THESIS

ON

High Current Transformer

Submitted to the faculty

of the

O R E G O N A G R I C U L T U R A L C O L L E G E

for the degree of

BACHELOR OF SCIENCE

in

Electrical Engineering

by

Darwin Carnegie

and

Roy Borden

June 9, 1911.

Redacted for privacy

Approved..........................

Department of Electrical Engineering.

Redacted for privacy

....

Dean School of Engineering

INTRODUCTION.

By reason of the fact that a thesis along the line of one's course or about some subject with which he is supposed to be familiar is required of every Senior electrical by the electrical department before his graduation, the following description of the design and construction of a 10 K. W., high current, welding transformer has been prepared and submitted to the faculty. This subject was chosen partly because of the practical experience to be gained in its design and construction, and partly because of the laboratory's need for such an apparatus, the high secondary current making the transformer one of the main adjuncts of an electric furnace. In the followingdescription the general theory of transformers is explained as well as time and space permit, after which attention is turned to the particular apparatus under discussion.

Transformer Design.

Theory.

The alternating current transformer consists of one magnetic circuit interlinked with two electric circuits, the primary circuit which receives energy , and the secondary circuit which delivers energy. The ratio of transformation is equal to the ratio of secondary turns to primary turns. An alternating e. m. f., E_0, impressed upon the primary electric circuit causes a current, which produces a magnetic flux Φ interlinked with primary and secondary circuits. This flux generates e. m. f_s, E, and E_c, in the secondary and in primary circuits, which are to each other as the ratio of turns.

The size and type of transformer depends upon the purpose for which the transformer is to be used. If electric energy is to be transmitted to a distance, it has been found that it is more economical to put in a transformer at the generating station and transmit the energy with the voltage stepped up several times the generated voltage and then step it down at the receiving end, than to transmit the energy at the generated voltage. The difference is in the cost of the amount of copper needed when transmitting energy at a low voltage. There are two classes of transformers, the core type and the shell type. One type is about as efficient as the other and both are used in transmitting energy at high voltage.

The transformer is not the only machine used in transforming energy from one voltage to another. For transforming continuous currents, a revolving apparatus is required consisting of a D. C. motor, which receives electrixal energy, driving a D. C. generator, which induces a secondary current at the desired pressure.

For transforming or converting alternating current into continuous current revolving apparatus is also needed. There are two classes of machines used for this purpose, the motor-generator set and the rotary convertor.

An alternating current transformer may be regarded as a species of a dynamo, in which neither armature nor field magnet revolves. The magnetizm of the iron core is made to vary through rapidly repeated cycles of alternating current. The primary coil of the transformer corresponds to the field magnet coil of the dynamo; the secondary of the transformer to the armature of the dynamo. That is, if an alternating current having a frequency of f periods per second be sent into the primary coils, there will also be in the secondary coils an alternating electromotive force having the same frequency. The reason for this is that the iron core undergoes an alternating magnetization of f cycles per second. If alternating current is put into the primary coil when the secondary circuit is open, there will be an electromotive force induced in the secondary coil but there will be no current and therefore no reaction of the secondary. The only reaction would be that of the primary coil on itself.

If the secondary circuit is closed on a load, and supposing the resistance to be a simple non-inductive resistance, there would be a secondary current in phase with the induced electromotive force, therefore in phase also with the back electromotive force and therefore also in almost exact opposition of phase to the primary current. When the primary current is at its maximum va ue, but flowing in the opposite direction around the core.

The theory of this is that $\Phi_t = \Phi_{max} \sin w t$

$$E_t = N \frac{d\Phi_t}{dt} 10^{-8} = N \frac{\Phi_{max} \cos d w t}{dt \times 10^8} = w N \frac{\Phi_{max} \cos w t}{10^8}$$

$$\frac{dE}{dt} = \frac{w^2 N \Phi_{max} \sin w t}{10^8} = 0. \therefore \sin w t = 0 = 0^\circ \text{ deq.}$$

for maximum E.

While the primary is magnetizing, the secondary is demagnetizing, because while the current in the primary is flowing in one direction the current in the secondary flows in the opposite direction.

Magnetic Leakage.

In all transformers there is some flux or stray field which is called magnetic leakage because it does not pass through the secondary coils. In an ideal transformer, when the secondary circuit is unloaded, all the magnetic lines produced by the primary magnetizing current would pass through the secondary coils. The reason why, in practical cases, all of this flux does not link through the secondary is, that there is not enough reluctance in the primary coil to force it through the iron core. This leakage flux produces self-inductance in the windings, because any such field, varying as it does with primary current, must produce an electromotive force in the windings effected by it, and as a field it would be in quadriture with the electromotive force, therefore the result would be the same as if the additional self-induction had been added to the primary and secondary windings. Magnetic leakage in a transformer has two effects on its performance, namely,--it increases the drops of pressure in the secondary, and it tends to diminish the power factor of the transformer. The first effect is of great practical importance in transformers designed for motor work, for if it was not for the magnetic leakage, the secondary deop would then be due to the ohmic resistance of the two windings and therefore would not be large. If N_p and N_s represent the values of the leakage field in the primary and secondary respectively, then

$$e_p = 4.44 \; f \; S_p \; N_p \div 10^8 = I_p X_p$$
$$e_s = 4.44 \; f \; S_s \; N_s \div 10^8 = I_s X_s$$

where e_p and e_s are respectively the values of the reactance voltages produced by the leakage fields N_p and N_s ; I_p and I_s the respective currents and X_p and X_s the respective reactances.

From this and the known resistance of primary and secondary a voltage diagram can be constructed and from this diagram the quantity, upon which the voltage regulation of the transformer entirely depends, can be obtained. It is proportional to the secondary current at all loads. But its phase relation to the secondary voltage depends upon the nature of the load. The magnetic leakage is greatest at full load because the magnetomotive-forces tending to produce leakage increases from no-load to full-load, and is about the same whether that load is inductive or non-inductive. The voltage-drop is greater on an inductive load, because with an increase in lag the drop due to leakage comes more nearly into phase with that due to copper resistance.

