THESIS

D. C. NEUTRAL FOR A THREE PHASE CONVERTER

A. P. BOCK

1920

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Relay computer

THESIS

ONE METHOD OF MAINTAINING THE NEUTRAL OF A DIRECT CURRENT THREE WIRE SYSTEM SUPPLIED BY A ROTARY CONVERTER

A Thesis Submitted

to

The Faculty

of

Michigan Agricultural College

By

A.P. Bock

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Bachelor of Science

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THESIS

Contents

Introduction

This thesis covers the design and construction and a study of the characteristics of interconnected star transformers to be used with a three phase inverted converter that is to supply a three wire Edison system. The ordinary conditions under which a converter supplies a three wire system is with the converter feeding from the A.C. side. But in the electrical laboratory at M.A.C., it was desirous to have a continuous 110 volt D.C. voltage. Since 220 volts and an inverted converter were available, it was decided upon to design and construct interconnected star transformersfor maintaining a neutral that would be free from triple harmonic voltages, and that would allow the unbalanced D.C. through the transformer windings without magnetizing the cores. These transformers were not designed with the purpose of highest operating efficiency obtainable, but simply to get results with a reasonable amount of material and to make something for the Electrical Engineering Department to build up on in increasing the equipment.

The core stampings used were previously cut, and while not the size to afford the highest economy in copper per turn for the capacity of the transformers constructed, they served their purpose very well.
As it was desirous to be able to get 110 or 220 volts A.C. from the converter, the design of the secondaries for those voltages is included in this thesis.

Introduction

Since this thesis covers the study of the interconnected star for deriving a D.C. neutral, the secondaries for the transformers were not constructed. A brief discussion of rotary converters and the theory of voltage relations will be included as it is important to be familiar with them before dealing with the derivation of the D.C. neutral by interconnected star transformers.

The author is indebted to Professor M.M. Cory for supervision and to Professor A.R. Sawyer for suggestions in the design of the transformers. The author also wishes to acknowledge his indebtedness to Mr, R.D. Wyckoff and Mr. R.M. Heasley in regards to the oscillograms furnished by them.

Voltage Relations in a Rotary Converter

The Rotary Converter, used to change A.C. to D.C. or D.C. to A.C. combines the characteristics of both motor and generator in one armature winding. When used to change D.C. into A.C. it is known as the inverted converter. This is the kind of converter dealt with in this thesis. Any synchronous converter can be operated inverted, the only difference being that the machine has the characteristics of a D.C. motor instead of the characteristics of a synchronous motor.

The matter of voltage ratios between D.C. and A.C. and what affects them is one of importance in this thesis since it is required to get the specified A.C. voltages for parallel operation with other machines and to have the D.C. to neutral voltages balanced.

First, the single phase converter, the value of the D.C. voltage is equal to the maximum value of the A.C. This is evident from the fact that the brushes in a D.C. machine are placed so that the D.C. voltage at all times is equal to the arithmetical sum of all the E.M.Fs of the armature coils that are in series. In the case of an A.C. machine or the A.C. side of the converter, the A.C. voltage is equal to the arithmetical sum of the armature coil voltages in series at a time when both sides of the coils of each phase are directly under poles. This is the point of maximum voltage and is equal to the D.C. voltage.

So for a single phase converter

$$^{m}E_{ac} = E_{dc}$$

$$\text{or} \quad E_{ac} = .707E_{dc}$$

In a quarter phase or two phase converter, the A.C. taps are taken out of the armature 90 electrical degrees apart while the D.C. brushes are 180 electrical degrees apart. The relation between the maximum A.C. voltage and the D.C. voltage in this case is the same as the ratio of the chord to the arc of the circle as shown in Fig. I.

$$^{m}E_{ac} = .707\ E_{dc}$$

$$\text{or} \quad E_{ac} = .707 \times .707\ E_{dc} \quad \text{or}\ .500\ E_{dc}$$

For 3Φ converter, the taps are taken out at 120 electrical degrees while the D.C. brushes are 180 degrees.

$$^{m}E_{ac} = \text{Sin}\ 1/2 \cdot 120^{\circ}\ E_{dc}$$

$$\text{or} \quad E_{ac} = \text{Sin}\ 60 \times .707\ E_{dc} \quad \text{or} \quad .612\ E_{dc}$$

