A STUDY OF THE CURRENTS IN THE VARIOUS COILS OF A SYNCHRONOUS CONVERTER

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PREFACE

The synchronous converter is a machine used to change alternating current to direct current or direct current to alternating current. When used to change direct current to alternating current, it is called an inverted converter.

Engineering students and others who have studied the synchronous converter have found that it is a combination of a synchronous motor and a direct current generator. They have also read that the current flowing in the armature coils is the difference between the synchronous motor current and the direct current delivered by the generator to the external direct current load. If this is true, the current flowing in each coil between two adjacent taps must be different.

This thesis consists of a description of a specially built synchronous converter which is so constructed that the current flowing in the leading tap coil, center coil, and lagging tap coil of one phase, can be brought externally through extra slip rings, where it can be measured by an ammeter or its wave shape examined by an oscillograph, and also the results obtained when this machine was tested.

The author wishes to express his sincere thanks to Professor M. G. Northrop for his assistance in designing and testing the synchronous converter mentioned in the preceding paragraph and to Mr. W. O. Leffel for his assistance in testing. The author also wishes to express his thanks

to Mr. W. M. Mahoney for furnishing the d. c. motor of which the converter is made, to his father, Mr. J. M. Gider, for his assistance and use of machinery during construction, and to Mr. Steffner, of the Chattanooga Armature Works, for furnishing the armature and field coils.

John E. Gider

STATEMENT OF PURPOSE

Many text-books, which give the theory and operation of synchronous converters, have curves which show the relation between the current flowing in the leading tap coil, center coil, and lagging tap coil for leading, unity, and lagging power factors. These curves were constructed by assuming the a. c. current wave to be sinusoidal, since it is supplied by the line as motor current; the d. c. current to be opposite the a. c. current because it is a generated current, and adding the d. c. and a. c. current waves.

No actual tests have been made to verify the validity of such curves. It is with this in mind that this paper has been written. The writer intends to show how the curves obtained by actual test compare with those constructed by the method described in the preceding paragraph.

GENERAL THEORY

The basic theory of a direct current generator and an alternator is the same. If a loop of wire be rotated between two fields of opposite polarity in such way that lines of force will be cut, a voltage will be induced. The voltage thus induced will be alternating. This induced voltage may be delivered externally through collecting rings as alternating current voltage, and the machine will be called an alternator; or it may be delivered through a commutator, where it will be rectified and delivered as direct current. If a commutator is placed on one end of the armature and collecting rings are placed on the opposite end, and both are properly connected to the same winding, direct current may be obtained from the commutator and alternating current can be obtained from the collecting rings at the same time. Such machine is called a double current generator.

If the direct current brushes are removed from the commutator and the machine is looked at from the slip ring end, one will see an alternator of the wound rotor type. The voltage induced in the rotor coils will depend upon the flux crossing the air gap, the number of inductors between two taps, and the speed at which the rotor is turning.

Any alternator will operate as a synchronous motor. The only difference between the two machines is the amortis-

seur or damper windings which are added to the synchronous motor for starting purposes and to prevent hunting. These windings are usually added to the synchronous converter for the same reason. Therefore, when one looks in from the a. c. end, one sees either an alternator or a synchronous motor.

If the brushes are raised from the slip rings and the machine is looked at from the d. c. end, one sees either a direct current shunt or compound wound motor or generator. The slip rings, being connected to points on the armature of equal potential, serve as equalizing rings.

It can be concluded from the two preceding paragraphs that the converter will operate as a synchronous converter, when a. c. power is supplied to the collecting rings and a load is connected to the direct current end, as an inverted converter when direct current is supplied to the direct current end and a load is connected to the a. c. end, and as a double current generator when power is applied mechanically by a prime mover and loads are connected to both the a. c. and the d. c. ends of the machine. Hereafter, only the synchronous converter in which a. c. power is supplied and a direct current load is connected to the d. c. end will be discussed.

