THE DESIGN AND CONSTRUCTION OF A 500 WATT POWER TRANSFORMER

by

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INTRODUCTION

This thesis is intended to be of special interest to anyone interested in the design and construction of small transformers for radio transmitting stations. The author is indebted to Dr. Charles A. Perkins for ideas and suggestions which were of considerable help in designing the transformer and to the Knoxville Power and Light Company for furnishing the core for the transformer. The transformer was designed to meet the requirements of the secondary load with the highest efficiency possible under these conditions. The transformer will be used in a radio transmitting station by the author.

GENERAL SURVEY OF THE FIELD

The evolution of the transformer began with the discovery of electro-magnetic induction by Faraday and Joseph Henry about the year 1831. Faraday used a solid iron ring upon which the primary and secondary windings were placed. All of these early experiments were performed with an interrupted direct current from a battery, current being delivered by the secondary winding when the current was established or broken in the primary circuit. In Faraday's ring is found the first use of the closed magnetic circuit of iron. In the subsequent development of the transformer the closed magnetic circuit was discontinued to appear later in a more perfect form. Although Faraday's ring had many of the essential features of the modern transformer, the latter cannot be thought of as having developed directly from this ring. This ring had a ratio of approximately one to one. Faraday had no conception of the use of alternating current, all of his experiments being carried out with an interrupted direct current. The primary and secondary windings were placed on opposite sides of the iron ring and were not in close magnetic relation. When the secondary winding was carrying current there would be an enormous magnetic leakage which would have prevented its working at any considerable flux density. The eddy current which would have been generated would have also been large. From these early experiments the transformer of today was gradually developed. At the present time transformers are built with capacities of several thousand KVA. Today the transformer is one of the most efficient pieces of electrical apparatus. The efficiency of a ten thousand KVA transformer is slightly above ninety-nine per cent.

GENERAL THEORY

The transformer is a device operating by virute of the principle of mutual induction whereby the energy of an alternating current circuit may be received at one voltage and delivered at a higher or lower voltage. It consists essentially of two coils wound on an iron core; one coil receives energy and is called the primary coil, the other delivers energy and is called the secondary coil.

There are two distinct types of transformers, the open and the closed core type. The open or straight core transformer is illustrated at Figure I. It consists of a laminated core upon which the primary winding of insulated copper wire is placed. Over the primary winding the secondary winding is wound. The two windings are separated by a suitable thickness of insulation and are not directly connected. The energy from one winding is transferred to the other winding by the magnetic flux (called Φ) through the core.

The physical action of the transformer is explained as follows: When the secondary is on open circuit no current flows in this winding. Under this condition the transformer is said to operate at no-load and only a small current flows in the primary winding. This current is called the magnetizing current and causes repeated reversals of the magnetic flux through the iron core. These reversals of magnetic flux induce electromotive forces in both the primary and the secondary windings. The electromotive force thus induced in the primary coil is opposite in direction and very nearly equal to the electromotive force applied to the primary winding. Only the difference between the applied electromotive force and the opposing induced electromotive force is available for producing current through the primary winding; and due to the fact that this difference is small the primary current is small at no-load.

When an alternating current is taken from the secondary winding, the transformer is said to be loaded. The action of this secondary current as it flows through the secondary winding is to oppose the magnetizing action of the slight current already flowing in the primary winding, thus decreasing the maximum value reached by the alternating magnetic flux Φ in the core, and thereby decreasing the induced electromotive forces in both coils. The amount of this decrease, however, is very small, inasmuch as a very small decrease of the induced electromotive force in the primary coil greatly increases the difference between the electromotive force applied to the primary winding and the opposing electromotive force induced in the primary winding, so that the primary current is increased. The flux in the core will be maintained approximately constant by the primary currentwhatever the value of the load on the secondary.

The electromotive forces induced in the respective windings of the transformer are proportional to the number of turns of wire in each; and from the above discussion it is evident that the electromotive force induced in the primary winding is practically equal to the supply electromotive force regardless of whether the transformer is loaded or not. Therefore

$$E_1 : E_2 :: N_1 : N_2$$

in which E_1 is the electromotive force applied to the primary, E_2 is the electromotive force at which the secondary winding delivers alternating current, and N_1 and N_2 the number of priary and secondary turns respectively.

The magnetizing action of the primary current I_1 of the transformer having N_1 turns of wire in the primary winding may be expressed by the product N_1I_1, that is by the ampere turns; and similarly, the magnetizing action of the secondary current I_2 may be expressed by the product N_2I_2 where N_2 is the number of turns of wire in the secondary winding. Therefore, since the magnetizing actions of the two windings is equal (and opposite) we have

$$I_1 : I_2 :: N_2 : N_1$$

in which N_1 and N_2 are the turns of wire in the respective windings; I_2 is the current delivered by the secondary winding; and I_1 is the increase of current taken by the primary winding over and above the no-load current, due to the fact that the secondary winding is delivering current.

Figure I illustrates an open core transformer. Part of the path of the magnetic flux is through air and the leakage flux is high. The efficiency of this type of transformer is low as compared to the closed core type illustrated at Figure II and III. Figure II is the core type transformer and Figure III the shell type transformer. In the shell type transformer the leakage flux is only in the space between the primary and secondary windings.