For a 6 Φ converter, the taps are 60 degrees

$$^{m}E_{ac} = \text{Sin}\ 30\ \ E_{dc}$$

$$\text{or} \quad E_{ac} = \text{Sin}\ 30 \times .707\ E_{dc} \quad \text{or} \quad .354\ E_{dc}$$

For an n phase converter the formula would be

$$E_{ac} = \text{Sin}\ \frac{180}{n}\ .707\ E_{dc}$$

The preceding ratios of E.M.Fs apply only to generated E.M.F.s and under the assumption of a sine wave of A.C. If the A.C. voltage wave is peaked, the D.C. voltage will be higher, and if it is flat, the D.C. voltage will be lower. This fact is made use of in the split pole converter,

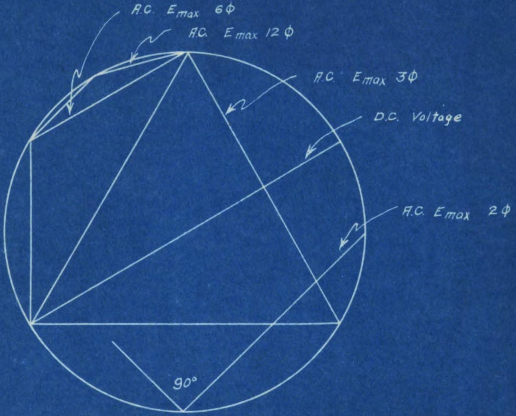
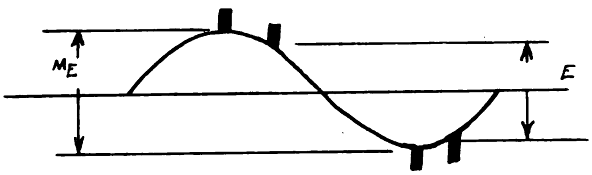


FIG. I

VECTOR DIAGRAM SHOWING VOLTAGE RELATIONS OF D.C. TO A.C. MAXIMUM FOR 2Φ, 3Φ, 6Φ AND 12Φ CONVERTER

where the A.C. voltage wave can be made peaked or flat at will. (See "Electrical Engineering" by Steinmetz)

The variation of the ratio due to brush shift is important, especially in the smaller size machines. When the D.C. brushes are in the neutral position, the voltage across the brushes is equal to the maximum value of the A.C. wave, but when not in the neutral position, the voltage is reduced accordingly, because they are not placed so that the coils have maximum voltage induced between the brushes.



When an inverted converter operates singly, its speed may be seriously affected by a change in load or power factor on the A.C. side. The speed change with change of power factor is so marked that safety devices are applied in some cases to prevent excessive speeds when a lagging power factor load is thrown on. In the case of a lagging power factor load, the current component that is 90 degrees behind the voltage furnishesa m.m.f that opposes the field flux and reduces the number of lines of force cut by the inductors. This in turn reduces the C.E.M.F. of the machine causing the speed to increase until the C.E.M.F. is up to normal value again.

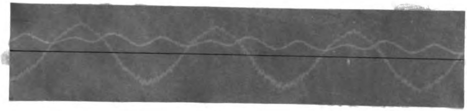
In a converter feeding a three wire system, the neutral can be derived by connection to the transformer neutral. For instance the neutral of a three phase star transformer connection can be used for the D.C. neutral with a three phase converter. The maximum voltage (^{m}E) of the A.C. from any line to neutral is equal to one half the voltage across the D.C. brushes, or is half way between the D.C. voltage across the brushes.

In the case of the converter R_2, the voltage across slip rings is 135. The voltage from any line to neutral is $135/\sqrt{3}$ or 78 volts. The maximum value of this voltage (^{m}E) is 78/.707 or 110 volts, which is the D.C. voltage from either brush to the neutral of the star.

Inverted converters are not as common as synchronous converters, but are used to supply a small amount of A.C. from a D.C. supply. Converter R_2 is to be used for obtaining 110 volts D.C. from the 220 volt mains by the use of interconnected star transformers.