It is the object of each designer of transformers to keep the magnetic leakage as low as possible. In order to do this there are certain conditions which should be fulfilled. These conditions are: (1) the magnetic reluctance of the iron core must be kept as low as possible; that is, there should be no bad joints and the core must be compact; (2) the depth of the coils should be kept down as much as possible so that coils will not heat up; (3) the primary and secondary windings should be sub-divided and interplaced, sections of secondaries windings sandwiched in between sections of the primary windings. In this was most of the lines produced by the primary magnetizing current will pass through the secondary coils.

Power Factor.

Most transformers operate with their primary windings connected to mains of unity power factor. The current taken by a transformer on no-load has to magnetize the core so that secondary pressure is always available for use when required, and it must balance the core losses, which consist of hysteresis and eddy currents in the laminated iron core. For this reason the power factor of the current in the windings is generally less than unity.

The current required to magnetize the core is called the magnetizing current. This magnetizing current is a wattless current, because it is in phase with the magnetic flux in the core, and the magnetic flux at no-load is practically in quadrature with the supply and is exactly in quadrature with the back electromotive-force. Whenever the transformer takes a large magnetizing current it causes the no-load power factor to lower.

Some of the points underlying the construction of a transformer were named above, but a few others in regard to the core and windings are: the core must have a cross section large enough to carry the necessary flux at a moderate flux density and should be built up of thin, soft iron plates. These plates should be lightly insulated if the voltage is high and have as little hysteresis as possible. The mean length of turn must be as small as possible in order to minimize the I^2R losses and leakage drop. The coils should be well distributed over the core so as to give plenty of cooling surface. The cooling surface should be large enough to get rid of the heat produced in the iron and copper parts. There are very few transformers which have enough cooling surface to get rid of the heat, so other means of cooling the transformer are necessary. Some of the different ways are: (1) to put the transformer in a case with oil around it. The oil carries the heat from the core and coils out to the case; (2) tubes are placed around and between the coils and water flowing through the tubes keeps the coils cool; (3) air cooled by fan motors.

The two main types of transformers as named above are the shell and core. A transformer in which the coils form an elongated structure and are surrounded by laminated iron, is called a shell-type transformer. A core transformer is one in which the coils of wire surround a more or less elongated core of laminated iron. There are several different forms of these two types of transformers.

In high tension transformers great care should be taken in insulating the windings, for if there is not enough insulation or if the insulation is of poor quality it may break down under the high voltage, which would cause a great deal of trouble if not destroy the transformer.

In low tension transformers the insulation does not need to be so heavy for there is no danger of it breaking down.

Constructed Transformer.

In the construction of this transformer we chose the core type. The proper size of core, number of turns and size of conductors were figured, as are given below. The primary turns were divided into two parts, half on each leg. The secondary coil were divided into eight coils, half on each leg. The four secondary coils on each leg were connected in parallel, and the two sets of four coils were connected in series.

These coils were made in the machine shop, and placed on the core after construction. The primary coils were placed on first and the secondary coils placed at the end of the primary coils. This is a poor arrangement of coils because the flux generated by the primary coils cannot all pass through the secondary coils. This causes a large leakage flux. A much better arrangement would have been to put two secondary coils at each end of primary coils, which would cut down the leakage flux. In order to get the best results the primary coils would have to be halved and sandwiched still more between the secondary coils.

The only available copper to be used in the coils was # 12 B & S. It would have been some better if bar copper had been used.

Design of High Current Transformer.

Preliminary Calculations.

The required area of the core is found from the formula $\frac{\Phi}{B}$, where Φ is equal to the flux in lines and B_m is the density per sq. in. Area = $\frac{515000}{43000}$ = 12 sq. in. A core of this cross section would be 4" wide and 3" thick.

Type of transformer.............core

Output in K. W...................10

Terminal volts (primary)...... 110

Terminal volts (secondary).... 11

Cycles per second............. 60

Flux in core..................515 megolines

Density per sq. in. (core)...43000 lines

Ratio of transformation.........10 to 1

Allowable cir. mils per ampere for:

Primary......................1300

Secondary....................1600

Calculation of Primary Coil.

The first thing about the primary coil is to be determined the number of turns it is to contain. The formula for finding the number of turns is $N = \frac{E' \times 10^8}{4.44 \Phi f}$ where is the flux in lines.

E' = primary voltage

f = frequency

$$N' = \frac{110 \times 10^8}{4.44 \times 515000 \times 60} = 80 \text{ turns.}$$

The coil is to be wound on both legs of the transformer, that is, one half the total number of turns, i. e., 40 turns, is to be placed on each leg. In order to get a coil that would not require too much core space and at the same time not heat up, the 40 turns were divided into 4 layers with 10 turns per layer.

Current in the Primary Coil.

The current in the primary is equal to the output, P, in watts divided by the primary voltage, E'. That is $I = \frac{P}{E}$ or $I = \frac{10000}{110} = 90.9$ amperes.

Size of Primary Conductor.

The number of cir. mils per ampere vary from 1000 to 1500. In this case 1300 cir. mils per ampere was taken because it is a good average of the two limiting values.

1300 x 90.9 = 118,170 cir. mils in the primary conductor.

The wire to be used in the construction of this coil is # 12 B & S guage. The number of cir. mils in a # 12 B & S wire is about 6550. The number of these wires required is 118,170/6550 or 18.

The dia. of # 12 B & S wire is .0808". The cross sectional area of 18 wires in sq. inches is

$18 \times (.0808)^2 \times 3.1416 \times .7854 = .29$ sq. in.