When an a. c. voltage is applied to the slip rings of a synchronous converter, an alternating current will flow in

the armature winding and a revolving field will be produced. The direction in which this revolving field will turn depends upon the phase rotation of the current supplied. When the armature is turning at synchronous speed in a direction opposite to the direction of rotation of the revolving field, the revolving field will be carried backward mechanically by the armature at the same speed at which it is advancing forward electrically. Therefore, it will be stationary in space with respect to the field coils and d. c. brushes. The field thus produced will interlock with the d. c. field in such a way as to make the path of the lines of force as short as possible. The inductors of the armature will have an alternating current voltage set up in them, due to cutting of the flux produced by the d. c. field and the rotating field, which is opposite to the applied voltage and just a little less. This voltage is called back e.m.f. The difference between the applied e.m.f. and the back e.m.f. is just enough to force the necessary current through the armature coils to drive the machine.

When a direct current load is connected to the machine, the speed of the armature tends to drop momentarily and to allow the rotating field to move a few degrees ahead of the d. c. field. This is shown in figure 2. Figure 1 shows the magnetic field and armature position at no load, and figure 2 shows the magnetic field and armature position at full load. The torque increases as the angle of shift increases until it

becomes a maximum. If the angle is increased beyond this value, the machine will pull out of synchronism and stop, because, although current increases the larger power factor angle results in a smaller torque.

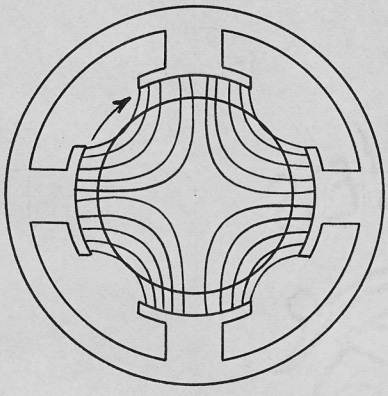

Fig. 1 Magnetic field of synchronous motor when the brake torque is zero.

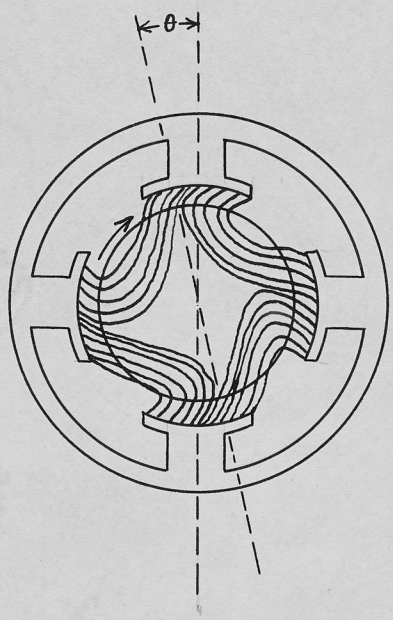

Fig. 2 Magnetic field when the synchronous motor is under load.

The easiest way to investigate the operation of the synchronous motor is to draw vector diagrams.

Let E_g = applied voltage

E_m = back e.m.f. of the motor

I = current circulating in the armature

If there were no load on the machine $E_g = E_m$ and the vector diagram for this condition is shown in figure 3. This condition cannot exist unless a mechanical torque is applied

to the shaft of the synchronous motor whose magnitude is sufficient to take care of the windage, friction, and iron losses of the machine. The flux crosses the air gap as shown in figure 1 and the angle $\theta = 0$.

The actual condition that exists in a synchronous motor when all losses are supplied to it electrically is shown in figure 4. E_r is the resulting voltage or effective voltage which causes the no load current to flow through the motor. θ is very small, but it is always greater than zero.



Fig. 3

Voltage vector diagram for synchronous motor with zero load.



Fig. 4

Voltage vector diagram for synchronous motor with no external load.

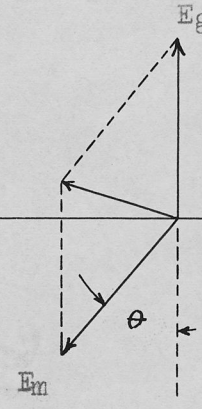

Fig. 5

Voltage vector diagram for synchronous motor under full load.

E_r in figure 5 is the resultant voltage that is effective in sending current through the motor at full load. The angle θ is practically the same as that shown in figure 2; therefore, the flux distribution at full load is also shown in

figure 2. The current that flows through the motor due to E_r is as follows:

$$I = \frac{E_r}{\sqrt{R_m^2 + X_m^2}}$$

Since the resistance of the a. c. winding is very small in comparison to the inductance, it may be neglected. The current I must lag the voltage E_r by approximately 90°. The power input to the motor is $E_g I \cos \phi$ where ϕ is the power factor angle.