The Interconnedted Star

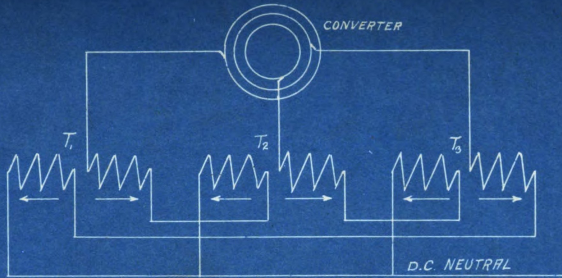
In a simple star connection, the voltage to neutral is distorted by a strong third harmonic. The reason for this is that since no third harmonics can exist in the magnetizing currentof star connected transformers, the hysteresis of the iron distorts the flux and hence any E.M.F. produced by the flux will have the same distortion as the flux. So the neutral of a simple star is not a true neutral, but has a triple harmonic E.M.F impressed upon it. When such a neutral is used for the neutral of a three wire system on D.C., these triple harmonic voltages at the neutral add themselves to the D.C. voltage to neutral and the resulting D.C. voltage will pulsate at a frequency of three times the frequency of the A.C. This is very marked as shown by the accompanying oscillogram which represents the D.C. voltage to neutral using a simple star for the neutral.



By interconnecting the star windings so that two of the phases pass through each transformer, the voltage to neutral (A.C.) will be equal to the vector sum of the voltages across the coils or half primaries, which are $(180^\circ \pm 120^\circ)$ or 60 degrees out of phase with each other. The 180 degree shift is due to the connection of the two coils on each transformer in opposite directions as shown by Fig.II. The sign of 120 degrees depends upon the sequence of phases. The coils being 60 degrees out of phase with each other would indicate that 6 Φ could be obtained. This is true and verifies the above reasoning. Fig. III shows the instantaneous voltages in each coil, and the triple harmonic voltages which exist in each coil voltage. It can be readily seen from the figure that the two fundementals will add up to a greater value- 3 times one coil voltage- while the sum of the triple harmonic voltages is zero at all points.

According to this, the D.C. voltage to neutral will be constant, using the interconnection, because the triple harmonic voltages are neutralized.

Another very important reason for using the interconnected star with a converter supplying a three wire system is the prevention of the saturation of the transformer cores by the neutralization of the m.m.f.s set up by the unbalanced D.C. which flows to the neutral.



PRIMARY CONNECTION INTERCONNECTED STAR TO 3 WIRE SYSTEM

FIG II

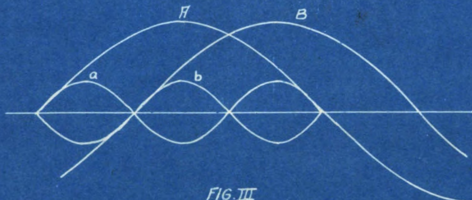


FIG. III

VOLTAGE RELATIONS IN PRIMARY OF ONE TRANSFORMER
SHOWING NEUTRALIZATION OF THIRD HARMONIC VOLTAGES.

A.B 1920

The effect of core saturation of the transformers is to increase the flux density of the transformer cores so that the magnetizing A.C. will increase enough to materially reduce the power factor of the A.C. circuit. The magnetizing or 90 degree lag current becomes great enough in the armature of the converter to decrease the field flux and cause the speed of the converter to rise. So if a sudden D.C. load were thrown on the neutral, the converter would tend to race.

By dividing each primary in two parts and connecting them so that two on the same transformer oppose each other as shown in Fig. II, the m.m.f.'s set up by the D.C. are neutralized and the flux density in the transformer cores remains the same, regardless of the D.C. load to neutral.

Design of Transformers

Symbols Used in Formulae

B - Flux Density in lines per sq. inch. (max. value)

A - Cross Sectional area of Core

f - Frquency in cycles per second

N_p - Number of turns on primary (Effective)

$_aN_p$ - Number of turns on secondary (Actual)

N_s - Number of turns on secondary

E_p - Primary voltage for each transformer

E_s - Secondary voltage (110)

R_p - Resistance of primary in ohms

R_s - Resistance of secondary in ohms (110)

I_p - Primary current in amperes

I_s - Secondary current in amperes

l_p - Mean length of turn of primary

l_s - Mean length of turn of secondary

T - Temperature rise in Degrees Centigrade

k - Coefficient of radiation (Average 180)

S - Surface of one coil unit in square inches

Design of Transformers

3 - 1.5 K.V.A. Transformers, primaries interconnected Star. Frequency 50 cycles per second.

