The Study of a Two Phase Alternator with a Special Rotor

A Thesis Submitted to

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By

C. C. White

W. E. Thomas

Candidates for the Degree of

Bachelor of Science

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PREFACE

The subject of this thesis is the modification of a three phase, 220 volt, induction motor, into a two phase generator. In this two phase generator we propose to put a rotor of special design and make a study of the conditions that exist under the different shapes of pole faces and types of rotors.

With this peculiar design we are endeavoring to build an alternator that will supply a ture sine wave. Many alternators are built to supply such a wave but when entering into the commercial field many of these features have been sacrificed. They approach the sine wave, but due to the fact that it is almost impossible to eliminate all of the odd harmonics and the effect of the fringing of the field flux a slight deviation from the sine curve has been the result.

It is our aim to take precautionary measures to eliminate as many of the harmonics as we can by changing the shape of the pole faces, thus eliminating the fringing of the field flux as much as possible, and get as near to a true sine wave as we can. Then we aim as far as possible to obtain a fair capacity from the machine so as tests may be run and have students become familiar with two phase machinery.

We wish to thank the Electrical and Mechanical Departments for the help they gave us while we were at work on this machine, also to Mr. Wyckoff for the help rendered in work on the Oscillograph.

"THE STUDY OF A TWO PHASE ALTERNATOR WITH A SPECIAL ROTOR"

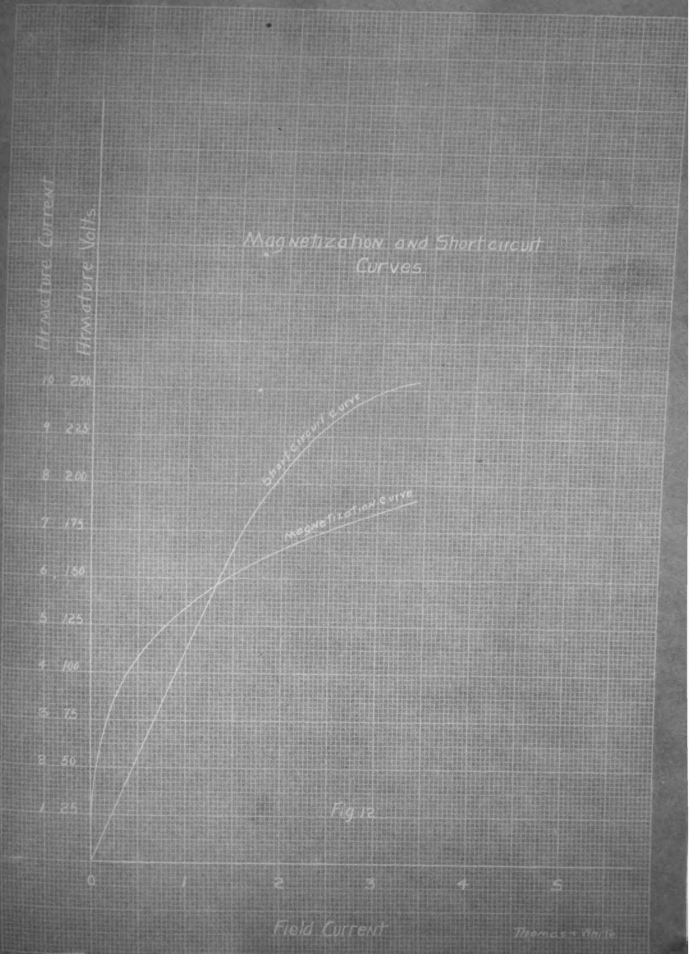
We will not enter into the construction of the rotor as it is adequately described in the detail and assemby drawings as is shown in figures 4, 5, 6, 7, 8, 9, 10 and 11. The materials used for the pole pieces is cast iron and the shaft is made of cold roll steel.

The whole rotor was assembled and balanced to eliminate vibration. The pole pieces were not made any particular shape only as a portion of the true arc, this was done to see the action of the different shapes of pole pieces on the form of the wave that would be generated.

The coil that we used was just an experimental coil. It is wound with No. 20 double cotton covered copper wire. The dimensions are as in (Fig. 8). The leads from the coil are brought out and soldered to the collector rings that are shown in Fig. 9. We did not design the coil, but merely used the space that we had to insert it and built a coil to fit this space.