Figure IV is the vector diagram of the transformer. (not drawn to scale) The voltage $_\phi E_2$ induced in the secondary by the flux Φ lags behind the flux by 90° and is therefore drawn in a positive direction along the X-axis. The impressed voltage in the primary, $_\phi E_1$, required to balance the voltage induced in the secondary is opposite in direction to $_\phi E_2$. Hence, $_\phi E_1$ is drawn along the X-axis in the negative direction. The RI drop is in phase with the current and the XI drop 90° ahead of the current. The primary impressed current, I_1, is equal to the vector sum of the equivalent primary load current I_{11} and the magnetizing current $_mI$.

STATEMENT OF PURPOSE

It is the purpose of this thesis to design a transformer of 500 watt capacity to fit a given core with as high an efficiency as possible under the given conditions. The secondary load is non-inductive. The formulas contained herein and from which the design calculations were made are all obtained from standard commercial design data.

DESIGN

Specifications:

This transformer is of the shell type and has one primary and two secondary windings. One secondary is wound for a low voltage and has a tap at the center of the winding. The other secondary is wound for a high voltage and consists of two coils. The low voltage secondary will be referred to in the following discussion as secondary I. Likewise the high voltage secondary will be referred to as secondary II. The two coils of secondary II will be connected in parallel in the following calculations.

The primary voltage is 110. Secondary I voltage is 10 and secondary II voltage is 750. The current in secondary I is 5 amperes and the current in secondary II is 0.6 amperes for the two sections connected in parallel. Assuming an efficiency of 90 percent the primary current is approximately 5 amperes. The frequency of the primary voltage is 60 cycles per second.

The material for the core is ordinary transformer sheet steel. The laminations are 0.015 inch thick and each layer is made up of two pieces. One is in the shape of an E and the other is a straight piece. The mean length of the magnetic circuit is 13.9 inches. Assuming a lamination factor of 0.9 the cross sectional area of the core is 2.91 square inches and the total volume of iron in the transformer is 44.5 cubic inches.

Size of wire for windings:

From a formula in the Handbook for Electrical Engineers by Pender the cross-sectional area of the conductor in square inches is equal to the current flowing in that conductor divided by a constant. The value of this constant for a small, poorly cooled transformer was found to be 1025 from a table in the above mentioned handbook. From a wire table in this handbook the size of wire corresponding to this cross sectional area was found. As the current in the primary and the secondary I windings are practically the same, the same size of wire will do for both windings. Size 12 B&S gauge wire meets the above conditions and it was used for these two windings. The secondary II required size 24 B&S gauge wire.

Primary and Secondary turns:

The number of turns for the primary winding was calculated from the following formula:

$$E_1 = 4.44 \, f \, N_1 A {}^m B \, 10^{-8}$$

Here ${}^m B$ was assumed to be 50,000 lines per square inch (flux density). A is the cross-sectional area of the core and is 2.91 square inches. f is the frequency and is 60 in this case. E_1 is the primary voltage which is 110 for this transformer. N_1 is the number of primary turns.

$$N_1 = 110 \times 10^8 \div 4.44 \times 60 \times 2.91 \times 50{,}000$$

$$N_1 = 284 \text{ turns}$$

The number of turns for the secondary windings was calculated from the following formula:

$$E_1 : E_2 :: N_1 : N_2$$

$N_2 = E_2 N_1 \div E_1$

For the secondary I:

$N_2 = 26$ turns

For the secondary II:

$N_2 = 1935$ turns

Reactance of windings:

The reactances are calculated using the following formula from the Handbook by Pender:

$$X = \frac{2 f \times 3.2\ KN^2U}{Ls}\left(\frac{t_1}{3} + \frac{t}{2}\right)10^{-8}$$

Where f is the frequency, K is a constant (1.06 for cylindrical coils), N is the number of turns in winding, U is the mean length of turn, t_1 is the thickness of the primary coil, t is the distance between coils, and L_s is the height of the coil.

The reactance of the primary winding:

$$X_1 = \frac{2 \times 60 \times 3.2 \times 1.06 \times (284)^2 13.5}{4}\left(\frac{0.66}{3} + \frac{0.125}{2}\right)10^{-8}$$

$X_1 = 0.98$ ohms

The reactance of secondary I winding:

$$X_{2I} = \frac{2 \times 60 \times 3.2 \times 1.06 \times (26)^2 1\ 0}{2.45}\left(\frac{0.095}{3} + \frac{0.0625}{2}\right)10^{-8}$$

$X_{2I} = 0.0027$ ohms

The reactance of secondary II winding:

$$X_{2II} = \frac{2 \times 60 \times 3.2 \times 1.06\ (1935)^2 21}{2}\left(\frac{0.91}{3} + \frac{0.125}{2}\right)10^{-8}$$

$X_{2II} = 192$ ohms.

Losses:

Core Losses:

The core losses consist of the hysteresis and eddy current losses in the steel laminations. The core loss is practically the same at all loads. The core loss was calculated from the following formula taken from Pender's Handbook:

$$\text{Core Loss (watts)} = K_1 f\, V \left(\frac{B}{1000}\right)^{1.6} 10^{-6} + K_2 V \left(tf \frac{B}{1000}\right)^{2} 10^{-5}$$

where K_1 is a constant depending for its value on the steel of the transformer, f is the frequency, V is the volume of iron in cubic inches, B is the magnetic flux density in lines per square inch, t is thickness of laminations in inches, K_2 is a constant depending on the steel used for the transformer core for its value.

Copper Losses:

The copper losses, unlike the core losses, are not constant but increase with increase in load. The values of the core losses and copper losses are given in tables in the appendix.