Punchings form a hollow rectangle whose area is 41.8 sq.in.

(See Blueprint of assembly)

Assumed Efficiency 90%

Iron losses--------------75watts

Copper losses----- -----75watts

Total 150 watts

Flux density used------ 60 000 lines per sq. in.

Loss per lb. of iron at 50 cycles for transformer iron 1.4 watts

$\frac{75}{1.4} =$ 53 lbs. or $\frac{53}{.26} =$ 204 cu. in. of iron

Lamination factor used----- .85

$\frac{204}{41.8 \times .85} =$ 5.7 inches high for the iron. Use 5.5 inches.

$A = 5.5 \times 1.75 \times .85 = 8.2$ sq. in.

Solving for effective number of turns in primary

$$E_p = \frac{ABN_p\,2\pi f}{10^8 \times \sqrt{2}}$$

It is interesting to note how this formula for counter E.M.F. corresponds to the formula for the voltage of a D.C. machine $E = \frac{\Phi \times Z \times N \times p}{10^8 \times p'}$. Φ corresponds to AB, $\frac{Z}{p'}$ corresponds to N_p , and N correspondsto w or $2\pi f$.

Design of Transformers

In the counter E.M.F. formula for transformers it is necessary to divide by the $\sqrt{2}$ since B represents the maximum value of the flux density.

The formula can be put into the form

$$E_p = \frac{f \times N_p \times A \times B}{10^8} \times 4.44$$

Since the transformers are star connected, the voltage across one primary will be equal to

$$\frac{135}{\sqrt{3}} = 78 \text{ volts.}$$

This is the same as the voltage to neutral. The slip ring voltage of the converter is 135.

$$78 = \frac{50 \times N_p \times 8.2 \times 60000 \times 4.44}{10^8}$$

$$N_p = \frac{78000}{5 \times 8.2 \times 6 \times 4.44} = 71 \text{ Effective Turns.}$$

Actual number of turns required for the interconnected star

$$\frac{71}{\sqrt{3}} \times 2 = 82. \quad \text{(see Fig. VI)}$$

For convenience in winding use 80 turns and solve for the new value of flux density.

The new value of flux density will then be

$$B = \frac{E_p \times 10^8}{4.44 \times f \times N_p \times A} = \frac{78 \times 10^8}{4.44 \times 50 \times 69.5 \times 8.2} = 61500$$

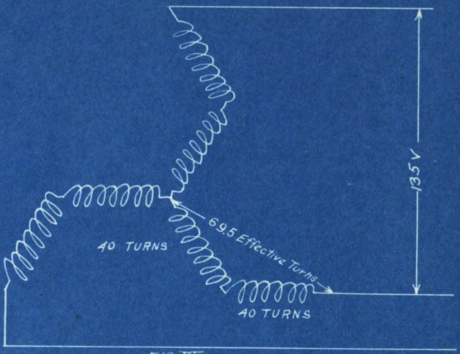
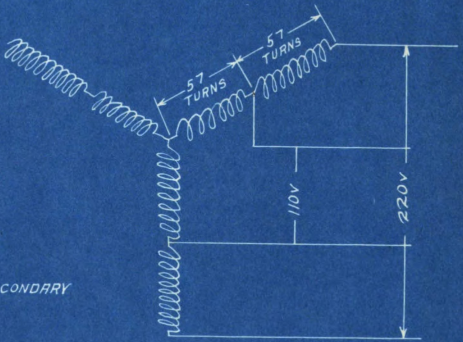


FIG. VI

INTERCONNECTED STAR PRIMARY



STAR SECONDARY

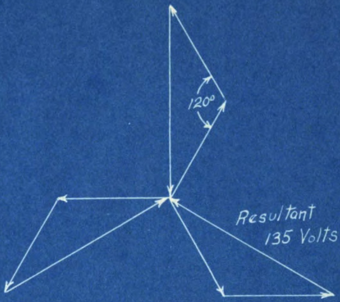


FIG. IV
VECTOR DIAGRAM OF INTERCONNECTED STAR VOLTAGES

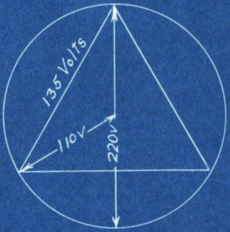


FIG. V
VECTOR DIAGRAM SHOWING VOLTAGE TO NEUTRAL
ON A THREE PHASE CONVERTER

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Design of Transformers

Since the effective turns produce the flux, the secondary voltage is proportional to the ratio of secondary turns to **effective** primary turns and not the actual number that is put on the primary.

