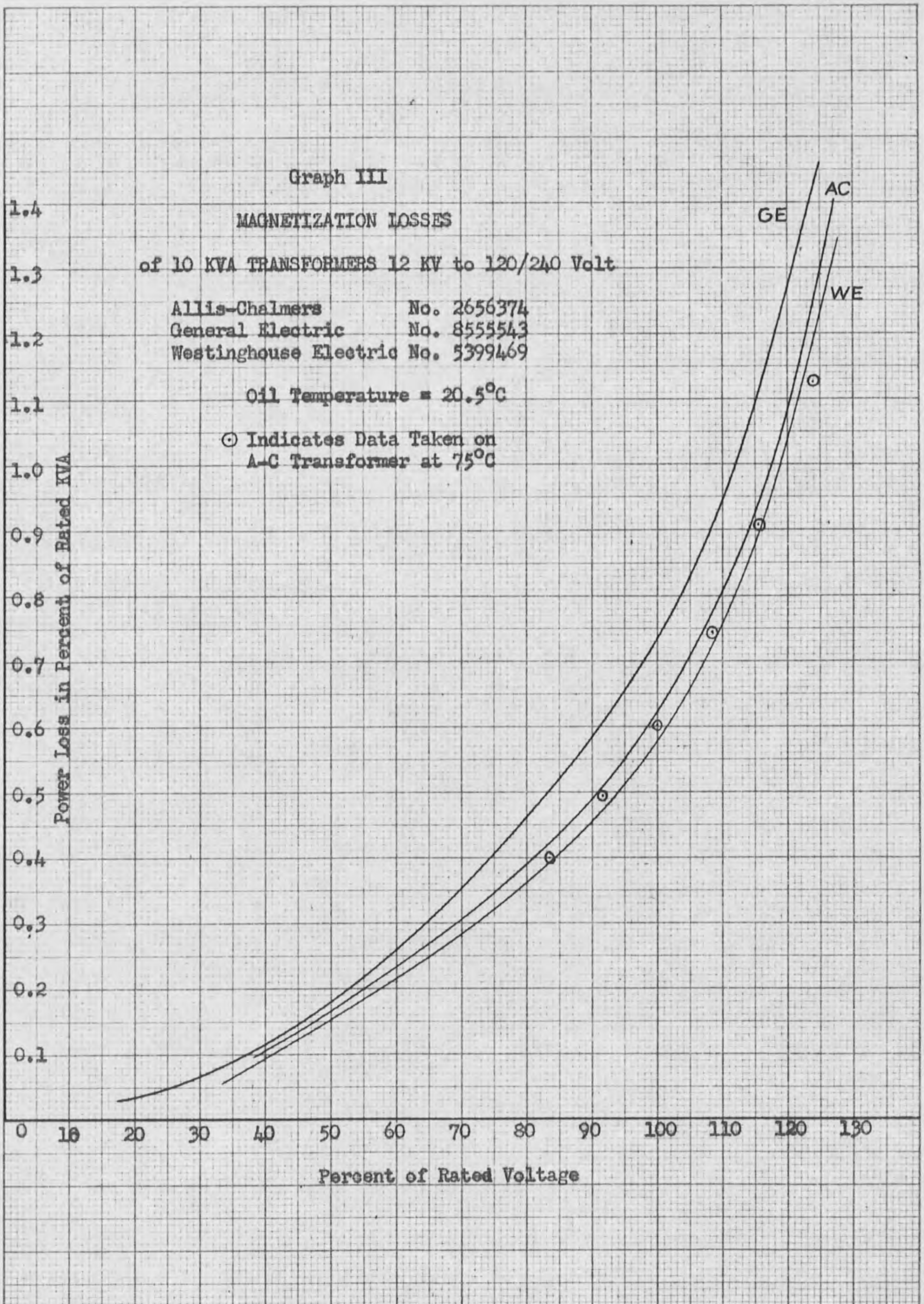

Graph III
MAGNETIZATION LOSSES
of 10 KVA TRANSFORMERS 12 KV to 120/240 Volt
Allis-Chalmers No. 2656374
General Electric No. 8555543
Westinghouse Electric No. 5399469
Oil Temperature = 20.5°C
⊙ Indicates Data Taken on A-C Transformer at 75°C
GE
AC
WE
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
10
20
30
40
50
60
70
80
90
100
110
120
130
Power Loss in Percent of Rated KVA
Percent of Rated Voltage

Table 3

Magnetization Power Loss [1]

in Percent of Rated KVA

Transformer	100% Voltage	116.7% Voltage	Percent Increase in Power Loss
W. E.	0.577	0.930	61.2%
A. C.	0.623	0.975	56.5%
G. E.	0.735	1.150	56.5%

Copper loss was also measured on all three transformers at 20.5°C and is illustrated on Graph IV, page 14. The curve of copper losses for the AC machine at 75°C shows the anticipated increase with higher temperature. These curves were obtained by short-circuiting the transformer secondary and measuring input, primary quantities. The data taken during the open and short-circuit tests reveal that the effective impedance presented to the primary winding is about 2,000 times greater on open circuit than it is on short circuit. Therefore, it is permissible to stipulate that all data taken on open circuit are characteristics of the core only and all data obtained under short circuit are characteristics of the windings only. For instance, at 14,000 volts, the Westinghouse transformer, with taps set to 100%, draws 83.3 milliamperes of exciting current which causes a primary winding loss of $(0.0833)^2$ (147.34) or 1.02 watts; the actual loss measured under open circuit is 93.0 watts. It is, therefore, concluded that overexcitation will have no effect on copper or winding loss.

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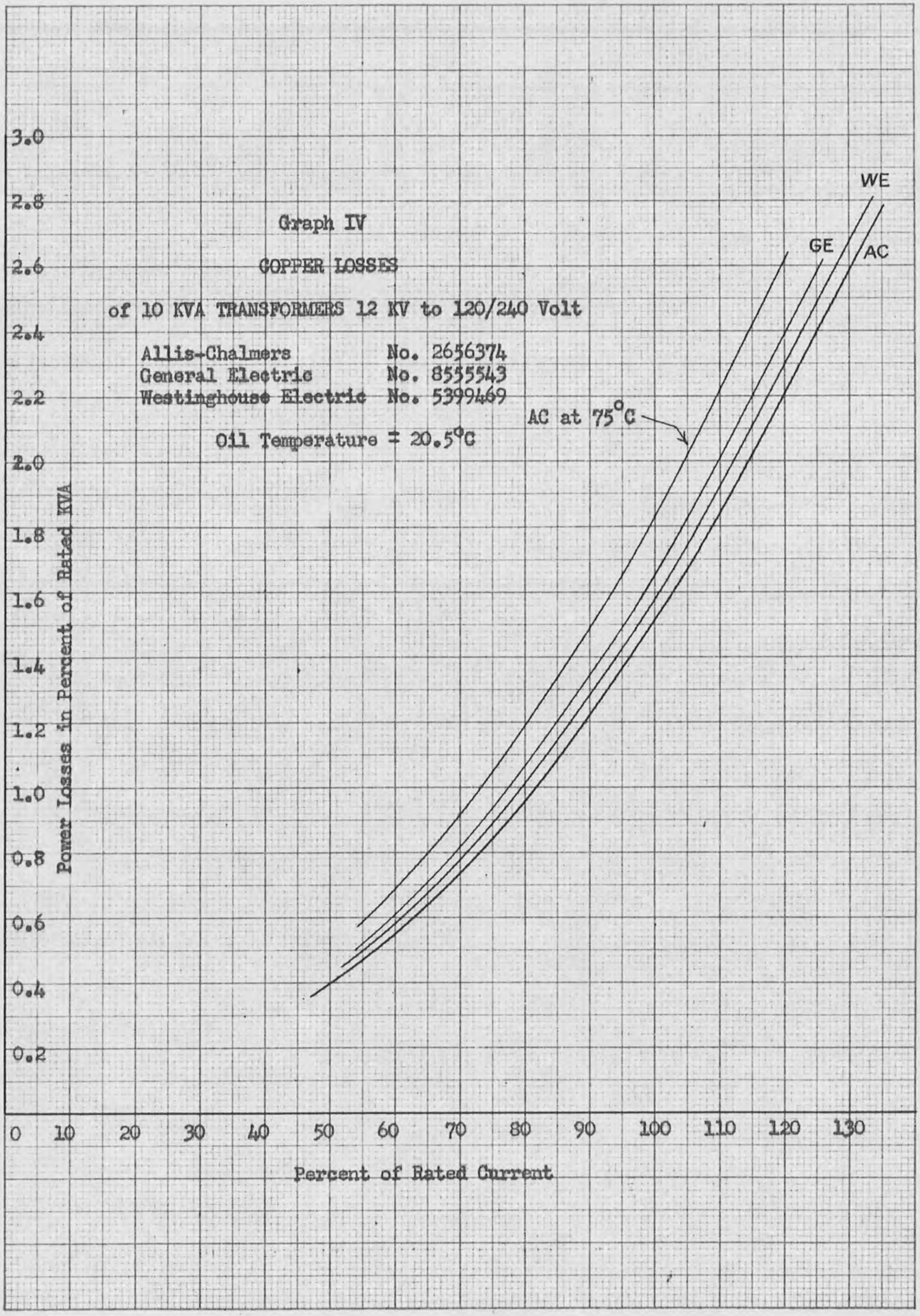
1 The amount of losses due to hysteresis and eddy currents, respectively, have been given thorough investigation for all three transformers. See Appendix.