10 turns of 18 # 12 B & S wire was placed in a 6" space. That is, the width of each winding is .29 x 10/6 = .483 in. The height of the 4 layers is 4 x .483 = 1.932 in.

The coil is a little larger than this because of the insulation on each wire and the tape on the whole conductor. The conductor of 18 wires was wrapped with two layers of cotton tape. After the coil of 40 turns was made it was taped with two layers of friction tape. The actual size of the coil when completed is 6" .2 x 2.2". The 2.2 is the thickness of the 4 turns plus insulation. The inside of the core was made some larger than the core or the dimensions are 4.3" by 3.3".

A mean turn of the coil is (4.3" plus 2.2") 2 plus (3.3" plus 2.2")2 = 24" = 2'. 40 turns x 2' = 80', the length of the conductor. The resistance of 1 ft. of # 12 B & S wire is .001589 x 80 = .1271 ohm. The resistance of the coil of 18 wires equals $\frac{1}{R} = \frac{18}{.1271}$ = 141.5 ohms, or R equals $\frac{1}{141.5}$ = .00706 ohm. The resistance of both coils equals 2 x .00706 = .01416 ohm.

Calculations of Secondary Coil.

Ratio of transformation = 10 to 1. The ratio of turns is equal to the ratio of transformation, that is,

$\frac{N'}{N''} = \frac{10}{1}$ where

N' = primary turns.

N" = secondary turns.

$N'' = \frac{80}{10} = 8$ turns.

The secondary turns are wound similarly to the primary coils, that is, 4 turns on each leg of the transformer.

Secondary Current.

The currents in a transformer are inversely proportional to the ratio of transformation, that is,

$$\frac{I'}{I''} = \frac{1}{10}.$$

I' = primary current.

I" = secondary current.

I" = 90.9 x 10 = 909 amperes.

1600 cir. mils per ampere was chosen because the current is so high.

909 x 1600 = 1,455,000 cir. mils in the secondary coil. # 12 B & S wire was used in the construction of these secondary coils. The dia. of # 12 B & S wire is .0808 or about 6550 cir mils. The number of wires needed in parallel to carry this current is 1,455,000/6550 = 220 wires. 220 wires in parallel would be too large to wind so they were divided into 4 bunches of 55 wires each. Each bunch was wound 4 times on itself and corresponding terminals of 4 coils were connected together, so that the four coils were connected in parallel. The four coils on one leg were connected in series with the four coils on the other leg.

The cross section of the secondary coil in sq. inches is $55 \times (.0808)^2 \times 3.1416 \times .7854 = .886$ sq. in. The width of the coil is 1.25". The thickness would then be $\frac{.886 \times 4}{125} = 2.84"$ high. The same insulation was used on the secondary coils as was used on the primary coils. The actual dimensions of each secondary coil is 1.75" by 3". These dimensions varies some. The inside dimensions of the coils are the same as the inside dimensions of the primary coils. A mean turn of a secondary coil is (4.3" plus 3")2 plus (3.3" plus 3")2 equals 27.2".

There are four turns in each coil or 4 x 27.2" equals 108.8", which equals 9.06' long. Leads were left on each end of the coils for connections, which makes the total length of a coil 10'. The resistance of 1 ft. of # 12 B & S wire is .001589 ohm. The resistance of one # 12 B & S wire 10' long is 10' x .001589 ohm = .01589 ohm. The resistance of 220 wires in parallel and 10' long is $R = 1/\frac{225}{.01589} = 1/14160 = .0000706$ ohm. The resistance of both coils at 50° C. in series is 2 x .0000706 = .0001412 ohm.

The weight of 1000 ft. of # 12 B & S wire is 19.77 lbs. The number of ft. of # 12 B & S wire in the primary coils is 36 x 80 = 2880 ft. The weight of primary coils is 2880 x 19.77/1000 = 57 lbs. The length of a # 12 wire in the secondary coil is 220 x 20 = 4400 ft. The weight of the secondary coils is 4400 x 19.77/1000 = 87 lbs. The total weight of the coils is a little more than this, due to insulation on the wire.

The Core.

The core of this transformer is designed to have inside dimensions of 13.5" by 6". As stated before, the cross-section of the core is 12 sq. in. or 4" by 3".

Therefore the outside dimensions are 19.5" by 12". The number of cubic inches in the core is 3" x 4" x 51" = 612 cubic inches. The weight of laminated iron is .283 lb. per cu. in. The weight of the core is .283 x 492 = 139.2 lb. Wood fiber insulation was put over the core and under the windings. This gives core a weight of 140 lbs.

Iron Losses in Core.

Hysteresis loss and eddy current loss are the losses in a transformer core. The formula for finding the hysteresis loss is:

$$P_h = K_h \, f \, V \, B_{max}^{1.6} \times 10^{-7}$$

where K_h = .003, which is a hysteresis factor taken from the standard hand book.

f = 60 cycles.

V = Volume of core in cu. cm. = $612 \times (2.54)^3$ = 16000 cu. cm.

B = density per sq. cm.

The density as given at the beginning is 43000 lines per sq. in. 43000 lines per sq. in. reduced to lines per sq. cm. equals 43000/6.45 equals 6670 lines per sq. cm.

$$P_h = .003 \times 60 \times 16000 \times 6670^{1.6} \times 10^{-7}$$

$6670^{1.6}$ = (log. 6670 x 1.6) = 3.82413 x 1.6 = 6.11860 anti log of 6.11860 = 1314000

$P_h = .003 \times 60 \times 16000 \times 1314000 \times 10^{-7}$ = 141.37 watts.