Magnetizing current:

As previously explained the magnetizing current is the small current which flows in the primary at no-load to produce the magnetic flux Φ. The magnetizing current is calculated from the following formula from Pender's Handbook:

$$_mI = \frac{H \times (\text{Length of mean line of flux, in inches})}{\sqrt{2}\ N}$$

where H is equal to the ampere-turns per inch of magnetic circuit, N is equal to the number of primary turns, $_mI$ is the magnetizing current in amperes.

$$_mI = \frac{4 \times 13.9}{\sqrt{2} \times 284} = 0.139 \text{ amperes}$$

Sometimes it is desired to allow for the minute air gaps at the joints of the laminations. Arnold finds that under practical conditions each joint represents a gap of 0.002 inch. Thus if there are n joints there should be added to $_mI$ an amount

$$\frac{0.313 \times 0.002\ BN}{\sqrt{2}\ N}$$

$$\frac{0.313 \times 0.002 \times 50{,}000 \times 2}{\sqrt{2} \times 284} = 0.156 \text{ amps.}$$

Then $_mI = 0.139 + 0.156 = 0.295$ Amperes.

Expressed in per cent of full-load current, the magnetizing current is :

$$\frac{_mI}{I} = \frac{0.260}{5} = 0.059 \text{ or } 5.9 \text{ percent}$$

Regulation

The regulation of a transformer is defined as the drop in secondary voltage, from no-load to full-load, in terms of the full-load voltage.

Calculation of Regulation:

$R_t = \left(\frac{N_I}{N_{2II}}\right)^2 R_{2II} =$ resistance of secondary reduced to primary

$$R_t = \left(\frac{284}{1935}\right)^2 24.9 = 0.54 \text{ ohms}$$

$X_t = \left(\frac{N_I}{N_{2II}}\right)^2 X_{2II} =$ reactance of secondary reduced to primary

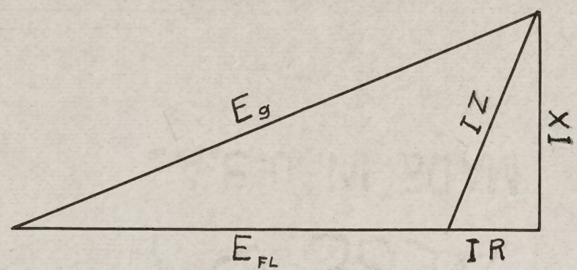
$$X_t = \left(\frac{284}{1935}\right)^2 192 = 4.14 \text{ ohms}$$

Drop in voltage due to resistance:

$$I_1 R_t = 5 \times (0.54 + 0.51) = 5.25 \text{ volts.}$$

Drop in voltage due to reactance:

$I_r x_t = 5 \times (4.14 + 0.98) = 25.60$ volts



$E_g = 110$ volts

$E_{FL} = \sqrt{E_g^2 - \overline{IX}^2} - IR$

$E_{FL} = 103.65$ volts

$$\text{Regulation} = \frac{100\,(E_g - E_{FL})}{E_{FL}}$$

$$\text{Regulation} = \frac{100\,(110 - 101.25)}{101.25} = 8.65 \text{ per cent}$$

Hysteresis angle of advance (called $\propto$).

No-load core loss = E I cos $(90 - \propto)$

No-load core loss = E I sin $\propto$

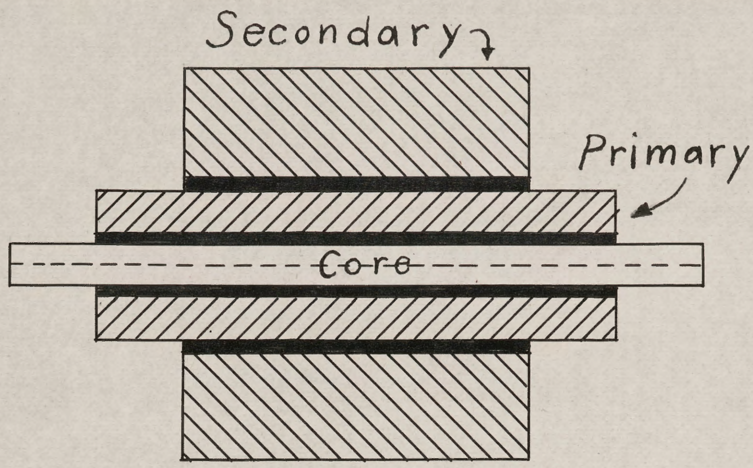
$\sin \propto = 18.41 \div 100 \times 0.295 = 0.578$