Graph IV
COPPER LOSSES
of 10 KVA TRANSFORMERS 12 KV to 120/240 Volt
Allis-Chalmers No. 2656374
General Electric No. 8555543
Westinghouse Electric No. 5399469
Oil Temperature = 20.5°C
AC at 75°C
WE
GE
AC
Power Losses in Percent of Rated KVA
Percent of Rated Current
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
2.6
2.8
3.0
0
10
20
30
40
50
60
70
80
90
100
110
120
130

LOAD LOSS

Transformers that will be operated according to the manufacturer's KVA rating but in excess of the KV rating must necessarily pass less than rated current. The more or less indirect effect of overexcitation then will be a reduction in copper losses that will tend to counteract the increase in core loss. For this particular study, the copper loss will decrease 23% providing the transformers maintain the same 10KVA load (calculated in Appendix). Table 4 was compiled from Graphs III and IV, taking into consideration 75°C resistance, the decrease of load current, and the change of tap settings.

Table 4

10 KVA Load Loss at 75°C

in Percent of Rated KVA.

	Taps set 100% 100% Voltage			Taps set 92.5% 116.7% Voltage			
Transformer	Core Loss	Copper Loss	Total	Core Loss	Copper Loss	Total	% DECREASE in Load Loss
W. E.	0.577	1.91	2.49	0.930	1.47	2.40	3.61%
A. C.	0.623	1.83	2.45	0.975	1.41	2.39	2.45%
G. E.	0.735	2.00	2.74	1.150	1.54	2.69	1.82%

The ratio of copper to core loss is about 3/1, and since copper losses decrease substantially, the resultant rise in load losses was not a rise at all; it actually decreased! Consider the increase in the daily energy loss, assuming 8 hours of operation at full load and 16 hours no load. (These transformers must be power installations.) The average load loss at 100% voltage for the three machines tested will be 2.05 KWH. No load loss will be 1.03 KWH. At 117.6% excitation, load loss would drop to only 1.99 KWH and no-load energy consumption to 1.63 KWH per day's time. The final result is that the increase in the daily energy consumption between 100% excitation and 116.7% excitation will be 17.5% for the transformers alone. The actual 12 KV system may hardly be affected.

POWER FACTOR

Using the data of Table 3 and Table 1, the no-load power factors of each machine were computed, and with these values, given by Table 5,

Table 5

No-Load Power Factor (Lagging)

Transformer	100% Voltage	116.7% Voltage
W. E.	27.7%	8.1%
A. C.	63.0%	23.5%
G. E.	39.7%	16.2%

the effective, average increase in exciting current for the three machines was computed (see page 7). At rated voltage, the average exciting current for these transformers is 13.6 milliamperes at a power factor of 0.396. At 116.7% voltage, the average exciting current is 54.2 milliamperes at 0.134 power factor. Under this basis, it would take 1,850 KVA of overexcited transformers to draw 10 amperes of exciting current.

The power factor of a machine under load, of course, depends upon the load power factor and the machine's impedance which does not undergo any appreciable change with excitation. The impedances as measured under short-circuit test are listed in Table 6 and are in approximate agreement with those given by the manufacturers.

Table 6

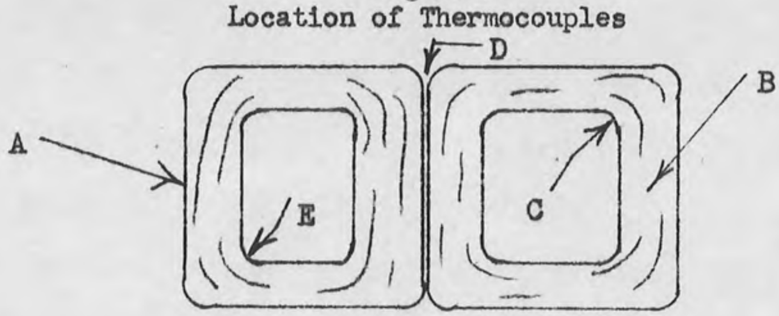
Transformer	75°C Impedance: Taps set 100%
A. C.	2.68%/47.3°
G. E.	2.91%/46.5°
W. E.	2.58%/42.3°

CORE HEATING

Up to this point, the transformers have been given an examination from a more or less external standpoint. A major effect of overexcited operation will be, perhaps, a substantial if not serious increase in the operating temperature. A study was conducted on the General Electric machine only (assuming the other transformers to perform reasonably the same) in an effort to make accurate measurements of ultimate core temperatures as a function of loading at various excitations.

The G. E. machine was dismantled, its core extracted, and five copper-constantan thermocouples were inserted between the laminations at various locations illustrated in Figure 1. The winding encloses the center legs. After doing this, the transformer was reassembled, positioned on four-inch wooden blocks and located in a closed room where

Figure 1
Location of Thermocouples



G. E. Transformer Core

ambient temperature did not undergo wide fluxuations. In measuring the minute potentials developed across the thermocouples, the most accurate apparatus available was utilized: a Leeds and Northrup Student Potentiometer, a Weston Standard Cell, a Rubicon Galvanometer, and L. and N. Standard Conversion Tables for copper-constantan thermocouples; reference junction was 0°C (ice-water mixture). The "pump-back" method of loading was chosen, using the Allis-Chalmers transformer. Results of this test are tabulated in Table 7.