If the excitation and applied voltage are kept constant and the load is increased, E_r must increase; therefore, the angle θ must increase. Increasing θ causes the angle between E_r and E_g to decrease, but the current lags E_r by approximately 90°; therefore, the power factor angle ϕ must increase. It can be concluded from the above that θ, E_r, I, and the power factor angle increase as the load increases. The power input $E_g I \cos \phi$ increases to a point of maximum output, and any further increase in the load will cause the motor to drop out of step and stop.

The effect of changing the excitation of a synchronous motor is shown in figures 6, 7, and 8. E_g and the load are assumed to be constant. Since the load is constant, the inphase component of the current and $E_g I \cos \theta$ must also be constant. The speed of a synchronous motor cannot change and

must always be synchronous speed; therefore, the voltage E_m must change with the excitation and may be either larger or smaller than Eg.

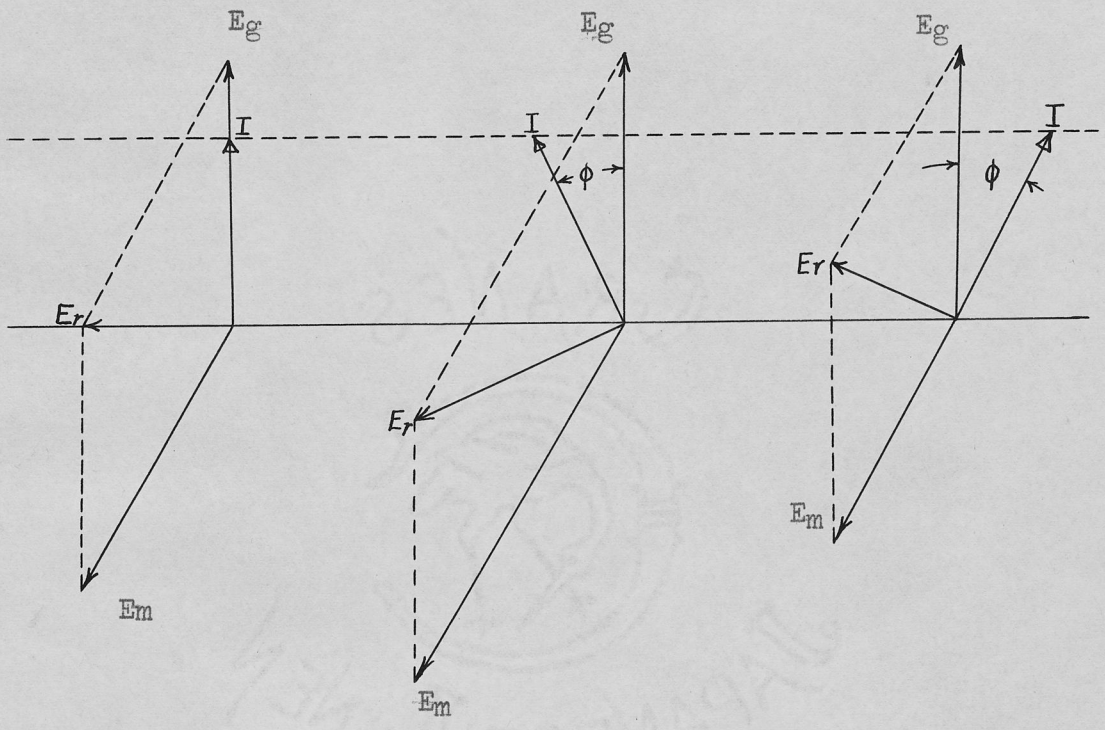

Fig. 6

Vector diagram of synchronous motor operating at zero power factor angle.

Fig. 7

Vector diagram of synchronous motor operating at leading power factor angle.

Fig. 8

Vector diagram of synchronous motor operating with lagging power factor angle.

Figures 6, 7, and 8 are vector diagrams of a synchronous motor having a constant load and applied voltage but having the excitation varied.

Figure 6 is a vector diagram of the motor having its excitation adjusted to give unity power factor. E_m is slightly larger than E_g.