$\propto = 35^\circ\ 18'$

Construction

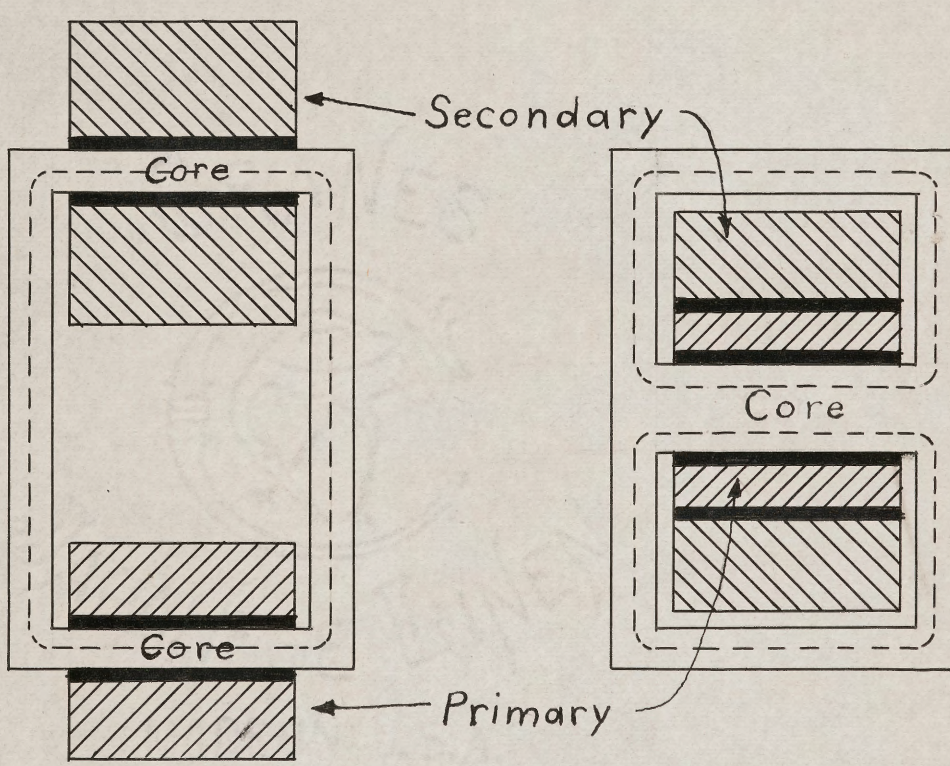
The windings were first wound on a wooden block a little larger than the core in cross-sectional area to allow for the insulation. The low voltage secondary winding was wound nearest the core. The primary winding was wound over the low-voltage secondary. Over the primary the high voltage secondary was wound. This winding was made up of two equal coils placed side by side and separated from one another by a fibre disk. Each winding was separated from the adjacent winding or the core by a suitable thickness of insulation. After completing the windings the wooden block was removed and cloth tape placed around the windings. This tape was then painted with a black compound. After the compound had dried thoroughly the core was built up around the windings. After the core was built up the transformer was mounted.

The bakelite panel containing the binding posts to which the terminals of the windings are connected is shown at Figure VI



Open Core Type Transformer

Fig. I.

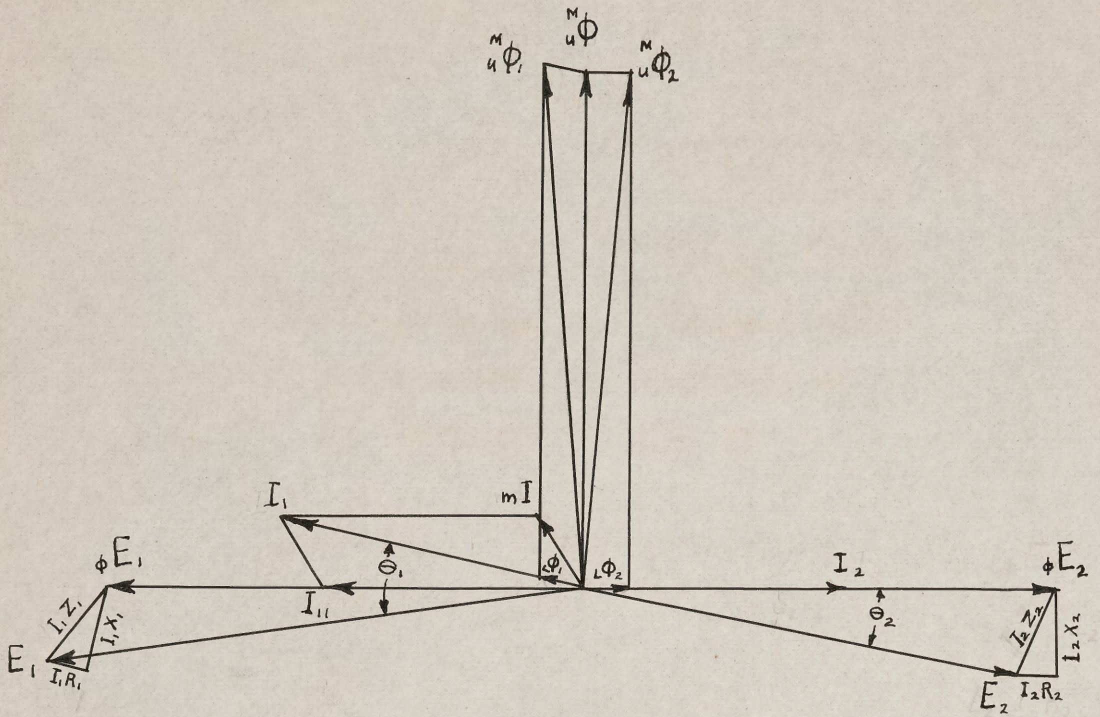


Core Type Transformer

Fig. II.

Shell Type Transformer

Fig. III.