Table 7

Ultimate Core Temperature of G. E. Transformer

Excitation	Loading	Average Temperature of 5 Positions (Figure 1)	Hot-Spot Temperature Location C (Figure 1)	Ambient Temperature
100% Voltage (Taps set 12 KV)	No Load	38.5°C	39.0°C	21.0°C
125% Voltage (Taps set 12 KV)	No Load	51.1°C	52.8°C	19.8°C
100% Voltage (Taps set 12 KV)	10 KVA Load (Rated)	63.9°C	65.8°C	20.0°C
125% Voltage (Taps set 12 KV)	12.5 KVA Load (100% Current)	78.4°C	81.4°C	23.0°C
116.2% Voltage (Taps set 11.1 KV)	10.45 KVA Load (90% Current)	67.4°C	69.6°C	22.0°C

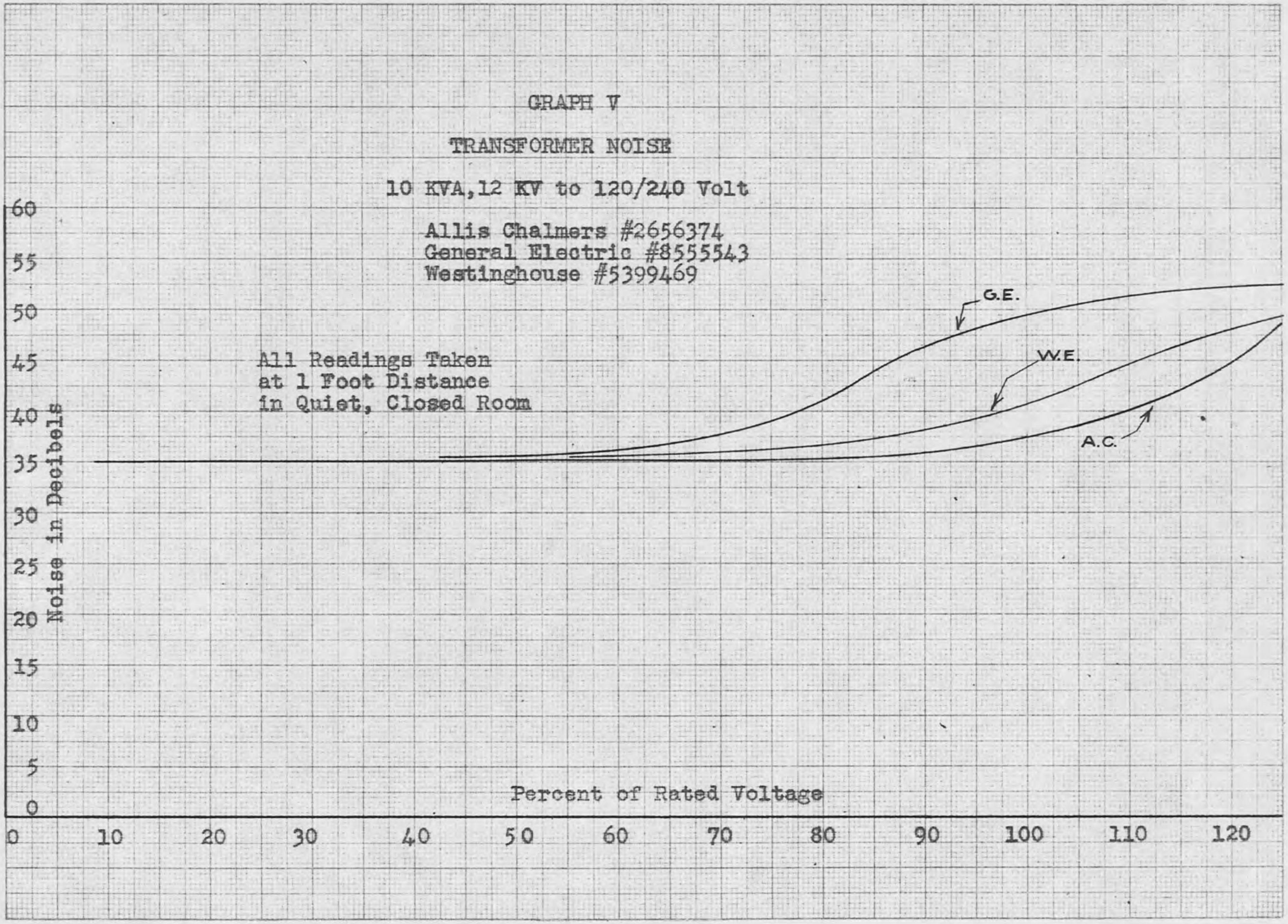
Nameplate data for this machine states a 55°C rise in a 20°C ambient, and Table 7 proves that this transformer, operating with slightly more than rated load at 116.2% excitation, is still more than

5^{o} C under the rating with even a 22^{o} C ambient. Of course, ambient temperatures may approach 32^{o} C (90^{o}F), but this will be infrequent in the Portland area. The conclusion drawn from analysis at Table 7 is that these transformers will not suffer serious overheating, and therefore, oil sludging, insulation damage, and core aging have not been investigated in this study. Incidentally, core aging has been almost eliminated by the addition of silicon to transformer metal.

NOISE

All transformers have some degree of 120 cycle hum, or noise associated with them. Inasmuch as the vibration causing this hum is primarily due to magnetostriction which in turn, is affected by flux density or impressed voltage, it was thought appropriate to investigate these 10 KVA transformers to determine whether or not the increase in noise might incite objections.

A General Radio Type 759-A sound-level meter (Standards approved) was used in measuring the noise emanating from each transformer as a function of impressed voltage. The microphone of the instrument was located midway between the top and bottom of the transformers, one foot away, and eight readings were taken at each voltage setting around the transformer. These readings were averaged and plotted as illustrated by Graph V, page 20. More specific details of the testing method are available in the Appendix. The ambient noise level was constant in the closed, sound-absorbent room used, because the tests were made from 2:00 to 5:00 A.M. when the building was not normally in use.


GRAPH V
TRANSFORMER NOISE
10 KVA, 12 KV to 120/240 Volt
Allis Chalmers #2656374
General Electric #8555543
Westinghouse #5399469
All Readings Taken
at 1 Foot Distance
in Quiet, Closed Room
G.E.
W.E.
A.C.
Noise in Decibels
0
5
10
15
20
25
30
35
40
45
50
55
60
Percent of Rated Voltage
0
10
20
30
40
50
60
70
80
90
100
110
120

The following noise levels, reprinted from the Allis-Chalmers Transformer Reference Book, are listed so as to obtain a comparison with Graph V:

MEASUREMENTS AT THREE FEET

Threshold of Hearing....................	0 db
Whisper................................	14 db
Country Roadside.......................	28 db
Average Dwelling.......................	35 db
Vacuum Cleaner.........................	49 db
Average Office.........................	50 db
Ordinary Conversation..................	56 db
Average Automobile.....................	60 db
Motor Truck............................	70 db
Typewriter.............................	71 db
Heavy Street Traffic...................	90 db
Riveting Machine.......................	96 db
Automobile Horn........................	100 db
Airplane Engine........................	110 db
Threshold of Feeling...................	120 db

Fortunately, at 100% voltage, the transformers' vibrations are already appreciable according to Graph V so that overexcitation does not cause as much increase. Between 100% and 116.7% voltage, the G. E. machine increased 2.5 decibels; the W. E. machine, 6.5 decibels, and the A. C. transformer, 5.5 decibels. The average increase is 4.8 decibels and with a 35 decibel ambient, amounts to 39.8 decibels of noise. The same instrument used to make the test was taken to an average Corvallis neighborhood and a 42 decibel reading was recorded at 1:00 P.M. If two identical noise-producing devices can be considered point sources, then their combined noise will be 3 decibels higher than one device by itself. Considering this, and the fact that all measurements were taken at only one foot from the transformer, add the probability that since these transformers must be power banks and therefore generally installed in noisier neighborhoods, then the only conclusion to draw from this study is that there will likely be few if any complaints against overexcited transformers making more noise than is normal.