The new value for effective turns when 80 actual are used is $\frac{80}{2} \times 3 = 69.5$.

$$N_s = \frac{E_s}{E_p} \times N_p = \frac{110}{135} \times 69.5 = 57 \text{ Turns for 110 volts}$$

$2 \times 57 = 114$ total turns for 220 vplts

Current Densities

Current in the primary is equal to the line current for the star connection.

Primary power input = Output + losses

Primary power input = $[1500 \times 3] + 450 = 4950$ watts.

$$I_p = \frac{4950}{135 \times \sqrt{3}} = 21.15 \text{ amperes.}$$

$$I_s = \frac{4500}{110 \times \sqrt{3}} = 23.6 \text{ amperes.}$$

Use a current density of about 1500 amperes per sq.in.

$\frac{21.15}{1500} = .0141$ sq.in. Use 2 No. 10's = .01631sq.in.

Current density will then be $\frac{21.15}{.01631} = 1295$ amp. per sq.in.

Design of Transformers.

Current in Secondary 23.6 amperes.

$\frac{23.6}{1500}$ = .01572 sq. in. Use 2 no. 10's = .01631 sq.in.

Current density will then be $\frac{23.6}{.01631}$ = 1450 amp./sq.in.

Resistances of Primary and Secondary

l_p = 18 inches or 1.5 ft.

l_s = 22 inches or 1.83 ft. (See Fig. VII)

$$R_p = \frac{80 \times 1.5 \times .558}{1000} = .067 \text{ Ohms.}$$

$$R_s = \frac{57 \times 1.83 \times .558}{1000} = .0583 \text{ Ohms.}$$

.558 = Resistance per 1000 ft. of 2 No. 10's.

Copper Losses

Primary = $I_p^2 \times R_p$ = $21.15^2 \times .067$ = 30 watts.

Secondary = $I_s^2 \times R_s$ = $23.6^2 \times .0583$ = 32.5 watts.

Total Copper losses 62.5 watts.

Iron losses

Loss per lb. at 50 cycles when B = 61500 1.42 watts.

53.5×1.42 = 76 watts.

Total losses at 1.5 K.V.A. 138.5 watts.

$$\text{Efficiency} = 1.00 - \frac{138.5}{1500 + 138.5} = 91.5\ \%$$

DRAWING OF WINDINGS SHOWING ACTUAL MEAN LENGTH OF TURN

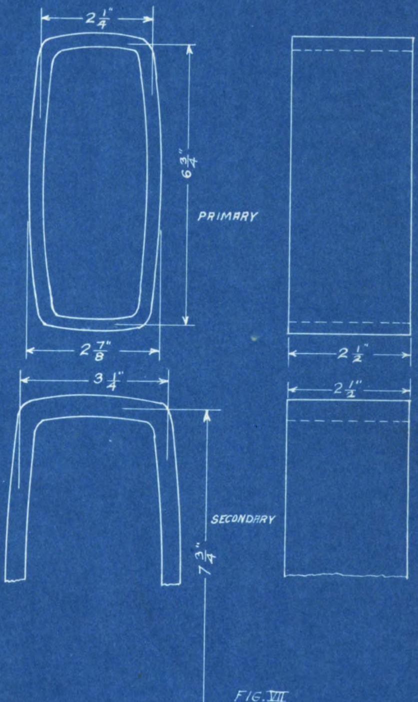


FIG. VII

Design of Transformers

Temperature Rise Calculations

The temperature rise was figured as one coil consisting of one primary unit and one secondary unit slipped over it. The currents in the two are nearly the same so the average of the two was used.

$$\text{Average current} = \frac{21.15 + 23.6}{2} = 22.37.$$

$$T = k\,\frac{I^2 R}{S} \qquad R = \frac{R_p}{4} + \frac{R_s}{2} = .045 \text{ Ohms.}$$

$$T = 180 \times \frac{22.37^2 \times .045}{85.8} = 47 \text{ Degrees Cent.}$$

Each unit consists of 1/4 of the primary and 1/2 of the 110 volt secondary.