Electricity, in its passage through the iron sheets, follows the laws common to all electric circuits and produces heat proportional to the product of the square of the current and the resistance of its path. The watts thus dissipated is called eddy currents and may be expressed by the formula:

$$P_e = K_e \ (t \ f \ B_{max})^2 \ x \ 10^{-11}$$

wherein t is the thickness of the sheets in cm., and K_e the coefficient of eddy current loss. The value of K_e for plain steel or wrought iron is 1.65. The value of t is 15.6 mils = 15.6 x 2.54/1000 = .04 cm.

P_e = 1.65vx 16000 x (.04 x 60 x 6670)^2 x 10^{-11}= 1.65 x 1.6 x 25.6 = 67.58 watts.

P_h plus P_e = 141.37 plus 67.58 = 208.95 watts.

The current required to overcome the core loss is called the primary exciting current and is represented by I_c. $I_c = P_h$ plus P_e/E, wherein E = primary volts.

$I_c = \frac{208.95}{110}$ = 1.9 amperes.

A formula for finding I_q, the effective magnetizing current, is

$$I_q = \frac{10B \ l}{4 \pi \ 2^{\frac{1}{2}} \ N \ u}$$

wherein l = mean length of magnetic circuit in cm.

N = no. of primary turns.

u = permeability of core.

u = 2800-3.2 (7500-B)^2 x 10^{-5} (from standard hand-book).

u = 2800 - 22 = 2778.

$$I_q = \frac{10 \times 6670 \times 129.6}{1.26 \times 80 \times 16000 \times 2778 \times 1.414} =$$

2.18 amperes.

$$i = \frac{515000 \times 129.6}{1.26 \times 80 \times 16000 \times 2778} = .0149$$

No-Load Current.

$$I_m = (I_c^2 \text{ plus } I_q^2)^{\frac{1}{2}}$$

wherein I_c is the current consumed by core loss.

I_q is the sattless exciting current.

$I_m = (1.9 \text{ plus } 2.18)^{\frac{1}{2}} = 2.9$ amperes.

Angle of Lag.

I_m lags behind the impressed e. m. f. by a time-angle the cosine of which is as follows:

$$\text{Cos } \theta = \frac{I_c}{(I_c^2 \text{ plus } I_q^2)^{\frac{1}{2}}} = \frac{1.9}{2.9} = .655$$

$\theta = 40^{\circ}\ 55'$ the angular difference between the primary voltage and the exciting current.

Total Leakage Reactance.

Total leakage reactance is the sum of the primary leakage reactance and a quantity equal to N^2 times the secondary leakage reactance, where N is the ratio of the turns in series in the primary to the turns in series in the secondary. The total leakage reactance is found when the secondary is short circuited upon itself and the impedance of the transformer is measured in the primary circuit.

Leakage Reactance.

The formula for finding the leakage reactance is

$$P = \frac{4 \pi N^2}{l} \left(\frac{X}{3} \text{ plus } \frac{Y}{3} \text{ plus } g\right)$$

where N' is the number of turns in the primary coil on one leg.   is the thickness of the coil in centimeters. l is the thickness of the primary coil. X & Y are the width of the primary and secondary coils respectively. g is the distance between coils.

$$P = \frac{4 \times 3.1416 \times 1600 \times 2.54 \times 4}{2.4} \times 2.7 = 229000$$

$$X = \text{reactance} = 2 \pi f P \times 10^{-9} = (6.28 \times 60 \times 229000 \times 10^{-9}) = .0865 \text{ ohm for one leg.}$$

The reactance X for both legs is 2 x .0865 = 173 ohm.

The resistance of primary = .01412 ohm.

The resistance of secondary = .0001412 ohm, as figured above.

In order to check the accuracy of the reactance, the different values were substituted in a combination of simple circuits which is equivalent to a transformer delivering current to a given secondary receiving circuit.

R' = resistance of primary.

R'' = resistance of secondary.

R = resistance of receiving circuit.

X = reactance.

R' plus R'' plus R = .0128 plus 0425 plus 1.28 = 1.335 ohm.

$Z = (R^2 \text{ plus } X^2)^{\frac{1}{2}} = (1.77 \text{ plus } .51)^{\frac{1}{2}} = 1.54$ ohm.

$I = \frac{E}{Z} = \frac{110}{1.31} = 84$ amperes

where I = current in primary coil.

The formula for finding the leakage reactance is not exactly correct for a transformer, which has the coils placed as these are. The actual resistance and reactance was measured and used in the computation. They are as follows:

$R' = .0128$

$R'' = .000425$

$R_t = R'$ plus $100\ R'' = .0553$

$I_{oo} = 1.840$

$I_{mag} = .925$

$I_w = 1.58$

$X_1 = .36$

$X_2 = .0036$

$X_t = .72$

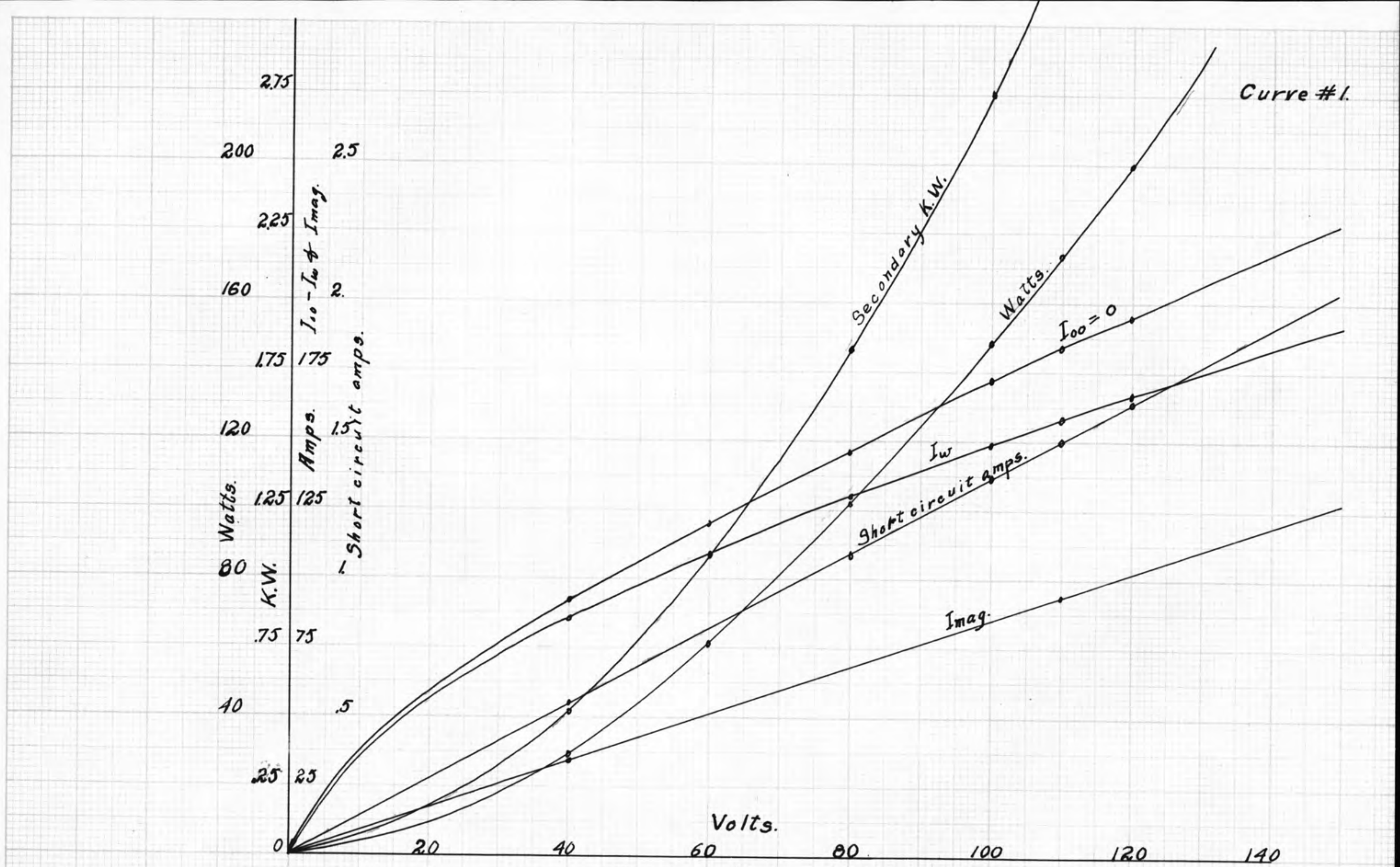
Primary admittance (no-load) $= \frac{I_{oo}}{E'} =$

$\frac{.925 \text{ plus } j\ 1.58}{110} = Y = .0084$ plus $j.0143$.

The following data was taken by actual test and used in plotting the curves on curve sheet #1.

Data for No-Load Curves.

Volts	Watts Sec.	Watts	I_{oo}	$I_{mag\ w}$	I_{mag}	I sec
40	.5	35	.925	.55	.25	55
60	1.1	67	1.23	1.1	.5	83
80	1.88	106	1.48	1.24	.7	110
100	2.75	150	1.73	1.5	.85	138
110	3.4	176	1.84	1.6	.94	150
120		200	1.95	1.66	1.05	165



Curves obtained from test.
Short Circuited through .000877 ohm.

Current and voltage relations as calculated from "Steinmetz" method, and to be used in circle and vector diagrams:

$Z_1 = (.000425 - j.0036)$ $Z_0 = (.0128 - j.36)$

Z = load res. plus Sec. res - j sec. reac. = .0085 plus .00425 - j.0036 = 10830e (.00895 plus j.0036)

Sec. imp. voltage = $E_1' = I_1 Z_1 = 10.83e(.0167 - j.0307) = e(.181-j.333)$

Sec. term. voltage = $e-E_1' = E = e(.819$ plus $j.333) = .885e$

reduced = .885e

Prin. counter gen. e. m. f. = 10 e

Prin. load $I = I' = .1xI_1 = 1083e\ (.00895$ plus $j.0036) = 10.83e(.895$ plus $j.36)$

Exciting current = $I_{oo} = E\,Y = e(.084$ plus $j.143)$

Total prim. current = $I_o = I'$ plus $I_{oo} = (97$ plus $j3.9)e$ plus $(.084$ plus $j.143)e - e(9.784$ plus $j4.043)$

Primary impetance voltage, $E_o' = Z_oI_o =$

$(\ (0128 - j.36) \times e(9.784$ plus $j4.043)\ ) =$

$e(1.5802-j2.A693)$ Expanded.

Thus, primary impressed e. m. f., E_o, = E_i plus $E_o' = 10e$ plus $e(1.5802 - j\,2.4693) =$

$e(11.5802 - j\,2.4693) = e(\ (11.58)^2$ plus $(2.47)^2)^{\frac{1}{2}} = 11.83\ e$

$e_o = 110$, therefore $e = 9.28$

Sec. current = I_1 = (902 plus j 362) =

972 ampere

Sec. term. voltage = E = .885e = 8.22 volts.