RE-CONNECTING THE STATOR.

The stator of this machine when operating as a three-phase, induction motor was connected as a four pole, three phase parallel star, (Fig. 1 - 1_a). This gave us a full pitch winding with four coils per pole per phase, or a total of 48 slots. Because of this condition we were able to re-connect it into a two phase machine. In the Electric Journal, Vol. 13, page 85, enough data was obtained to aid us in this re-connection, first studying the three phase connections, then making the changes so as to have it connected as a two phase, four pole, series delta. In order to do this it was necessary for us to connect six coils in series instead of four.
We also referred to the thesis of W. A. Siefert and H. G. Carrow; "A Study of Reconnection Induction Motors".


Magnetization and Short circuit Curves.
Armature Current
Armature Volts.
10 250
9 225
8 200
7 175
6 150
5 125
4 100
3 75
2 50
1 25
Short circuit Curve
Magnetization Curve
0
1
2
3
4
5
Field Current
Thomas - White
Fig 12

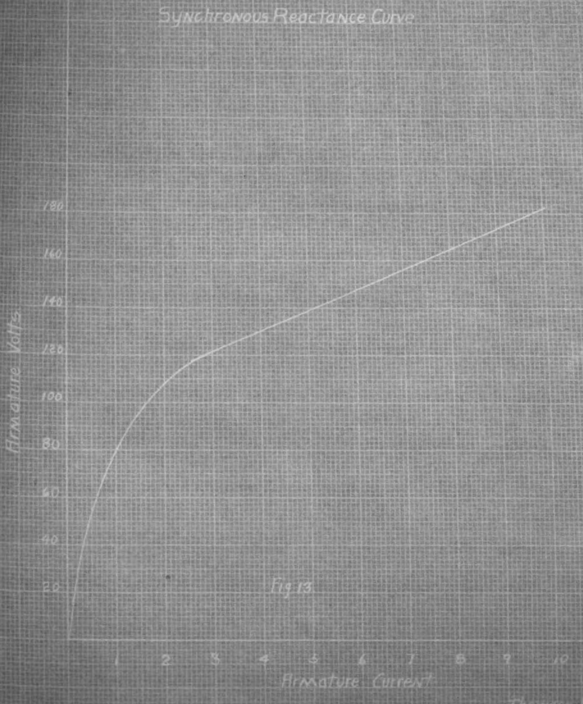


Fig 13

Thomas White

After we finished the rotor and had the brushes in place, we assembled the alternator and belted it to a 7 H.P. D.C. motor which served as a prime mover. We ran preliminary tests to find out what work the machine was doing. We found that the machine would generate alternating current and that the current was ninety degrees apart or two phase current. The next thing to determine was the shape of the wave, so we connected a non-inductive load thru an ammeter with a voltmeter at the terminals of the machine to see what effect a load would have, each phase being loaded equally.

In running this test we found that we could not load the machine up to the load we expected and when the wave form was obtained thru the oscillograph many interesting things became evident. Without load the alternator gave a very good wave but as the load was applied it was distorted. The harmonics that we tried to eliminate came in so strong that they could be determined on the screen. We also found that as the load was applied the voltage on the machine dropped down, the speed of the machine remaining constant. The field excitation remaining constant. With these conditions in view we ran the following test to see if we could determine the cause of this voltage drop.

The First was the magnetization test, (See Curve of Fig. 12).

Regulation test was made as follows: The armature was short circuited thru an ammeter. Then the generator brought up to synchronous speed without any field excitation. Current was then passed thru the field and a series of readings taken of the field and the corresponding armature currents until the armature current readings reached about 50% above the normal full load value. From the magnetization curve, voltages corresponding to the field current readings can be obtained. The curve was plotted as on Fig. 12. Then with armature currents as abscissa and terminal voltages corresponding to the field currents as ordinates the curve was plotted (Fig. 13). The curve is nearly a straight line droop-

ing as the saturation point is appreached. After performing these tests we were convinced that the voltage drop was due to synchronous reactance. Both armature reaction and reactance are proportional in magnitude to the current, the voltage consumed by both are in phase for all power factors. Both may be represented by one equivalent reactance. This is called synchronous reactance.

The voltage consumed by the synchronous reactance is practically equal to the total voltage as the part taken by the resistance is small and almost in phase with the induced voltage.