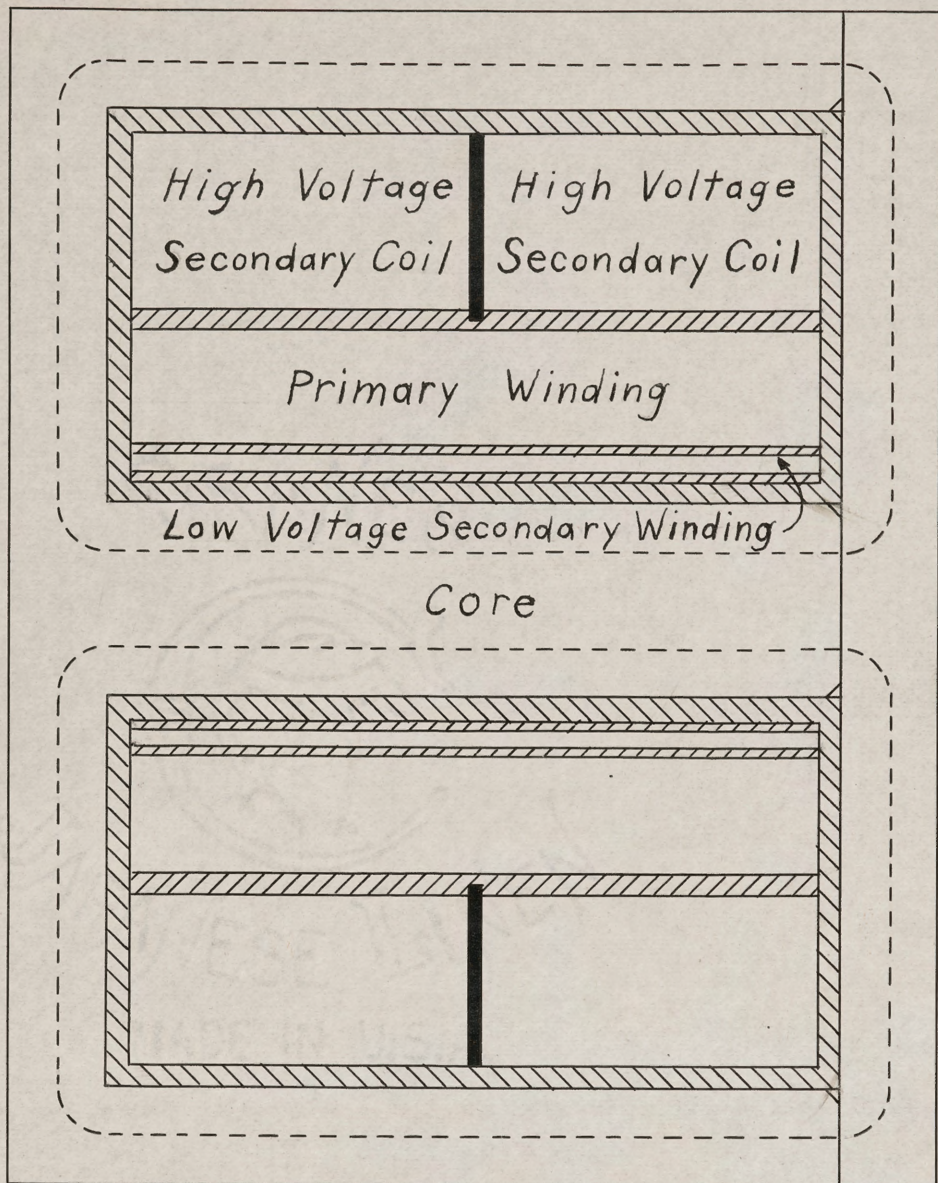
Vector Diagram Of The Transformer

Non Inductive Load

Low Voltage Secondary Not Shown

Diagram Not Drawn To Scale

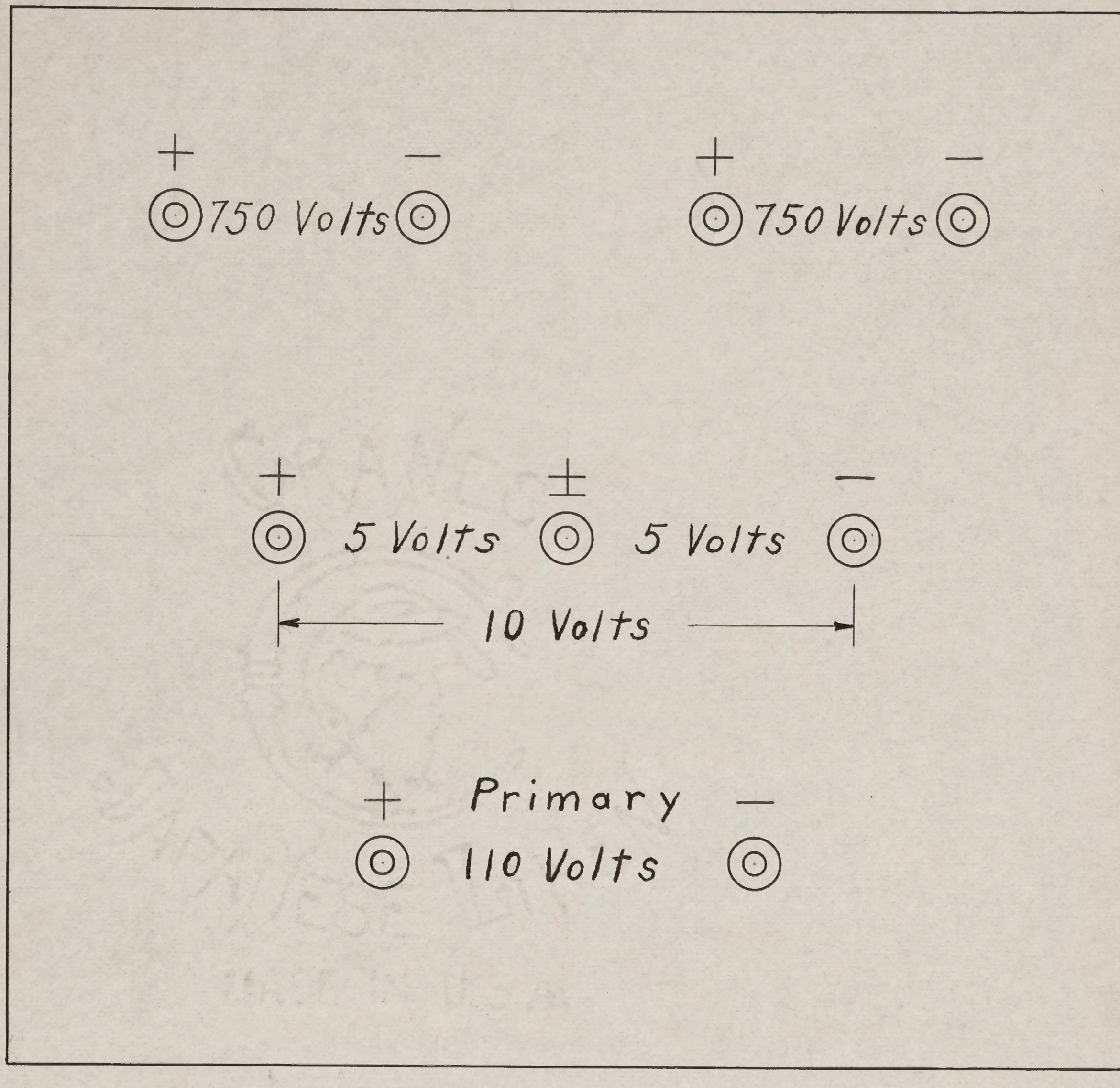
Fig. IV.