Data on Transformers

Primary-- 4 coils of 20 turns each of 2 No. 10 B&S gage D.C.C. Wires in parallel.

$_aN_p$ --- 80

N_p--- 69.5 effective turns

Secondary.. 2 coils of 29 turns each of 2 No. 10 B&S gage D.C.C. Wires in parallel.

2 coils of 28 turns each of single No. 10 B&S gage D.C.C. Wire.

R_p --- .067 Ohms.

R_s---- .0583 Ohms.

l_p--- 1.5 ft.

l_s--- 1.83 ft.

Lbs. of copper required for primaries (3 transformers) 23

Lbs. of copper required for secondaries " " 31

54

Size of form for winding secondary

Cross section---- 2 7/8 in. x 7 in.

Results

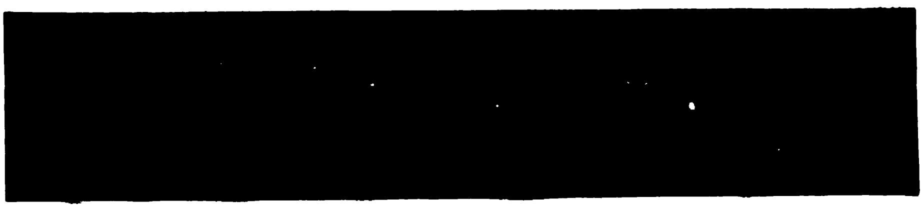
The transformers were connected to the slip rings of the converter R_2 as shown in Fig. II and D.C. at 220 volts was fed in at the brushes. Upon measuring the voltage across the slip rings, it was found to be 120 instead of 135 volts according to the ratio. Upon further examination it was found that the brushes were not in the neutral position. The had been used as a D.C. generator just previous to this and the brushes had been shifted in order to get sparkless commutation under those conditions. Upon bringing the brushes back to the neutral position, the voltage was 135 at the slip rings.

Upon measuring the D.C. voltages to neutral, it was found that they differed by about 8 or 10 volts. This was first thought to be due to the three transformers being unbalanced. To make sure, the transformers were connected to converter R_1. The D.C. voltages to neutral were then found to be balanced within 2 volts, so the trouble seemed to be in the spacing of the D.C. brushes. of the converter R_2. Each brush spans four bars and upon counting the bars between brushes, it was found that there was a difference of 2 bars on the lower brushes. To correct the unbalance, two diametrically opposite brushes were split with a hack saw in such a way as to even up the spacing and so that these two brushes spanned two bars instead of four. This brought the D.C. voltages to neutral within 2 volts of each other. This change did not affect the sparking, even when the converter was loaded.

The D.C. voltage to neutral is shown by the accompanying oscillogram.

The voltage is practically free of triple harmonic voltages. The very slight triple present is possibly due to thevariation of amplitude of the thirds in each transformer which might be caused by slight differences of flux densities in each transformer core.

Below is an oscillogram of the D.C. to neutral voltage of converter R_1.



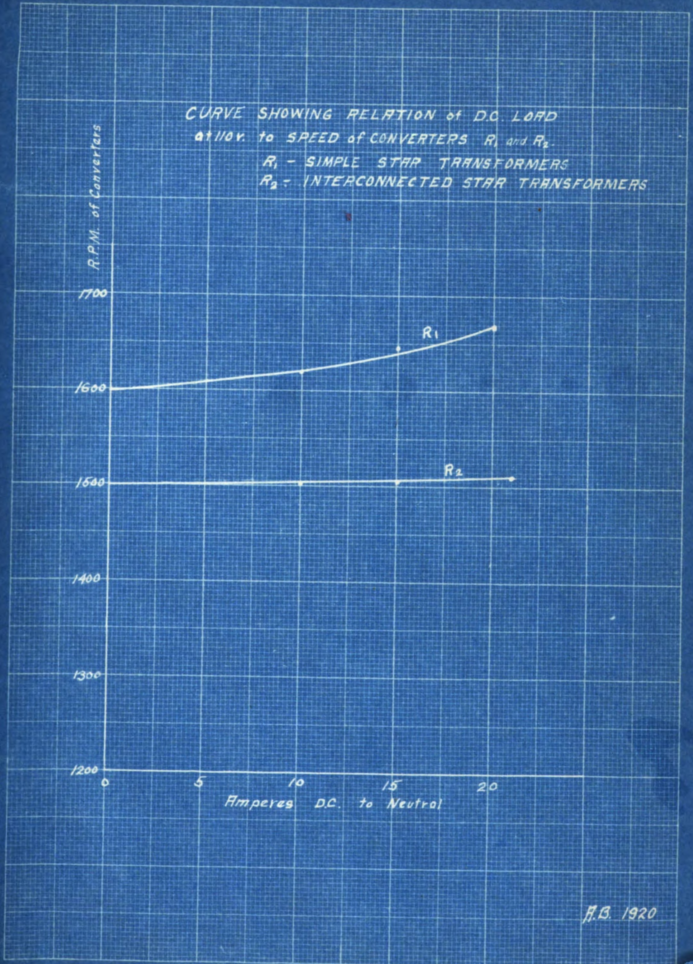
The presence of triple harmonic voltages superimposed on the D.C. is very marked in this case. Transformers are connected simple star.