Figure 7 shows what happens when the excitation is increased. E_m increases as the excitation increases and is much larger than E_g. Increasing E_m causes the angle between E_r and E_g to increase. Since the angle between E_r and I is always approximately 90°, the angle between I and Eg will increase, thus causing a leading power factor. It will also be noticed that a larger current is drawn by the motor for the same power delivered when the power factor is leading and increases as the power factor angle increases. The in-phase component of the current remains constant as long as the load remains constant, but the reactive component increases as the power factor increases. If the current increases, E_r must increase also. This can be seen to be true by comparing figures 6 and 7.

Figure 8 shows the condition that exists when the excitation is reduced to such an extent that the power factor becomes lagging. The current drawn by the motor is a minimum when the power factor angle is zero, and increases as the angle of lag of the power factor increases. E_r is shown to decrease as the excitation decreases.

It has been shown that a back e.m.f. was induced in the inductors of the armature, and these inductors are con-

nected to the commutator in the case of the synchronous converter. If brushes are properly placed with respect to the field coils of the machine, a direct current voltage will be induced between any two consecutive brushes, and direct current will be delivered if an external load is connected to the direct current terminals of the converter.

One can see from the above that there is a motor current flowing in the armature coils in one direction due to the applied a. c. voltage, and the current supplied to the d. c. load also flows through the same coils but in an opposite direction, since it is due to the induced or back e.m.f. The current which actually flows in the conductors at any instant is the difference between the a. c. motor current and the d. c. generator current. Part of the current flowing in the external d. c. circuit is part of the a. c. supply current rectified. Very peculiar wave shapes of current are obtained, and examples of such waves are given in figures 9 to 26. "Each conductor will be found to have a different wave shape."[1] The wave of the instantaneous current in a given coil and position relative to the d. c. brushes will be different when the power factor changes. The applied a. c. voltage is always exactly 180° out of phase with the d. c. volts, therefore, when the power factor is unity the currents will be 180° out of phase or exactly

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1. Tarboux, J. G. Alternating current theory, vol.2, p.167-171.

opposite.

The a. c. current does not always stay in phase with the a. c. voltage. A leading or lagging power factor will cause the current to lead or lag the applied voltage. When this condition exists, the a. c. current is not 180° out of phase with the d. c. current. It is $180^{\circ} \pm$ the power factor angle. Therefore, the current flowing in the conductors of the armature is the sum of the a. c. and d. c. currents for part of a cycle and the difference for the remainder. The relative position of the a. c. current and the d. c. current is shown in figures 9 to 26 by the dotted sinusoidal wave and the dotted rectangular wave. The dotted sinusoidal wave represents the a. c. motor current that would flow in a given coil if no d. c. current were present, and the dotted rectangular wave represents the d. c. current that would flow in the same coil if no a. c. motor current were present. The heavy solid curves show the current that flows in the given coil when the a. c. motor current and the d. c. generator current both flow simultaneously.

One method of determining the magnitude and wave shape of the current flowing in an armature coil of a synchronous converter is to cut the coil and carry the two ends out of the machine through slip rings to an ammeter and an oscillograph. An armature winding diagram of a synchronous converter which was designed for this purpose is shown in figure 27. There are seven collecting rings on this machine. The

three rings marked 1,2, and 3 are running rings, and those marked 4,5,6, and 7 are testing rings.

The machine illustrated in figure 27 is a four pole machine. There are two different points on such winding that are at the same potential and each running ring is connected to two such points. It will also be noticed that the taps on one ring are always connected to points on the winding which are 120 electrical degrees from a tap of either of the other two running rings.

The leading tap coil is cut and one end of the coil is connected to the running ring number 3, and the other end is connected to ring number 7. This makes an open circuit in the coil, and ring number 3 must be connected to ring number 7 before current can flow in the coil. This is done externally and the circuit is closed through an ammeter so the current flowing in the coil can be measured. The center coil and the lagging tap coil of the same phase are opened. The ends of the center coil are brought out to rings number 5 and number 6, and these rings are shorted externally through an ammeter so the current flowing in the center coil can be measured. The lagging tap coil is done likewise through rings number 2 and number 4. An oscillographic study of the current flowing in the various coils can be made by connecting the oscillograph in series with one of the ammeters.

DESCRIPTION OF THE APPARATUS AND METHOD USED

The only machine available for making a synchronous converter was a 2.5 H.P. 250 Volt D.C. Fairbank-Morse Motor. Some of the changes made in this motor are described in the succeeding paragraphs.