Prin. current = I_0 = 9.28(9.784 plus j 4.043) =

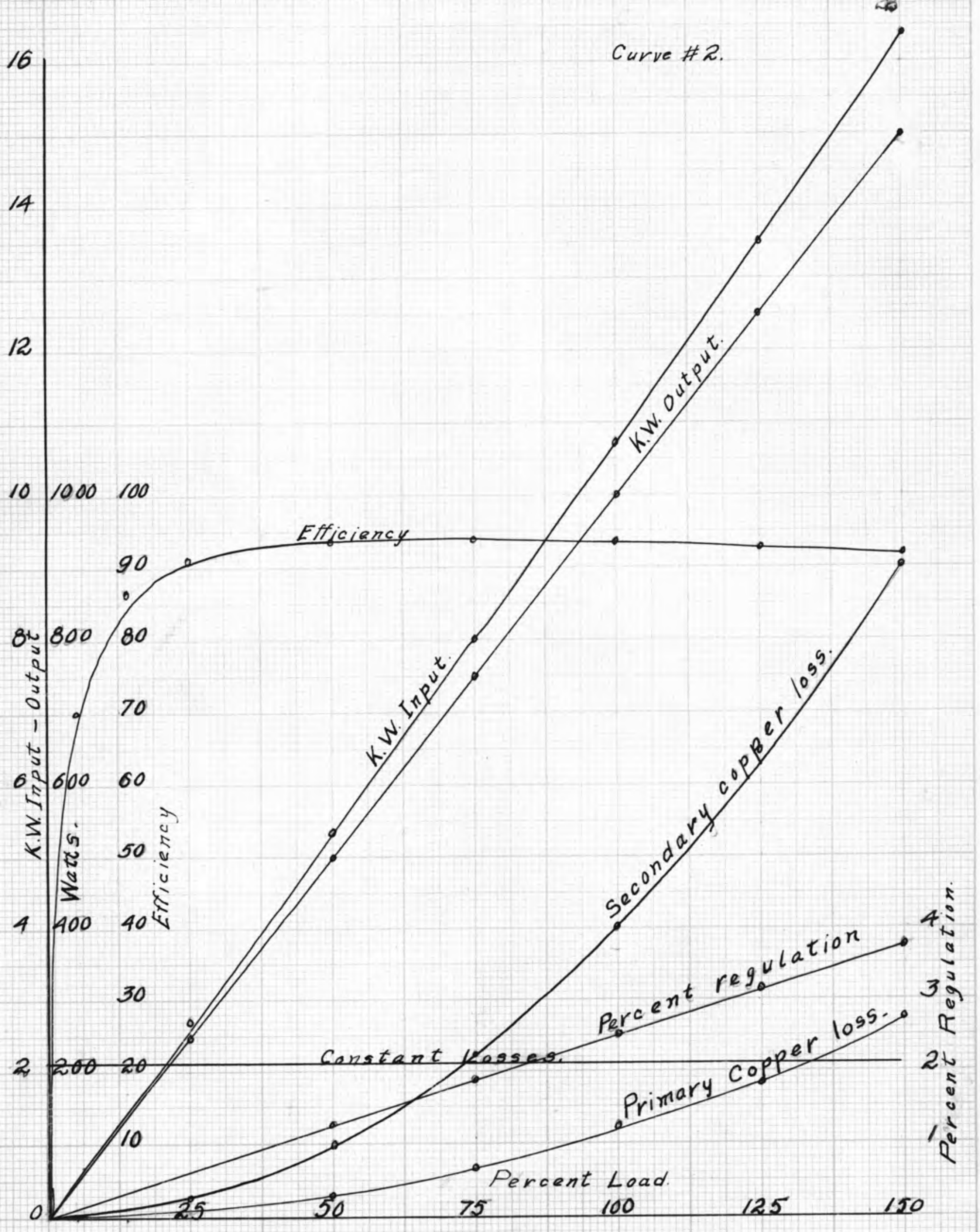
90.8 plus j 37.5 = 98.2 amperes.

Data for Performance Curves.

The primary current, secondary current, and watts output, at full load are known, so that their values, at any other percent load, can be obtained by direct proportion. The resistance of primary and secondary coils are known, therefore the watts lost in them was found from the formula $I^2R =$ watts lost. The input is equal to the sum of the output and losses. The efficiency is found by dividing output by input.

$I_p^2 R_p$	$I_s^2 R_s$	Constant Loss	Input	Output	%Eff.
7.7	25	209	2741.7	2500	91.2
30.9	100	209	5339.9	5000	93.7
69	226	209	8004	7500	93.7
123	402	209	10734	10,000	93.3
182	630	209	13531	12,500	92.3
276	905	209	16390	15,000	91.7
2.80	9	209	1720.8	1500	87
.3	.63	209	710	500	70.4

%Load	%Voltage Regulation	Volts drop
25	.63	.695
50	1.26	1.39
75	1.89	2.085
1	2.52	2.78
125	3.15	3.475
150	3.78	4.170
15		
5		



Performance Curves of a High Current Transformer.

Circle Diagram.

It is easily seen that the locus of the current produced by a constant voltage in a circuit of constant reactance and variable resistance is a circle. The diameter of this circle is at right angles to the primary voltage. To vary the resistance of the secondary receiving circuit is to change the resistance in the main circ it without changing its reactance. At this condition the locus of the load current I' in the primary coil of a transformer is a circle. The line OE, curve #3, represents the constant primary voltage, the line M represents the magnetizing current in its phase position, and the line I' drawn from the point O' to any point P on the circular locus represents a possible value of the load current in the primary coil. The diameter O' D represents the current which E' would produce in a circuit of reactance wP and zero resistance, this diameter therefore represents E' / wP amperes. The total primary current is the vector sum of M and I' and it is represented by the line O P. The line O P_1 represents the value of the short circuit current in its phase position.