From the synchronous reactance curve, (Fig. 13):

$E_0 = l_a \quad R_a^2 + sXa^2$ or

$sXa = E_e \; l_a$

sXa = synchronous reactance.

E_0 = Terminal volts.

l_a = Armature current.

R_a = " Resistance.

The value obtained for the synchronous reactance is much larger than actual synchronous reactance when operating under full load. The synchronous impedence and reactance varied with the load. It is important that we know the synchronous reactance when studying the characteristics of an alternator. The calculated regulation is only an approximation of the actual value. In many alternators from 10 to 25% of the total synchronous reactance is due to the armature reactance and this in turn is due to the armature reaction.

As in Fig. 15, the flux is pushed down from, say a north pole to the south pole by the synchronous reactance this is another theory of the dropping of the voltage which is due to the synchronous reactance. The flux should pass over the small air gap into the stator iron and thus around and back thru the south pole, but instead of doing this it is

distorted and pushed straight down to the south pole as in Fig. 15. If the flux is driven down in this manner the number of lines out is reduced and the voltage will drop. These characteristics seem to be evident in this case and as the load is applied the current rises and the synchronous readtance increases and the voltage drops. Therefore, the voltage drop must be due to this reaction. We ran a test to find out if the voltage drop was due to the decreasing speed and found that the speed of the alternator was practically constant. Then the reactance will distort the field flux so that it leaks up thru the teeth rather than threading thru the armature coils and in this manner the flux density would be reduced and thus cause a drop in voltage. It does not seem possible with a non-inductive load that the armature reaction would have a demagnetizing effect, this would be true, however, if the load was an inductive one.

As is stated before the pole faces were that of a pure arc, and when the picture of the current in the wire was taken with the oscillograph, we found the wave form to be distorted as is shown in Fig. 14. The general trend of the curve is that of a sine wave but when analyzing the curve we find that the third harmonic is present. The portion that is designated in Fig. 14 by the pointe (a) and (b) show the distorted portion of the curve. This curve is the resultant of the third harmonic and the fundamental combination of the both gives us the peculiar shape. Note the amplitude of the higher harmonics as pointed out by point (b) Fig. 14, the higher harmonics begin at the zero point and gradually increase until at the point (b), then decrease to the zero point again and then repeats itself only in the negative direction.

In any circuit the first source of disturbance or distortion is in the alternator. With no current flowing, which is a condition of an open circuit, the voltage at the alternator terminals is proportional to the rate of cutting the lines of force. In the case of an alternator it is

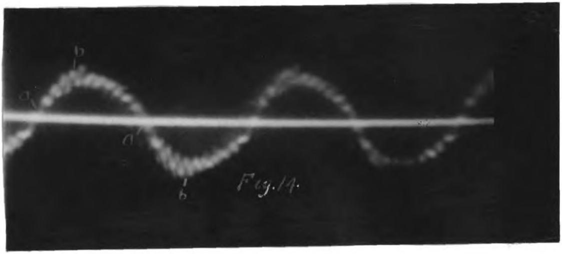


Fig. 14.

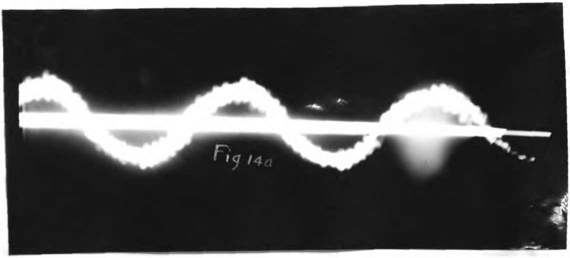


Fig 14a

instantaneous values. Distortions may therefore be caused by the following reasons:

1. Non-uniform or a pulsatine field.
2. Variation in speed.
3. The distribution of the conductors in which the current is generated.

In our case the speed was constant so the distortion was not due to this condition. There are a number of turns per coil and the coils fill the six adjacent slots and might be the cause we have no way of finding out only by making experiments on the different distribution of the conductors. It may be that the field flux is not distributed uniformly due to the quality of the cast iron and the shape of the pole faces. Then the slotted armature, or stator in our case, affects the distribution of the magnetic flux and produces a pulsating field these both cause distortions of the voltage wave. In Fig. 14 and 14a is shown a voltage wave having a very definite 23 harmonic which is most surely produced by the tooth reaction on the field flux. In alternators having a few slots and teeth per pole the movement of the slots across the field produces a pulsation of the magnetic reluctance of the field circuit and this would cause a pulsation in the magnetic flux. The excitation in every case is kept constant. Therefore, a machine having s slots per pole, the magnetic flux pulsates with 2s frequency.