There were no changes made in the front end frame, commutator, or brush rigging of the motor except one commutator bar was added. The back end frame and armature bearing were extended so seven collecting rings could be placed on the shaft near the armature. A rocker arm, brush holders, and brushes were added to conduct the a. c. current from the supply line to the slip rings and armature windings.

The armature winding was changed from a wave winding to a lap winding. The winding was tapped and connected to the collecting rings as shown in figure 27. Changing the armature winding from a wave winding to a lap winding caused the d. c. output voltage to be decreased from 250 to 125 volts.

The shunt field coils were all connected in series and across the line when the machine was operating as a 250 Volt D.C. Motor. When the voltage was reduced by changing the armature winding, the field coils were reconnected two in series across the line. A double-pole double-throw switch was connected in series with the field coils in such a way that the direction of the current flowing in them could be reversed.

Amortisseur or damper windings were placed on the pole piece. These windings made it possible to start the converter from the a. c. end. The converter made by making the above changes in the d. c. motor differs from any other synchronous converter only in the number of slip rings and the connections made for testing. If rings number 3 and number 7, number 5 and number 6, and number 2 and number 4 are shorted together by closing switches x, y, and z in figure 28, the machine will operate as any other three-phase synchronous converter.

Figure 28 shows the connections for measuring the current flowing in the center coil by an ammeter and also the connections for using the oscillograph to determine the wave shape of the current flowing. One turn of the center coil is cut and the two ends are brought out to rings number 5 and number 6. The current flowing in the coil must go through ring number 5, the ammeter, the oscillograph, and through ring number 6 to the other side of the coil. The two leads going to the ammeter and the oscillograph can be connected to the ends of either switch, and when the switch is opened, the amperes flowing and the wave shape of the current flowing in that circuit can be determined. It is important to see that the circuits indicated are always short circuited through the ammeter or by having the switches closed when the converter is running. If one of the switches is opened, full d. c. line voltage will be impressed across

two adjacent bars and the mica insulation would probably break down. When there is no current flowing in that part of the armature there would be no IX or IR drop.

The current in the leading tap coil flows through circuit Z, the current in the center coil flows through circuit Y, and the current in the lagging tap coil flows in the X circuit. Photographs of the current flowing in each of the X,Y,Z circuits were taken when the power factor angle of the supply current was 30° lag, unity, and 30° lead. The current flowing in each circuit was measured by the ammeter and its magnitude recorded as data.

OBSERVATIONS

The ammeter readings show that the current flowing in the leading tap coil and the lagging tap coil is greater than the current flowing in the center coil, when the power factor angle is zero. Changing the power factor angle changes the magnitude of the current flowing in each of these coils. Since the ammeter records effective values of current it will not show this but it may be seen by inspection of figures 9 to 36. These figures show that the wave shape of the current flowing in these coils changes when the power factor angle changes.

The photographs show that the current flowing in one coil changes for two cycles as follows: the current flowing during the first half-cycle is the difference between the a. c. motor current and the d. c. generator current as described in the theory, the current flowing during the next half-cycle, which is the negative half of the cycle, is the sum of the a. c. motor current and the d. c. generator current, and the current flowing during the next whole cycle is approximately a sine wave whose magnitude is approximately the sum of the a. c. motor current and the d. c. generator current. The third cycle is just like the first, and the fourth is just like the second.

CONCLUSIONS

The instantaneous currents flowing in the different coils between two taps of a synchronous converter are different.

The magnitude of the instantaneous currents flowing in the different coils between two taps vary when the power factor is changed.

The first-half cycle of the current wave verifies the theory that the current flowing in any coil of the synchronous converter is the sum of the a. c. motor current and the d. c. generator current. The following three half cycles do not. Time was not available for further investigation; therefore, no conclusion can be made as to the validity of this theory.