SUMMARY

It was convenient and effective to summarize the foregoing study in tabulated form as is shown on page 23. This tabulation is applicable to the average of the three transformers tested and gives all important factors or changes in operation when the machines' taps were reduced from 100% to 92.5% and the impressed voltage increased from 12,000 volts to 12,900 volts. The rated, 10 KVA (not rated current) load remains constant.

Transformer: Average of three Unidentical 10 KVA, 12,000 Volt Machines	
Load	10 KVA
Taps	Changed from 100% to 92.5
Voltage	Changed from 12,000 to 12,900 Volts
Exciting Current	Increased 300%
Telephone Interference	Difficult to Estimate (See Page 7)
Magnetization loss	Increased 58%
Copper loss	Decreased Approximately 23%
Load loss	Decreased Approximately 2.6%
Daily Energy loss	Increased Approximately 17.5%
Power Factor	(No-load) Decreased from 0.396 to 0.134
Core Temperature	Increased Approximately 6% (See Page 18)
Noise	Increased 12% (In a very quiet Ambient)

CONCLUSION

Inasmuch as core temperature will not be serious according to this study, the transformer itself will not suffer appreciable damage. In view of the Summary, and providing the actual ratio of overexcited transformers to normally excited transformers is reasonably small, this author believes there will be no appreciable effect on the 12 KV system. Therefore, it would be permissible to operate these machines as anticipated <u>if</u> one may assume that this study is applicable to a multitude of various make-and-rating machines and providing these transformers shall not be overloaded.

A P P E N D I X

(Indluding Separation of Core Losses)

NAME PLATE DATA

Portland General Electric Co. No. 4958-10
General Electric Co.
Single-Phase; Type HS, Form W2, Frequency, 60 cps Sub. Pol.
No. 8555543, KVA10, Continuous 55°C rise
Voltage Rating 12000 volts-120/240 v
Taps: 100% rated, 97½%, 95%, 92½%, 90%
Approximate Impedance at Rated Volts, 75°C 2.9%
SPIRAKORE TRANSFORMER

Portland General Electric Co. No. 10800-10
Allis Chalmers
KVA 10, 55°C Rise, Serial No. 2656374
Type CBS, 60 cps, 11 gal oil, 2.7% Impedance at 75°C
Single-Phase, Subtractive Polarity, DBPC, Total Wt. Lbs
Voltage 12,000 volts-120/240 volts
Taps; 100%, 975%, 92.5%, 95%, 90%
CURVACORE TRANSFORMER

Portland General Electric Co. No. 7590-10
10KVA, 55oC Rise, Serial 5399469, 12000 Volts-120/240 Volts
Taps: 100%, 97.5%, 95%, 92.5%, 90%
Westinghouse Electric Corp.
75oC Impedance 2.4% Single Phase, 60 cps
Cat. No. 5090-001 Style 1191184-C
S-HYPERSIL TRANSFORMER, Subtractive Polarity

INSTRUMENTS

A . . . . . Westinghouse Type PC-137 current transformer
Style 1001033-B, 4453570, Compensated for 5 volt-amps
1000, 100, 50, 25, 10 to 5 amps, 25 to 133 cycles

B . . . . . 0-150-300 volt G. E. voltmeter. No. 3320366 Type P-3
25°C Resistance: (150v) 2026.5 ohm, (300v) 4054, 7 ohm
Self Inductance (mean), 0.067 Henry Electrodynamic Inst.
Accuracy 0.2% Full Scale Tested March 7, 1950

C . . . . . Potential transformer 2000, 1000, to 100 volts No. 116930
15 watt, Style No. 10442A 25 cps, Westinghouse Elec. Co.

D . . . . . 0-150-300 volt G. E. Voltmeter #3219291 Type P-3
25°C Resistance (150v) 1985.3 ohm, (300) 3970.3 ohm
Self Inductance 0,067 Henry (mean)
Accuracy 0.2% Full Scale Tested Jan. 18, 1949

E . . . . . Ammeter 0-5 amp. No. 3320349 General Electric Type P-3
Resistance at 25°C 0.06 ohm Self Inductance (9) (10^{-5}) Henry
Iron Vane, Accuracy 0.2% full scale Tested Dec. 12, 1949

F . . . . . G. E. A-C Ammeter 0-1.5/3.0 amps Accuracy 0.5% full scale
Iron Vane, Type P_3 No. 540069

G . . . . . G. E. Single Phase Wattmeter, Type P-3, No. 3217510
Amp 5/10, Volts 100/200, Watts 150/300/600
Resistance 25°C (100)2370 ohm, (200v) 4741 ohm

H . . . . . G. E. A-C Voltmeter Type P-3 0-300-750 volts #598915
Accuracy 0.4% full scale: Resistance,
300 volt, 7914,2 ohm: 750 volt, 19040.0 ohm

I . . . . . Sylvania Oscilloscope

J . . . . . 0-500 lb Platform Scale M. E. Lab. No. 4730

K . . . . . General Radio Type 759-A Sound Level Meter

L . . . . . Wattmeter, Compensating Type, used for making frequency test.
Number not recorded

PORTLAND GENERAL ELECTRIC CO. Transformer Slip
(Duplicated)

Transformer No.	4958-10	10800-10	7591-10
Manufacturer	G.E. Co.	A.C. Co.	W.E.M. Co.
Serial No.	8555543	2656374	5399469
Capacity	10 KVA	10 KVA	10 KVA
Type-Polarity	HS SUB	SUB	S SUB
Form or Style % Imp	W2F 2.9	2CB 2.7	2CB 2.4
	12000	12000	12000
	11700	11700	11700
Primary Voltages	11400	11400	11400
	11100	11100	11100
	10800	10800	10800
Secondary Voltages	120	120	120
	240	240	240
Cut in on primary tap			
Cut in on secondary tap			
Ratio Adjuster	Yes	Yes	Yes
Primary fuse			
Drawing No.	Name Plate	Name Plate	On Plate
Dimensions over all	30-19-19	40-20-26	35-22-19
Weight with oil	350 lbs	450 lbs	300 lbs
Gallons of oil	12 Gal	17 Gal	12 Gal
Load			
Location			

VOLTAGE RATIO TESTS AT VARIOUS TAP SETTINGS

Impressed voltage on high side of transformers at all tap settings is constant at 2600 volts; measured with B and C where B reads 130.0 volts and C set 20/1. Instrument D used to hold high side voltage constant thereafter.

MEASUREMENTS

TRANSFORMER	TAP SETTINGS				
	100%	97½%	95%	92½%	90%
	Volts measured with instrument B. (240 volt coil)				
G.E.	51.2	52.4	53.9	55.5	57.0
A.C.	51.1	52.4	54.0	55.4	57.0
W.E.	51.1	52.5	54.0	55.4	57.0

DIRECT-CURRENT RESISTANCE MEASUREMENTS

Low side measured by Kelvin Bridge; high side by Wheatstone Bridge.

A.C.	Low side; (0.07590) (0.5) ohms	
	High side; 101.05 ohms	Taps set 90%
	Temperature, 18.8°C	
G.E.	Low side; (0.09557) (0.5) ohms	
	High side; 98.31 ohms	Taps set 90%
	Temperature, 18.2°C	
W.E.	Low side; (0.07740) (0.5) ohms	
	High side; 108.25 ohms	Taps set 90%
	Temperature, 18.2°C	

To correct for 75°C multiply by $\left(\frac{234.5 + 75}{234.5 + \text{Temp.}}\right)$

To correct high side for 100% tap setting multiply by $\left(\frac{100}{90}\right)$.