Assuming that the pulsations follow a simple sine law and have $K^m \phi$ amplitude, the instantaneous flux interlinked with the armature coil is:

$$\phi = {}^m\phi \cos (wt) (1 + k \cos (2swr - r))$$

The voltage generated is :

$$e = \frac{-nd\phi}{dt}$$

then from the two above equations

$$e = 2pifn^m \phi(\sin (wt) (1 + k \cos (2swt - r))$$

from trigonometry

$$2\sin x\cos y = \sin(x + y) + \sin (x - y)$$
$$2\cos x\cos y = \sin (x + y) - \sin (x - y)$$

Hence: $e = 2\pi f n^{m} \phi \left(\sin nwt + k \frac{2s-1}{2} \sin ((2s+1) wt - r + K \frac{(2s+1)}{(2)} \sin ((2s+1) wt - r) \right)$

The pulsations of the magnetic flux due to the armature slots is therefore the source of two harmonics in the voltage curve of frequencies 2s+1 and 2s-1 times the fundamental.

In the voltage wave as is shown in Fig. 14, we have the higher harmonic present which is the twenty third. We have 12 slots per pole then from the equation 2s-1, s = 12 then solving the equation we get 23 denoting the 23 harmonic using the first equation 2s+1 and solving it we get a twenty fifth harmonic, but by taking an oscillograph picture we find that we have the twenty third.

The wave shape of the electromotive force of an alternator is determined primarily by the distribution of the magnetic flux in its air-gap. If the flux density in the air-gap varies sinusoidally with the distance measured along the circumference of the armature, the E.M.F. will be sinusoidal or (the wave will be a pure sine wave), assuming the armature conductors to be symmetrically placed. Such a distribution of flux can be approximated by properly shaping the field poles, but can never completely realized in a slotted armature. The effect of teeth is to produce harmonics of relative high order, as evident by the sharp jags in the resultant curves.

Taking the general outline of the curve we find that we have a curve that resembles the ideal curves which illustrate the third harmonic. The third harmonic is produced by the non-uniform distribution of the field flux. To remove this distortion and distribute the flux more evenly we champhered the sides of the pole faces so that they did not have the shape of an arc, but such a shape that the air-gap was increased 1/8 of an inch at the edges and gradually decreasing to the arc or starting at 1/8 of an inch and then decreasing to .04 of an inch air-gap. Then we again assembled the alternator and then took pictures of the action of the current by the oscillograph and found that the higher harmonics had almost disappeared and that the third harmonic had disappeared entirely. Then we found the higher harmonics also disappeared when the load was applied (that is, a non-inductive load). Figures 16 and 16a are pictures taken of the oscillograms of the voltage waves. Figure 16 is the picture of the voltage wave as it is taken from the alternator, and 16a is the picture as it is taken when the non-inductive load is applied, both phases being loaded equally.

So far the discussion and pictures of wave forms have been either with or without an inductive load so to see what action the inductive load would have on the shape of the wave we connected a Scott transformer to the alternator. We first took a picture of the voltage wave taken from the alternator on the primary, the primary being the two phase connection of the transformer, and found the wave form to be as is shown in Fig. 17. In Fig. 17 note the points (a) and note the hump that is produced and at (b) as light depression. Referring back to Fig. 16 you will note that there is a similarity in both of these curves the depressions and the hump appears in the same position only not so pronounced. In Fig. 16a these characteristics do not appear. Another element that will affect the wave form is the variation in the permeability and the hysteresis with the flux density in iron-clad circuits. This variation of the permeability and hysteresis in the transformer together with that of the alternator is, no doubt, the reason for this curve showing the variation so much more pronounced in Fig. 17, that is shown in Fig. 16. To determine the real effect of the conditions mentioned above a number of transformers with different values of permeability and hysteresis should be connected to the alternator and oscillograms taken of each condition and compared. In Fig. 17a, is a wave form of an inductive load taken off of the three phase

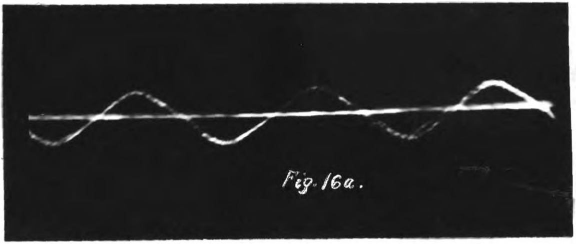


Fig. 16a.