Results

Comparative speed tests were made on R_1 and R_2 to show the absence of saturation of the transformer cores in the case of the interconnected star. The curve shows that the speed change of R_2 is practically nil for a heavy D.C. load to neutral.

In the case of R_1, the core saturation of the transformers causes a great enough increase of magnetizing current to the transformers to demagnetize the field flux of the converter considerably, thus increasing the speed. The curve showing speeds at different D.C. loads to neutral for converter R1 is shown on the same sheet as the R_2 speed curve for comparison.

The voltage curve for D.C. to neutral loads is shown. The regulation for a 10 ampere load is 7.2% and for a 20 ampere load, 10.9%.


CURVE SHOWING RELATION of D.C. LOAD
at 110v. to SPEED of CONVERTERS R_1 and R_2.
R_1 - SIMPLE STAR TRANSFORMERS
R_2 - INTERCONNECTED STAR TRANSFORMERS
R.P.M. of Converters
1700
1600
1500
1400
1300
1200
R_1
R_2
0
5
10
15
20
Amperes D.C. to Neutral
A.B. 1920

Data on Speed Tests

Converter R_2

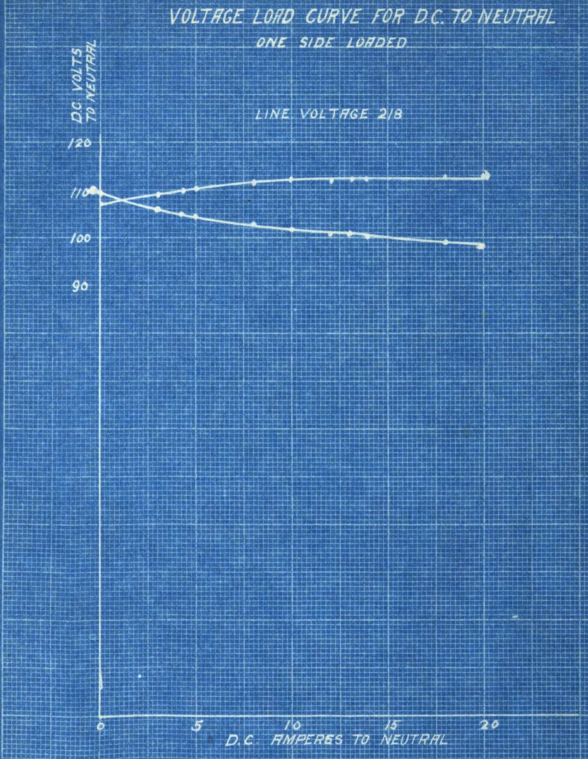
Interconnected star Transformers

D.C. Amperes to Neutral	R.P.M.
0	1500
10	1500
15	1505
21	1510

Converter R_1

Simple Star Transformers

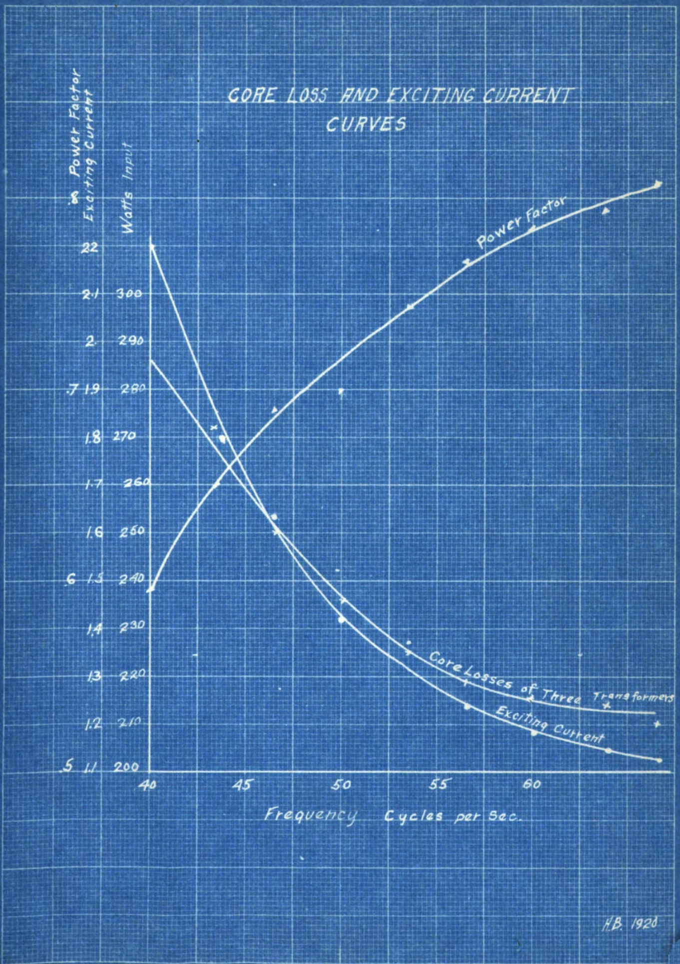
D.C. Amperes to Neutral	R.P.M.
0	1600
10	1620
15	1650
20	1670


VOLTAGE LOAD CURVE FOR D.C. TO NEUTRAL
ONE SIDE LOADED
LINE VOLTAGE 218