CALCULATION OF 23% DECREASE IN COPPER LOSS WHEN 10 KVA, 12000 VOLT TRANSFORMER WITH TAPS SET TO 12000 VOLTS IS CHANGED FROM 10 KVA LOAD AT 12000 VOLTS TO 10 KVA LOAD AT 12900 VOLTS WITH TAPS SET TO 11100 VOLTS.

Assume that resistance seen by primary is equal to primary resistance with taps set to 100% (a-c resistance).

If "I" is primary current and "R" is primary resistance, then the loss before the change is...

(A.) I^2R loss equals $\left(\frac{10000^2}{12000}\right)(2R)$.

After the change,

(B.) loss equals $\left(\frac{10000}{12900}\right)^2 (0.925R+0.925^2R)$

(C.) equals $\left(\frac{10000}{12900}\right)^2 (0.925)(1.925R)$

$\frac{A}{C}$ equals $\left(\frac{12.9}{12.0}\right)^2 \left(\frac{2}{0.925+1.925}\right)$

equals 1.3

or,

$\frac{C}{A}$ equals $\frac{77\%}{100\%}$

In other words, the loss has decreased 23%.

NOISE TESTS ON TRANSFORMERS

Location: Illumination laboratory. Dearborn Hall.

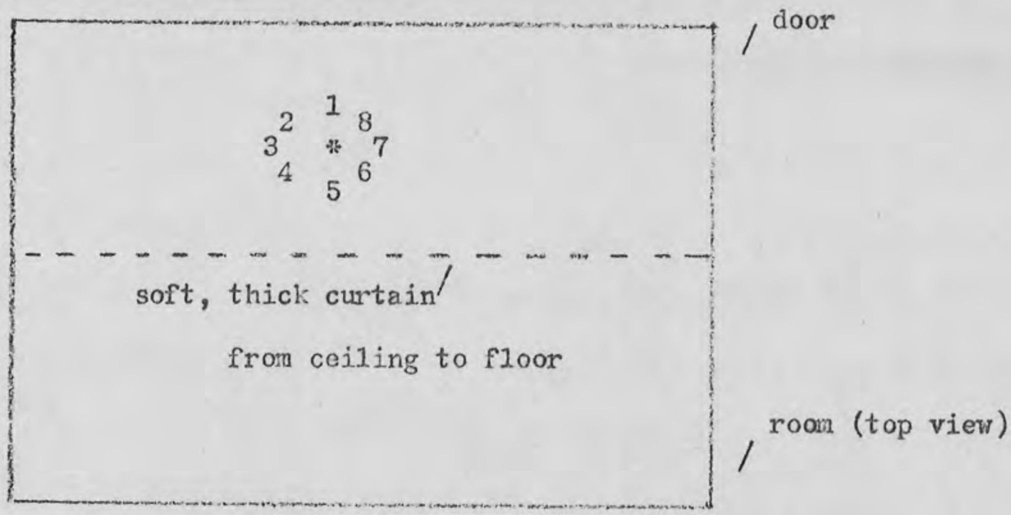
This room has a sound absorbent ceiling, concrete floor, and plaster walls. It is approximately 34 ft. long and 32 ft. wide.

The transformer was located at position * on a thick rug, with the secondary side facing the upper right-hand corner of the room.

Measurements were taken at positions 1, 2, 3, 4, 5, 6, 7, 8, for each voltage setting. 240 volt coil used.

This room is on first floor and shop generators were operating in basement which kept ambient sound relatively high, but constant.

Time: early morning.



MEASUREMENTS

A.C. Position	Reading	G.E. Position	Reading	W.E. Position	Reading
Volts, 0		Volts, 0		Volts, 0	
1	35.2 db	1	35.0 db	1	35.3 db
2	36.0	2	35.5	2	35.5
3	35.5	3	35.5	3	35.0
4	35.0	4	35.5	4	35.0
5	34.8	5	35.0	5	34.5
6	34.8	6	35.0	6	34.9
7	34.5	7	34.7	7	35.0
8	35.0	8	34.9	8	35.5
Volts, 50		Volts, 170		Volts, 220	
1	36.0	1	38.3	1	39.8
2	36.0	2	36.5	2	41.0
3	35.0	3	36.5	3	38.5
4	35.0	4	36.2	4	35.3
5	34.5	5	36.8	5	38.0
6	34.8	6	37.5	6	38.9
7	34.5	7	39.0	7	39.5
8	?	8	39.5	8	38.3
Volts, 100		Volts, 210		Volts, 260	
1	35.0	1	46.7	1	42.2
2	35.4	2	41.5	2	44.3
3	34.9	3	42.2	3	45.5
4	34.9	4	42.9	4	42.0
5	34.5	5	45.5	5	42.0
6	35.5	6	46.4	6	44.0
7	34.8	7	48.4	7	46.0
8	35.0	8	48.8	8	45.0

NOISE-continued

A.C.

Volts, 150	
1	35.2 db
2	35.5
3	35.3
4	35.8
5	35.0
6	34.8
7	34.5
8	35.0

Volts, 200	
1	35.3
2	36.5
3	35.3
4	35.0
5	36.5
6	35.0
7	34.8
8	35.0

Volts, 240	
1	38.8
2	40.5
3	40.8
4	40.2
5	39.7
6	39.4
7	37.0
8	38.0

Volts, 275	
1	40.5
2	42.0
3	43.5
4	42.5
5	41.5
6	41.0
7	39.0
8	40.3

Volts, 300	
1	49.0
2	49.2
3	47.2
4	48.5
5	52.0
6	49.0
7	47.0
8	48.3

G.E.

Volts, 240	
1	51.0 db
2	44.5
3	46.8
4	48.3
5	51.8
6	52.7
7	53.8
8	53.0

Volts, 275	
1	50.2
2	47.5
3	43.0
4	49.9
5	54.0
6	53.0
7	53.6
8	52.5

Volts, 300	
1	54.2
2	49.9
3	48.5
4	43.8
5	56.4
6	53.4
7	53.0
8	54.5

W.E.

Volts, 298	
1	48.0 db
2	47.9
3	50.5
4	47.0
5	49.0
6	47.5
7	49.0
8	52.2

TEMPERATURE TEST OF G.E. TRANSFORMER

Location: High Voltage Laboratory, Dearborn Hall.
Location of thermocouples: See text.