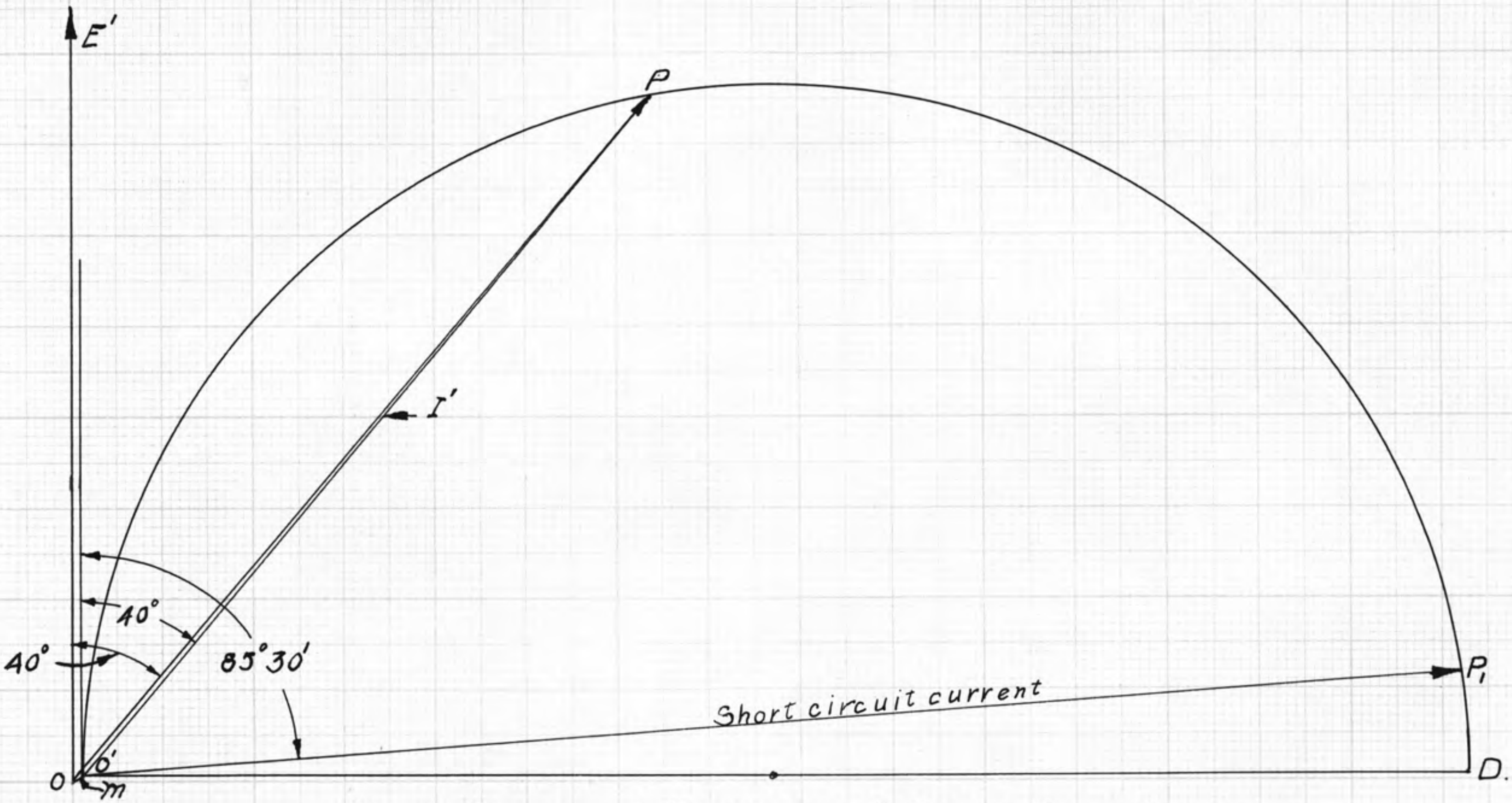
Vector Diagram.

The values used in the vector diagram were obtained partly from previously figured data and partly from trigonometrically figured data. Most of the angles weze obtained trigonometrically, although some were found by

Steinmetz method, which is given above. The values of the different quantities used in the diagram are:

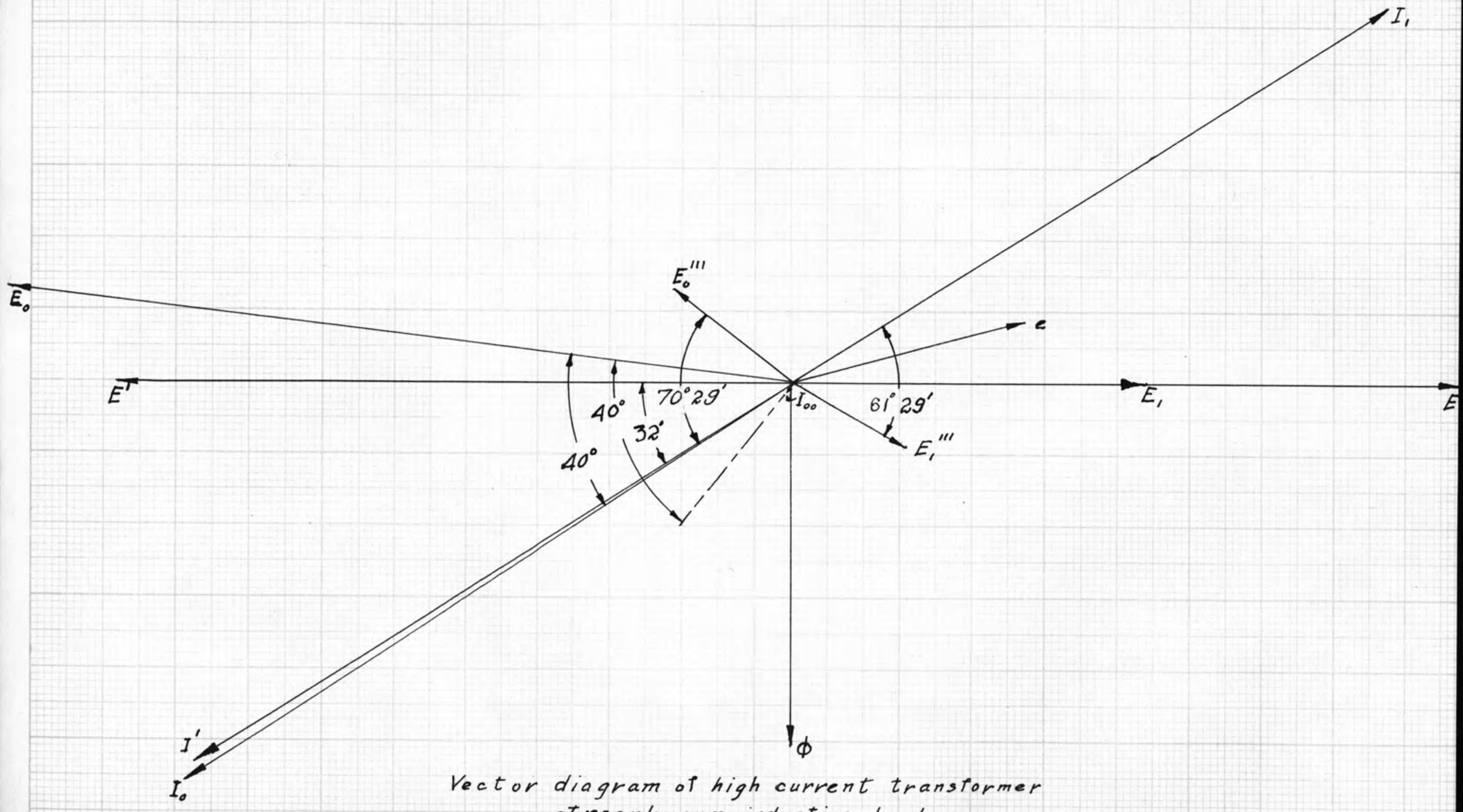
Φ (megolines)	.515
E_0	110.
E'	93.
E''_0	20.4
I'	98.2
I_0	101.
I_{00}	1.54
E_i	92.8
E''_1	18.5
E_1	8.22
e	9.28
I_1	972.