OBSERVED DATA

P. F. Angle Degrees	Ea. c. Volts	Ed. c. Volts	I f Amps.	Ia. c. Amps.	Id. c. Amps.	Resulting Current in Coils: Leading Coil	Center Coil	Lagging Coil
0	57.0	79	0.90	10.05	5.05	2.40	2.08	2.40
30° Leading	88.8	124	2.07	8.50	6.55	1.55	1.55	2.90
30° Lagging	62.0	90	0.65	15.00	2.70	3.27	3.50	3.45

DRAWINGS AND PICTURES

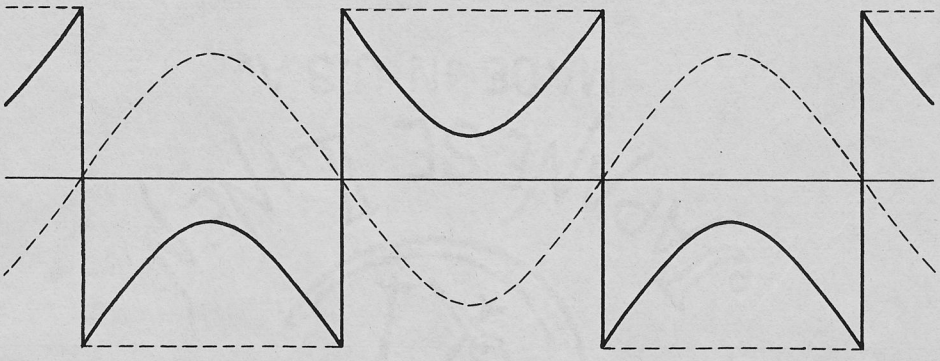

Fig. 9. Theoretical curve of the current flowing in the center coil of a synchronous converter at zero power factor angle.

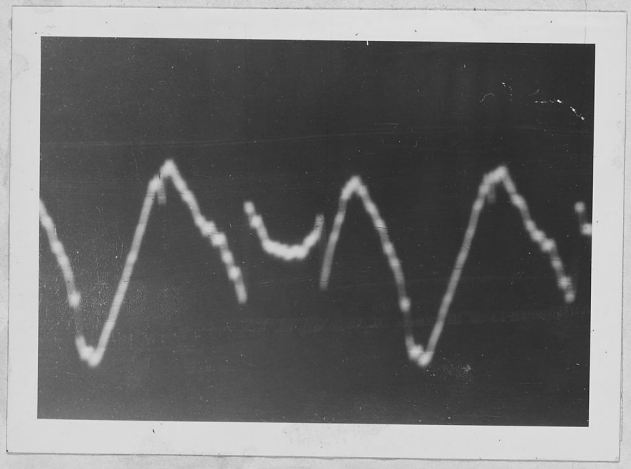

Fig. 10. Actual curve of the current flowing in the center coil of tested synchronous converter at zero power factor angle.

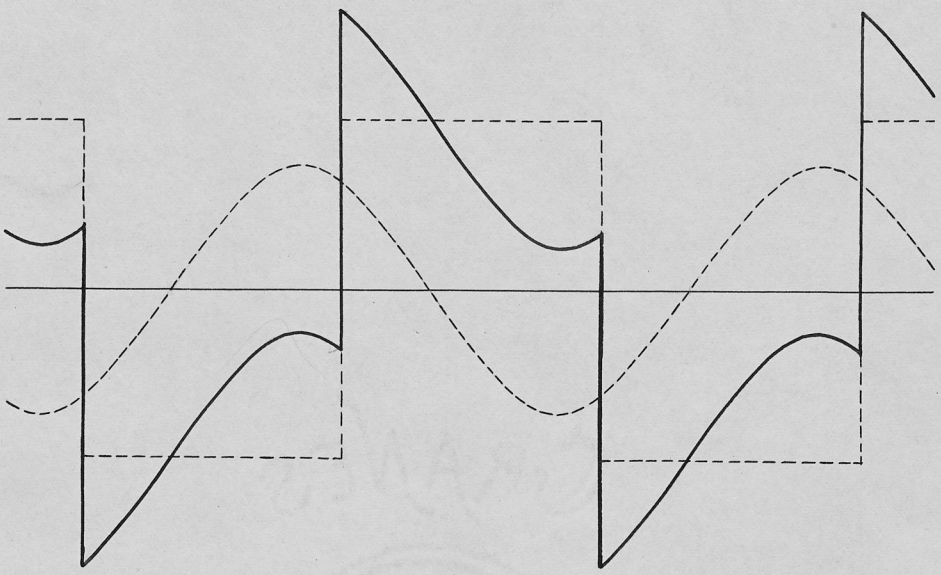

Fig. 11. Theoretical curve of the current flowing in the leading tap coil of a synchronous converter at zero power factor angle.