Cross-Section Of The Transformer

Actual Size

Fig. V.



Details Of The Panel

Fig. VI.

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Electrical Engineering	Berg and Upson
Alternating Currents	Magnusson
Practical Electricity	Croft
Transformer Practice	Reed
Electrical Machine Deisgn	Gray
Alternating Current Machinery	Esty
Handbook for Electrical Engineers	Pender
Standard Handbook for Electrical Engrs	Fowle

A P P E N D I X

TABLE NO. 1

Flux Density (lines per sq in)	Loss due to Hysteresis (watts)	Loss due to Eddy Currents (watts)	Total Core Loss (watts)
0	0	0	0
5,000	0.28	0.07	0.35
10,000	0.85	0.29	1.04
15,000	1.63	0.65	2.28
20,000	2.57	1.15	3.72
25,000	3.67	1.80	5.47
30,000	4.91	2.60	7.51
35,000	6,30	3.53	9.83
40,000	7.85	4.63	12.47
45,000	9.43	5.84	15.27
50,000	11.20	7.21	18.41
55,000	13.01	8.73	21.75
60,000	14.95	10.39	25.34
65,000	16.95	12.20	29.15

TABLE NO. 2

Per cent Load	Core Loss (watts)	I^2R Loss Primary (watts)	I^2R Loss Sec I (watts)	I^2R Loss Sec II (watts)	Total I^2R Loss (watts)	Total Loss (watts)	Output (watts)	Input (watts)	Eff. %
0	18.41	0	0	0	0	18.41	0	18.410	0
6.25	18.41	0.05	0.003	0.02	0.073	18.483	31.3	49.783	62.9
12.5	18.41	0.20	0.013	0.16	0.373	18.783	62.5	81.283	76.9
25	18.41	0.81	0.054	0.64	1.504	19.914	125.0	144.914	86.3
50	18.41	3.25	0.215	2.24	5.705	24.115	250.0	274.115	91.1
75	18.41	7.33	0.484	5.25	13.064	31.474	375.0	406.439	92.3
100	18.41	13.00	0.860	8.96	22.820	42.230	500.0	542.230	92.3
125	18.41	20.43	1.380	13.98	35.790	54.200	625.0	679.200	92.0