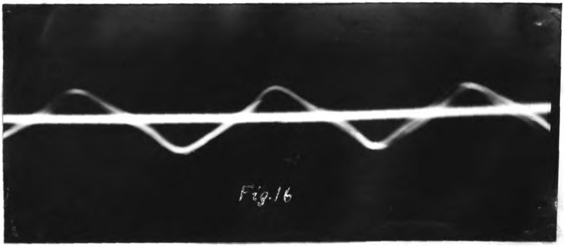


Fig. 16

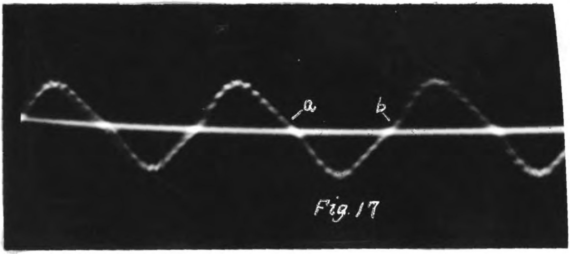


Fig. 17

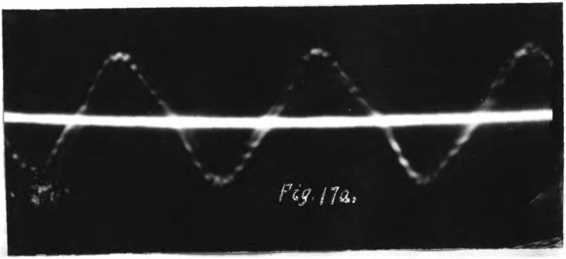


Fig. 17a.

side of the Scott transformer. The shape of the curve is similar to those in Fig. 16 and 17, but at the very peak of the curve note the amplitude of the higher harmonics. In studying the curve it seems as if the higher harmonics seem to have been transmitted thru the transformer but this is not very likely to be the case. It is the characteristic wave of the harmonics produced by a transformer that is connected in the line.

In the Figures 18 and 18a are curves of the inductive load with a load on the three phase side of the Scott transformer. In Fig. 18 is the wave of the transformer,on the two phase side note the similarity to the wave of Fig. 17. The wave as is shown in Fig. 18a is the wave of the transformer connected on the three phase side. Note how the characteristics of the wave of Fig. 18 have been greatly magnified. The reason for this is probably the action of the transformer connected on the line.

Figure 19 is the oscillogram of the voltage wave taken of the two phases at the same time. It is distinctly brought out that the voltages are 90° apart. This is the real proof that the connection as made when re-connecting are correct.

The pole faces are made so that they are 70% of the pole pitch. This was done according to the statement of Mr. Smith of the Westinghouse Company, to eliminate the harmonics. It would be interesting to have a number of pole faces that could be inserted in the alternator and note the effect of them on the wave form, form factor, and the other characteristics of alternators. Take the rotor that we have and champher the pole faces still more and see what effect it would have on the generated voltage.

It is well understood that small alternators cannot have revolving poles as are supplied in large commercial alternators, but regardless of this fact we designed a special rotor to fit this machine and rotated it in the stator and found that possible and not practical because of the