D.C. VOLTS TO NEUTRAL
120
110
100
90
0
5
10
15
20
D.C. AMPERES TO NEUTRAL
A.P.B.
1920

Data on D.C. to Neutral Voltages

Amperes	E1	E_2
0	107	109
3	109	106
4	110	105
5	110.5	104. 5
8	112.	103
10	112	101.5
12	112	101
13	112	101
14	112	100.5
18	112.5	99
20	113	98

The voltage of the line was 218 when these readings were taken. The load was connected across E_2.


CORE LOSS AND EXCITING CURRENT
CURVES
.8 Power Factor
Exciting Current
Watts Input
22
2.1 300
2. 290
.7 1.9 280
1.8 270
1.7 260
1.6 250
.6 1.5 240
1.4 230
1.3 220
1.2 210
.5 1.1 200
40
45
50
55
60
Frequency Cycles per Sec.
Power Factor
Core Losses of Three Transformers
Exciting Current
H.B. 1928

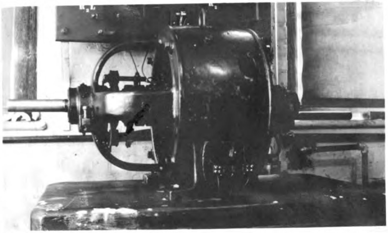
Data for Core Loss, Exciting Current, and Power Factor

Curves for the Transformers

W_1	W_2	P. F.	R.P.M.	f	I_{ex}
150	60	.81	2000	66.6	1.12
155	59	.793	1900	63.4	1.14
158	58	.785	1800	60	1.18
162	57	.768	1700	56.7	1.24
170	55	.745	1600	53.3	1.38
185	52	.697	1500	50	1.42
200	50	.692	1400	46.7	1.64
230	45	.65	1300	43.3	1.8
255	30	.595	1200	40	2.2

Core loss by curve--- 78 watts per transformer.

Core loss by calculation-- 76 watts per transformer.



Converter R_2 with which the Interconnected Star Transformers are used for obtaining 110 volts D.C. from 220 volts D.C.

The Assembly and mounting for the Interconnected Star Transformers used with Converter R_2.

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