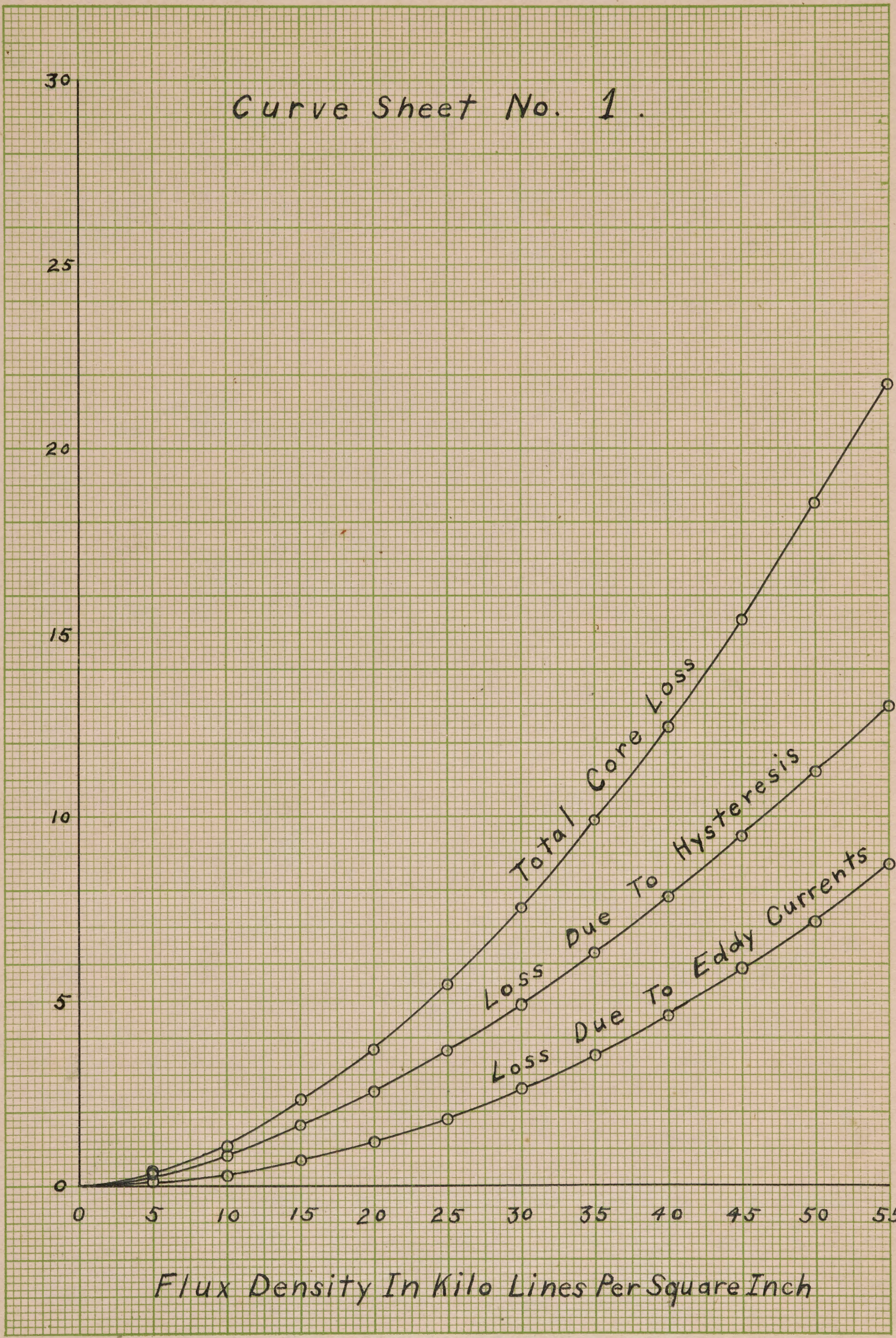
TABLE NO. 3

Winding	Turns	Size of wire B&S Gauge	Turns per sq.in.	Cross Sectional area of winding (sq. in.)
Primary	284	12	112.4	2.53
Sec. I	26	12	112.4	0.11
Sec. II	3870	24	1,090	3.55

TABLE NO. 4

Winding	Mean Length of turn (feet)	Length of Winding (feet)	Size of wire B&S Gauge	Resist. 1000 feet of wire (ohms)	Resist of Winding (ohms)
Primary	1.13	320	12	1.588	0.51
Sec. I	0.83	21.7	12	1.588	0.03
Sec. II	1.75	3,390	24	25.67	24.9

FormE-5



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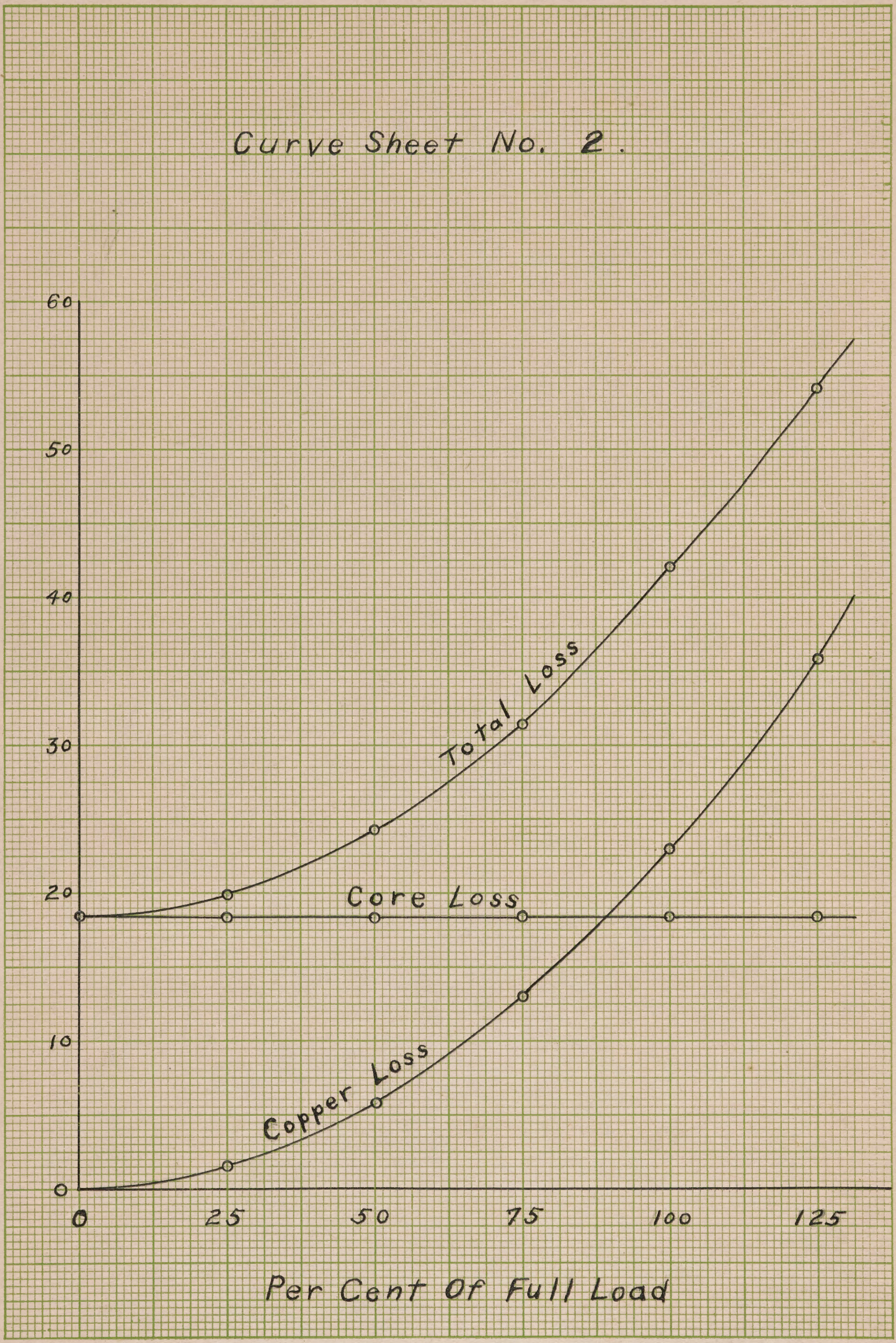