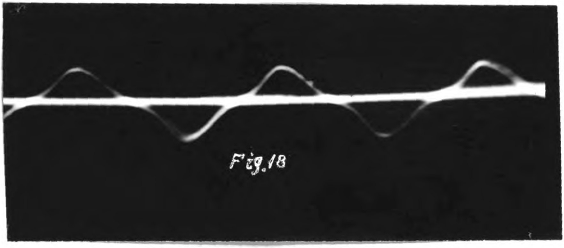


Fig. 18

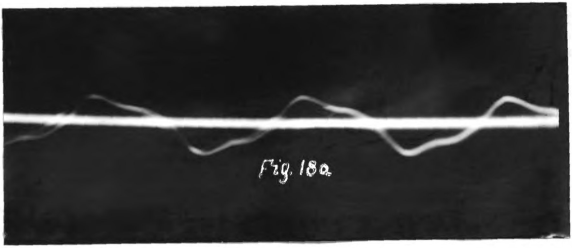


Fig. 18a

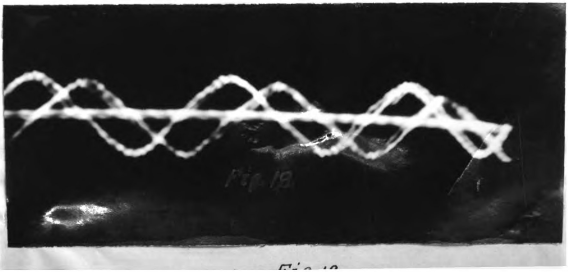


Fig. 19

leakage of the field flux. It is true that salient pole pieces would be very much better but due to the small size of the rotor this also would not be practical.

When designing alternators that are to work as a separate unit and not to be operated in parallel with other machines, no attention need to be paid to the harmonics, as this was the general condition of the early development of the electrical industry little attention was given to wave forms. During recent years the central stations have increased enormously and made it necessary to operate long-distance transmission lines of high potentials. This makes it necessary to study carefully all the factors that may produce wave distortion.

If the wave form of two alternators operating in parallel are not of the same shape, it is evident that for any instants during the time the two waves are not equal the difference in the voltages cause cross-currents to flow thru the two armatures. These cross currents will heat up the armature and reduce the rating and the efficiency of the machines since the out-put or rating of well designed machines are based upon the temperature rise.

This thesis has been valuable to the authors as it has broadened their view point of the alternating current phenonima. It has also brought clearly before their mind some of the factors that enter into the design of alternating current machinery. It has helped us become familiar with the oscillograph both in its operation and theory. We believe that the oscillograph is an asset to the teaching of alternating currents as the theories that are brought out in the class-room can be made more clear by its use. This oscillograph is not designed for scientific investigation, but it is designed for a lecture demonstration of alternating currents.

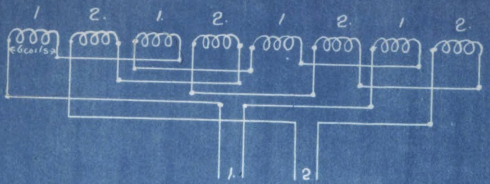


Fig II

Fig IIa

4 Pole 2 Phase Series Delta

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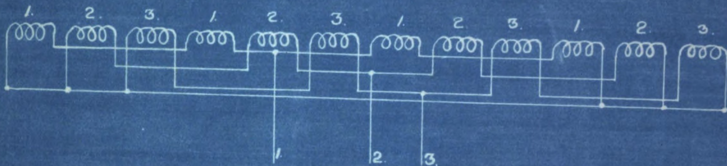

Fig. I

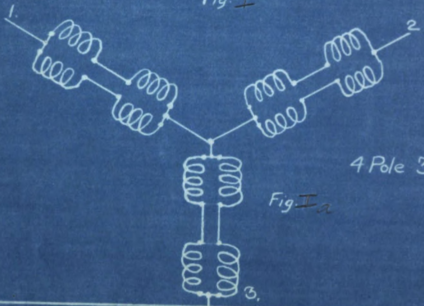

Fig. I a

4 Pole 3 Phase Parallel Star.

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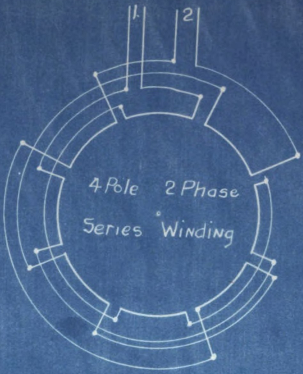
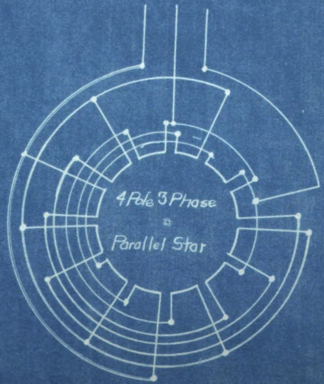


Fig



Fig

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