MEASUREMENTS

(Excited with rated voltage 5:00 PM 1-13-54)

1-16-54

Time	Thermocouples	Millivolts	Temperature	
1:PM	A	1,472	36.8°C	
	B	1.532	38.0	
	C	1.564	39.0	Ambient
	D	1.515	37.5	20.0°C
	E	1.440	36.0	

CHECK: Thermometer, 32.2°C ---------- Thermometer, 0°C
Potentiometer, 1.290 mv, 32.25°C ---------- Potentiometer, 0.032 mv, 0.05°C

(excited with 125% voltage 3:PM 1-16-54)

1-18-54

9:30 AM
CHECK: Thermometer, 26.4°C
Potentiometer, 1.025 mv, 26°C

Time	Thermocouples	Millivolts	Temperature	
9:30 AM	A	1.944	47.8°C	
	B	2.000	49.2	
	C	2.075	51.0	Ambient
	D	1.972	48.5	19.4°C
	E	1.923	47.3	

1-19-54

Time	Thermocouples	Millivolts	Temperature	
9:50 AM	A	2.022	49.8°C	
	B	2.067	50.7	
	C	2.128	52.1	Ambient
	D	2.059	50.5	20.0°C
	E	2.006	49.5	

1-20-54

Time	Thermocouples	Millivolts	Temperature	
9:30 AM	A	2.039	50.2°C	
	B	2.113	51.8	
	C	2.147	52.8	Ambient
	D	2.092	51.2	19.8°C
	E	2.018	49.5	

(excited with 125% volts and loaded with 100% current)

1-21-54

Time	Thermocouples	Millivolts	Temperature	
3:30 PM	A	3.112	74.6°C	
	B	3.270	78.0	
	C	3.341	79.6	Ambient
	D	3.138	75.1	22.5°C
	E	3.124	74.9	

1-22-54

Time	Thermocouples	Millivolts	Temperature	
5:PM	A	3.227	77.0°C	
	B	3.334	79.4	
	C	3.418	81.4	Ambient
	D	3.299	78.8	23.0°C
	E	3.166	75.6	

(escited with 100% volts and loaded with 100% current)

TEMPERATURE TEST - continued

	1-25-54				
9:30 AM					
	A		2.537 mv	61.6°C	
	B		2.653	64.2	
	C		2.724	65.8	Ambient
	D		2.627	63.8	20.0°C
	E		2.474	60.0	

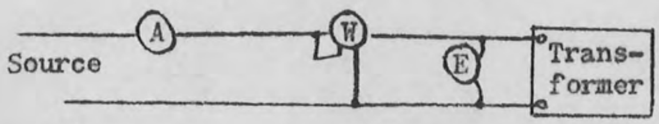
1-26-54

(transformer taps changed from 12000 volts to 11100 volts; impressed voltage on secondary set to 279 volts which corresponds to 12900 volts on primary (116.2% rated). Primary current set to 90% (810 ma) which means the transformer has a 10450 volt-ampere load, and should give approximately the same loss as operating at rated with taps set to 100%.)

11:PM	1-27-54				
	A		2.734 mv	66.1°C	
	B-		2.815	67.9	
	C		2.887	69.6	Ambient
	D		2.772	66.8	22.5°C
	E		2.680	64.8	

OPEN (HIGH SIDE OPEN) AND SHORT (LOW SIDE SHORTED) CIRCUITED TESTS

General Circuit



In the columns of data appearing on the next two pages there are instrument letters given with subscrips which denote changes of potential coils.

For making corrections, the following equations were used:

$$\text{True Power, } P = W - \frac{E^2}{R_W} - \frac{E^2}{R_V}$$

$$\text{True Current, } I = \sqrt{A^2 - E^2\left(\frac{1}{R_W} + \frac{1}{R_V}\right)^2 - 2W\left(\frac{1}{R_W} + \frac{1}{R_V}\right)}$$

SHORT-CIRCUIT MEASUREMENTS

A.C.

E, volts	A, amps	W, watts
B_1	F_1	G_1
131.0	0.450	44.9
150.0	0.512	58.2
B_2		
175	0.565	72.8
200	0.648	95.0
		G_2
225	0.698	109.6
250	0.775	135.0
275	0.852	163.0
300	0.930	193.8
H_2		
325	0.955	206.2
350	1.032	240.4
375	1.109	278.4
388	1.159	300.0
	Temp. 22.6°C	

G.E.

E, volts	A, amps	W, watts
B_2	F_1	G_1
150	0.460	51.5
175	0.535	70.7
		G_2
225	0.650	104.2
250	0.723	128.8
275	0.796	154.6
300	0.867	184.6
H_2		
325	0.889	195.6
350	0.962	227.8
375	1.032	262.0
400	1.105	300.0
	Temp. 20.0°C	

W.E.

E, volts	A, amps	W, watts
B_2	F_1	G_1
150	0.520	60.2
175	0.601	81.9
B_2		G_2
225	0.738	124.2
250	0.819	152.4
275	0.898	184.6
300	0.979	219.0
H_2		
365	1.145	300.0
350	1.095	274.2
325	1.006	235.8
	Temp. 20.0°C	

OPEN-CIRCUIT DATA (measurements)

G.E.

E, volts	A, amps	W, watts
B_1	F_1	G_1
57.8	0.10	7.5
86.2	0.20	17.0
134.9	0.30	39.8
B		
183.5	0.40	63.8
		G_2
210.0	0.50	76.0
225.0	0.60	76.0
231.5	0.70	93.0
235.0	0.75	95.6
240.0	0.805	100.0
250.0	0.99	109.0
263.9	1.50	127.0
	F_2	
270.0	1.80	135.0
284.5	3.00	160.0
	E	
290.0	3.75	172.0
300.0	5.00	192.0

Temp. 21°C

A.C.

E, volts	A, amps	W, watts
B_1	F_1	G_1
50.0	0.10	5.4
93.9	0.20	18.9
150.0	0.30	45.5
B		
215.8	0.40	79.5
		G_2
225.0	0.399	77.0
230.0	0.415	80.0
235.0	0.442	83.8
240.0	0.471	88.0
245.0	0.510	92.0
250.0	0.566	98.0
260.0	0.745	108.0
270.0	1.45	119.6
279.0	1.50	131.6
290.0	2.55	150.0
	E	
300.0	4.06	170.8

Temp. 20.9°C

W.E.

E, volts	A, amps	W, watts
B_1	F_1	G_1
37.0	0.10	2.9
61.0	0.20	7.7
103.5	0.30	21.1
142.5	0.40	38.9
B_2		
182.5	0.500	54.5
		G_2
223.5	0700	70.1
230.0	0.759	76.0
209.5	0.600	62.0
240.0	0.900	84.0
250.0	1.130	93.0
258.0	1.500	102.4
	F_2	
270.0	2.55	116.4
	E	
273.0	3.00	120.4
280.0	4.15	129.6
284.4	5.00	136.0
	E: A_1	G_2 : A_1
290.0	6.64	147.2
300.0	9.68	164.0

Temp. 19.5°C

OPEN-CIRCUIT DATA ON A.C. TRANSFORMER AT 75°C AND SHORT-CIRCUIT DATA

D-C Resistance:
High Side, 138.73 ohms Taps set 100%
Low side, (0.5)(0.09377) ohms

OPEN-CIRCUIT

E, volts	A, amps	W, watts
B_2	F_1	G_2
200	0.314	58.2
220	0.372	71.6
240	0.490	86.4
260	0.753	105.6
278	1.425	126.0
297.5	3.000	153.0
	F_2	

SHORT-CIRCUIT

E, volts	A, amps	W, watts
H_2	F_1	G_2
386	1.068	300.0
375	1.038	242.0
350	0.963	245.0
325	0.890	205.6
300	0.825	180.2
B_2		
275	0.795	166.4
250	0.722	166.4
225	0.650	112.0
200	0.580	89.2

TRANSFORMER TELEPHONE INTERFERENCE DATA

240 volt coil used; instrument B used to measure impressed voltage with high side open circuited.

Db Noise Measuring Set.No. 2-B Serial 88788 connected in shunt with Current Coupler 101863 C.O.E. connected in series with 240 volt winding. These instruments loaned by Pacific Telephone and Telegraph Co., Portland, Oregon.

K_1 and K_3 switches set to normal. "Plug" in "line" jack.
Instrument calibrated beginning of each test.
Column 144 refers 1935 response curve weighting network.
Column FIA refers to 1941 response curve weighting network.