Curve #3.



Circle Diagram of Transformer Delivering Current
to Non-inductive Receiving Circuit.

Curve # 4.



Vector diagram of high current transformer at nearly non-inductive load.

SUMMARY OF SPECIFICATIONS AND TECHNICAL DATA.

1. Output in kilo-watts or K. V. A, 10
2. Primary voltage, 110
3. Secondary voltage, 11
4. Frequency in cycles per second, 60
5. Type of transformer, Core.
6. Maximum flux in mega-lines, .515 mg
7. Maximum flux density, lines per sq. in. 43000
8. Number of primary turns, 80
9. Number of secondary turns, 8
10. Area of cross section of iron in core, 12 sq. in.
11. Allowance in % for insulation between laminations, 10%
12. Size and shape of primary conductor, .48" x .55"
13. Number of circular mils per ampere in primary, 1300
14. Thickness of tape, 40 mils. Thickness of paper.
15. Total thickness of paper on primary winding.
16. Composition of insulation on primary, tape, linen and compound.
17. Size and shape of secondary conductor, 1.25" x .71"
18. Number of circular mils per ampere in secondary, 1600
19. Total thickness of insulation on secondary, mils, 40
20. Composition of insulation on secondary, friction tape and compound.
21. Arrangement of primary and secondary coils, primary at end of secondary.
22. Number of turns per section of primary winding, 40

23. Number of turns per section of secondary winding
24. Number of sections of primary,
25. Number of sections of secondary,
26. Manner of separating coils from core, wood fiber.
27. Size of opening in core for coils, 13.5" x 6".
28. Dimensions of core tongue.
29. Complete outside dimensions of core, 19.5" x 12"
30. Cubic contents of core, cu. in., 612
31. Volume of iron in core, cu. in., 551
32. Thickness of laminations, mils, 17
33. Factor of hysteretic loss, .003
34. Factor of eddy current loss, 1.65
35. Hysteresis loss, watts, 141.4
36. Eddy current loss, watts, 6758
37. Total iron or constant loss, watts, 209
38. Mean length of magnetic circuit, 45"
39. Ampere turns per inch at maximum density, 8
40. Virtual primary amperes required for magnetization, 1.33
41. Power component of exciting current, .78
42. Value of and phase position of exciting current with reference to E_0, 1.54 and 59° 40'.
43. Mean length of primary turn, 24"
44. Resistance of primary winding at 50 deg. C., ohm, .0128
45. Mean length of secondary turn, 2.72

46. Resistance of secondary winding at 50
deg. C., ohm, 000425

47. Primary copper loss at full load, watts, 123

48. Secondary copper loss at full load, watts, 402

49. Total copper loss at full load, watts, 525

50. Copper loss plus iron loss at full load, watts 734

51. Efficiency at 1/4 load 97.2

Efficiency at 1/2 load 93.7

Efficiency at 3/4 load 93.3

Efficiency at 1 load 93.7

Efficiency at 1 1/4 load 92.3

Efficiency at 1 1/2 load 91.7

52. Formula used for calculation of leakage
reactance. Determined by test.

53. Leakage reactance in primary terms, 72 ohm.

54. Diameter of circular current locus, 157 amperes.

55. Maximum short circuit current and phase position
with E_0, 135 amperes.

56. Value and phase position of primary current with
reference to E_0 at full load (non-inductive) 98.2
amperes.

57. Secondary terminal voltage at full non-inductive
load. 8.22 volts.

58. Maximum efficiency of transformer. Unity
power factor. 93.7

59. Position of maximum efficiency. 1 load.

60. Weight of iron in core, 156 lbs.

61. Weight of copper in coils, 136 lbs.

62. Copper loss per square inch of coil surface, .694 watt.

63. Total transformer loss per square inch of external surface.

64. Method of cooling. Air cooled.

65. Maximum increase of temperature at full non-inductive load.

66. Output per pound weight of active material, 34.2 watts.