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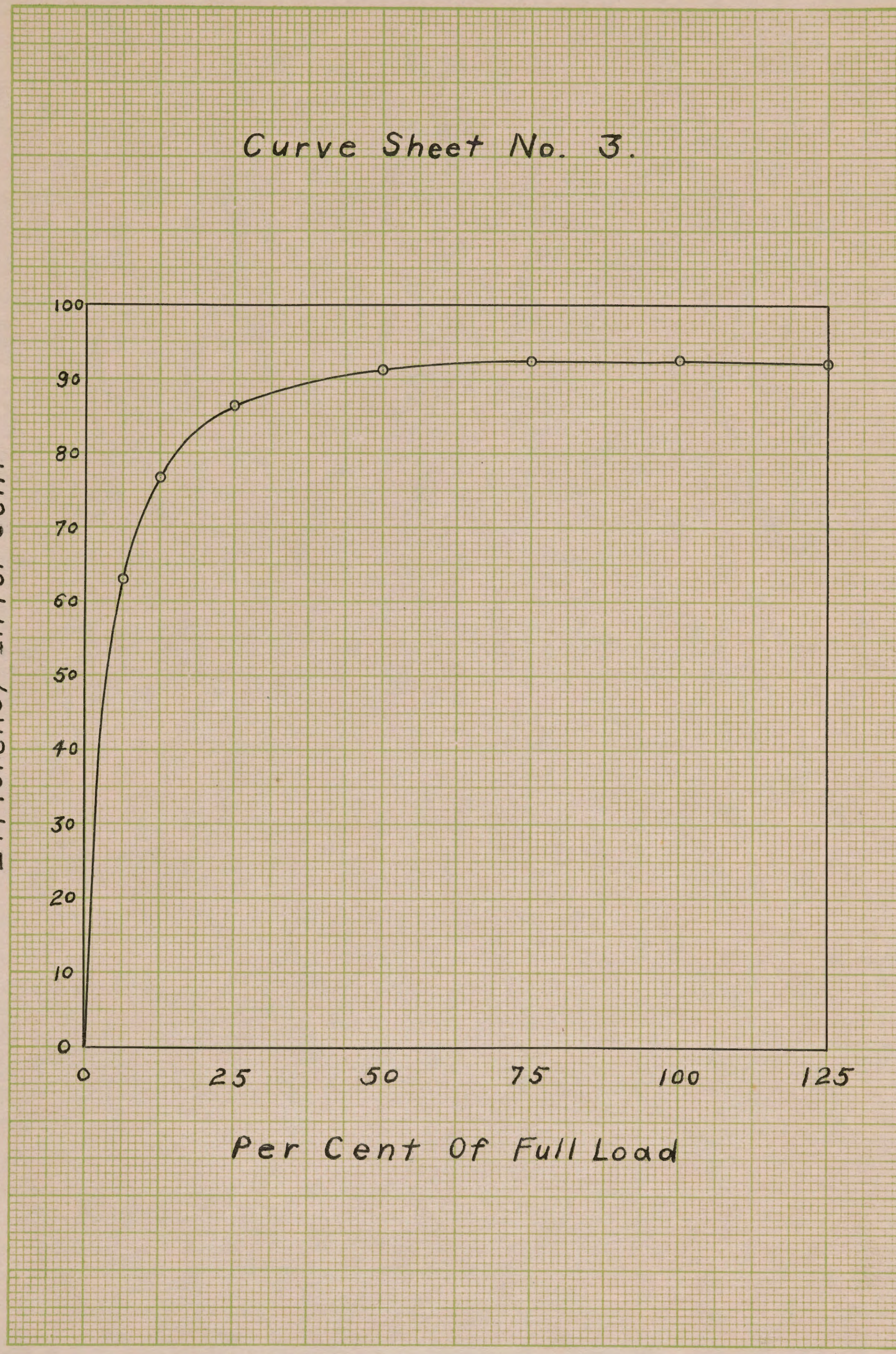

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APPROVAL

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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