Applicable equations (see text).

$$R_{35} - 13.3 = 20 \log(I)(TIF_{35}) \text{ db}$$

$$R_{41} - 6.6 = 20 \log(I)(TIF_{41}) \text{ db}$$

MEASUREMENTS

	G.E.			W.E.			A.C.	
Volts	db	db	Volts	db	db	Volts	db	db
100	24.5	21.2	100	25.6	22.0	100	20.6	18.8
125	26.6	23.2	125	27.7	24.0	125	21.7	19.8
150	28.7	25.6	150	30.4	26.8	150	23.4	21.6
175	32.0	29.3	175	33.4	29.7	175	26.2	24.3
200	36.0	35.2	200	37.3	34.3	200	30.9	28.9
225	39.7	37.9	225	43.2	40.3	225	37.3	35.4
230	41.0	39.5	230	44.7	41.7	230	39.5	37.0
240	43.6	42.0	240	48.0	45.4	240	42.7	39.9
250	46.0	44.6	250	51.7	48.5	250	47.3	44.4
260	48.8	47.6	260	54.5	52.6	260	52.0	49.2
270	52.8	51.7	270	59.1	57.4	270	55.4	52.8
280	55.2	54.0	278	62.1	60.0	280	58.4	55.9
288	57.2	55.8	280	63.0	60.7	290	62.4	59.7
290	58.5	56.7	290	66.8	64.2	296	63.8	61.0
300	61.4	59.5	300	64.1	60.1		(144)	(FIA)
	(144)	(FIA)		(144)	(FIA)			

ESTIMATED MEAN LENGTH OF ONE THE TWO "D" CORES IN G.E. TRANSFORMER

26.5 Inches

FREQUENCY TEST DATA

Wattmeter: G.E. No. 579561, 0-150 watts, 150 volts.
Potential coil resistance is 3301 ohms.
Used with Potential Transformer No. A-136891

Voltmeter: G.E. No. 598915, 0-300-750 volts.
300 volt coil resistance is 7614.2 ohms. (E_1)
750 volt coil resistance is 19040.0 ohms. (E_2)

DATA

G.E.

freq.	volts	watts	P-T
	E_2		
90	360	41.9	4-1
85	340	34.3	4-1
80	320	68.0	2-1
	E_1		
75	300	66.2	2-1
70	280	59.4	2-1
65	260	52.4	2-1
60	240	46.9	2-1
55	220	41.0	2-1
50	200	35.2	2-1
45	180	30.1	2-1
40	160	53.3	out
35	140	43.0	out
30	120	34.0	out

A.C.

freq.	volts	watts	P-T
	E_2		
90	360	32.3	4-1
85	340	29.5	4-1
80	320	59.0	2-1
	E_1		
75	300	58.1	2-1
70	280	52.1	2-1
65	260	46.1	2-1
60	240	41.0	2-1
55	220	35.8	2-1
50	200	31.0	2-1
45	180	26.0	2-1
40	160	46.8	out
35	140	37.4	out
30	120	29.2	out

W.E.

freq.	volts	watts	P-T
90	360	30.0	4-1
85	340	27.1	4-1
80	320	24.8	4-1
	E_1		
75	300	54.9	2-1
70	280	49.1	2-1
65	260	43.7	2-1
60	240	39.0	2-1
55	220	34.0	2-1
50	200	29.6	2-1
45	180	25.1	2-1
40	160	45.2	out
35	140	36.8	out
30	120	28.9	out

Frequency was measured with an oscilloscope used in conjunction with a Hewlett-Packard Oscillator.

SEPERATION of CORE LOSSES

Core loss equals Hysteresis loss plus Eddy-Current loss.

$$P_c = P_h + P_e \qquad 1.$$

$$P_c = K_1 B_{max}^n f + K_2 B_{max}^2 f^2 \qquad 2.$$

where the Ks are constants, f is frequency, B_{max} is maximum flux density, and n is the Steinmetz exponent.

The goal of this study is to empirically determine the core-loss equation as a function of frequency and impressed voltage, E, using the data on the next page. It's easily shown that,

$$B_{max} = K\frac{E}{f} \qquad 3.$$

which when substituted in equation 2, combining constants, shows that,

$$P_c = K_h E^n f^{1-n} + K_e E^2 \qquad 4.$$

During the test the flux density was maintained at its rated value so that E divided by f was held constant at 4.

$$\frac{P_c}{f} = K_h 4^n + K_e 4E \qquad 5.$$

Equation 5 is a straight line. It is plotted on Graph A-1 which shows this foregoing theory is applicable to the 200-280 volt range only.

The slope of the straight lines is $K_e 4$.

$$\begin{aligned} &G.E. \quad K_e = 5.75 \times 10^{-4} \\ &A.C. \quad K_e = 4.89 \times 10^{-4} \\ &W.E. \quad K_e = 4.09 \times 10^{-4} \end{aligned} \qquad 6.$$

The intercept, at E equals zero, is $K_h 4^n$; this point is easily determined from the graph to be:

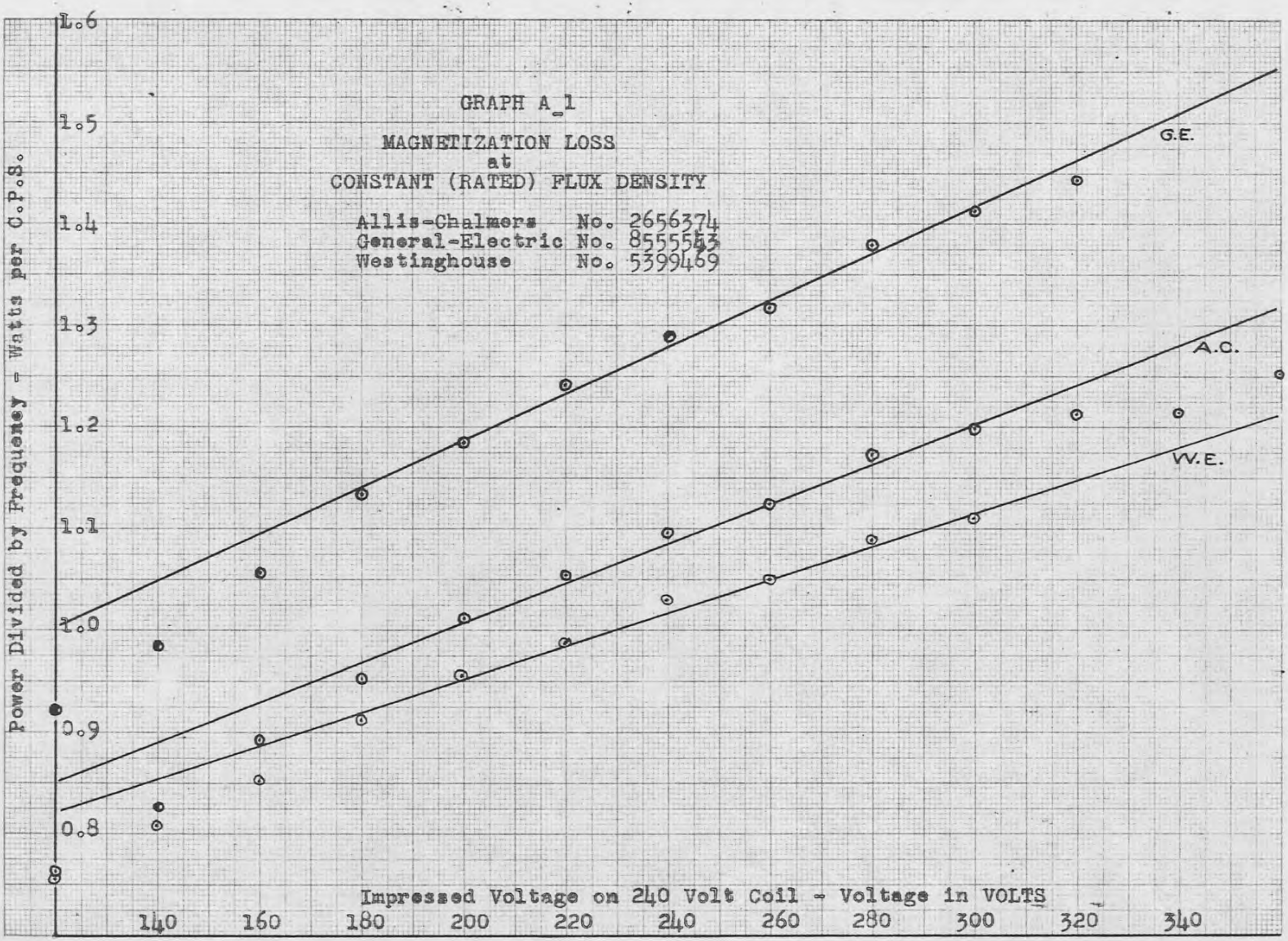
$$\begin{aligned} &G.E. \quad K_h 4^n = 0.727 \\ &A.C. \quad K_h 4^n = 0.614 \\ &W.E. \quad K_h 4^n = 0.624 \end{aligned} \qquad 7.$$

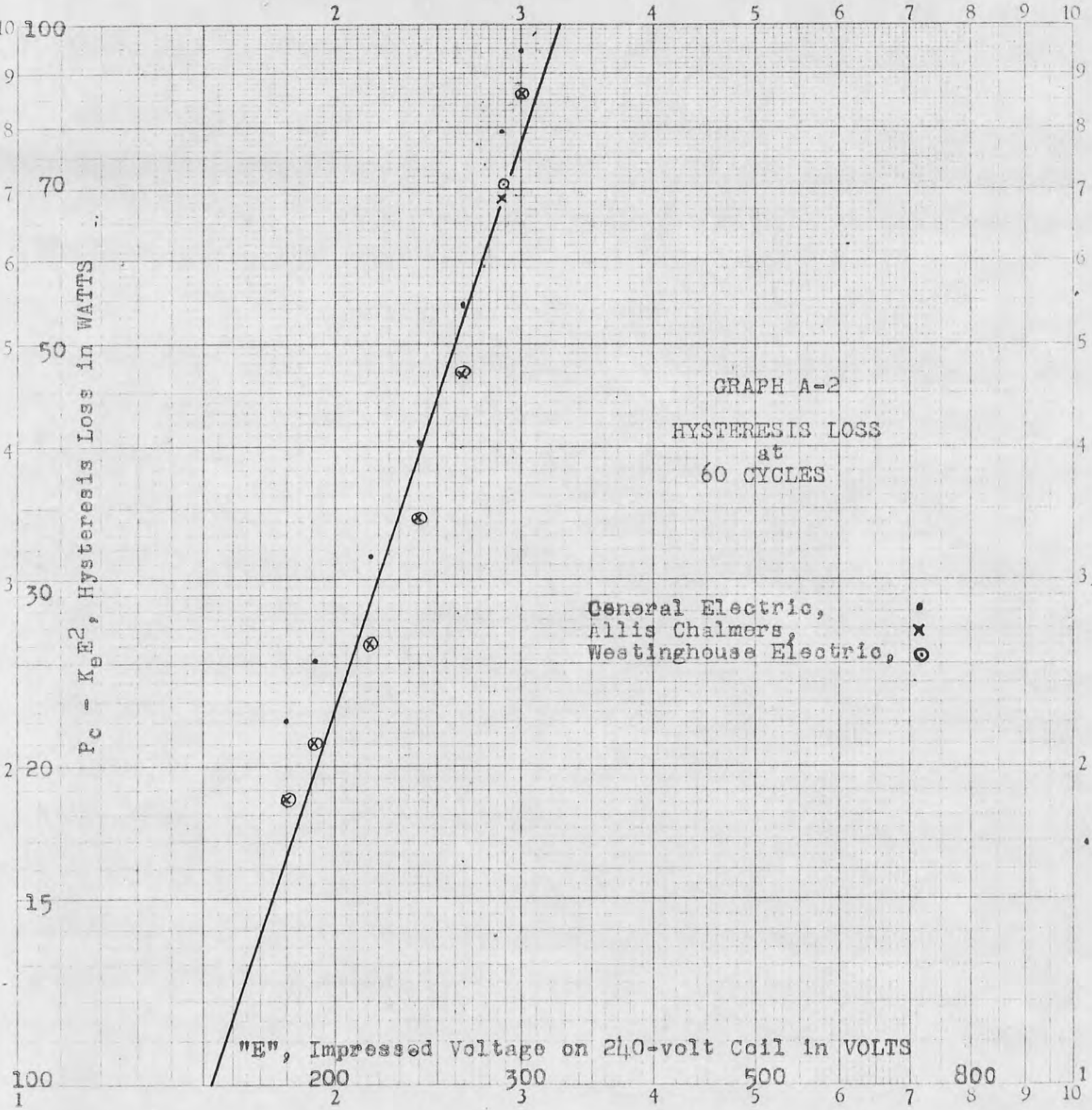
From equation 4,

$$P_c - K_e E^2 = K_h E^n f^{1-n} \qquad 8.$$

The left side of equation 8 plotted on log-log coordinates as a function of E is a straight line whose slope is n. This curve is shown on Graph A-2; the data was taken from equation 6 and the curves on page 12.

Measuring the slope of the straight line on Graph A-2 gives n equal to 2.54 for all three transformers. From equation 7, (continued on last page)- - - - -


GRAPH A-1
MAGNETIZATION LOSS
at
CONSTANT (RATED) FLUX DENSITY
Allis-Chalmers No. 2656374
General-Electric No. 8555553
Westinghouse No. 5399469
G.E.
A.C.
W.E.
Power Divided by Frequency - Watts per C.P.S.
1.6
1.5
1.4
1.3
1.2
1.1
1.0
0.9
0.8
Impressed Voltage on 240 Volt Coil - Voltage in VOLTS
140
160
180
200
220
240
260
280
300
320
340


GRAPH A-2
HYSTERESIS LOSS
at
60 CYCLES
General Electric, •
Allis Chalmers, ×
Westinghouse Electric, ⊙
$P_c = K_s E^2$, Hysteresis Loss in WATTS
"E", Impressed Voltage on 240-volt Coil in VOLTS
100
70
50
30
20
15
100
200
300
500
800

$$G.E.\quad K_h = 214 \times 10^{-4}$$

$$A.C.\quad K_h = 181 \times 10^{-4}$$

$$W.E.\quad K_h = 184 \times 10^{-4}$$

Inasmuch as test curves do not obey the academic theory too closely all constants have been averaged below and a general core-loss equation obtained for modern distribution transformers operating at 60 cycles. (10 KVA transformers)

$$P_c = (0.351E^{2.54} + 4.91E^2) \times 10^{-4}$$

where P_c is core loss in watts and E is the number of volts measured on the 240 volt coil of the secondary winding.

A check will show that this equation approximates the curves on page 12 very closely in the 200-280-volt range. At rated volts, the ratio of hysteresis loss to eddy-current loss is about 1.4 to 1 .

This equation of core loss can be applied to various KVA and KV rating machines by employing the "percentage" system ---- with due caution.

------------------------THE END------------------------