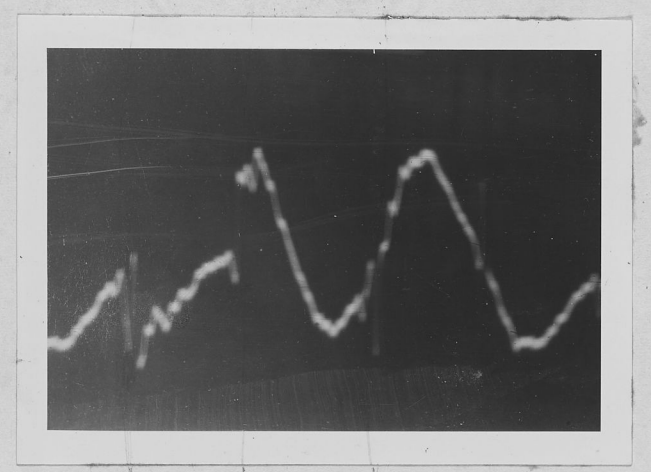

Fig. 12. Actual curve of the current flowing in the leading tap coil of tested synchronous converter at zero power factor angle.

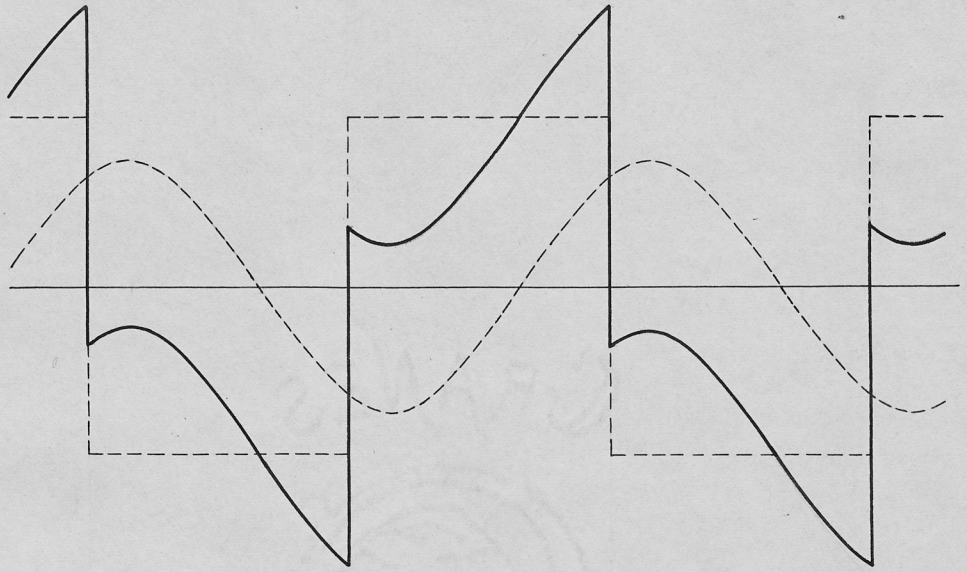

Fig. 13. Theoretical curve of the current flowing in the lagging tap coil of a synchronous converter at zero power factor angle.

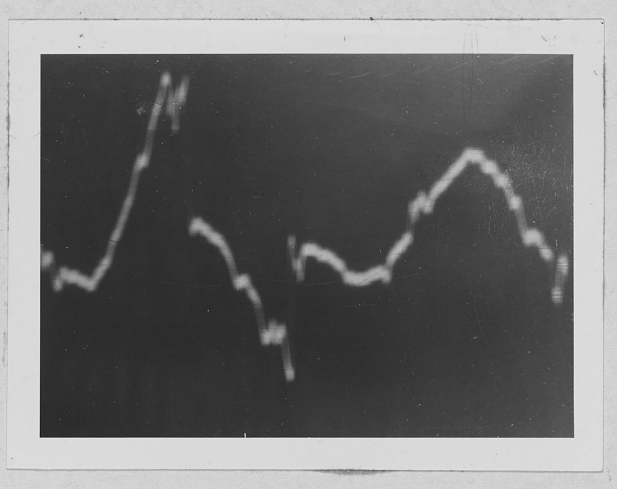

Fig. 14. Actual curve of the current flowing in the lagging tap coil of tested synchronous converter at zero power factor angle.

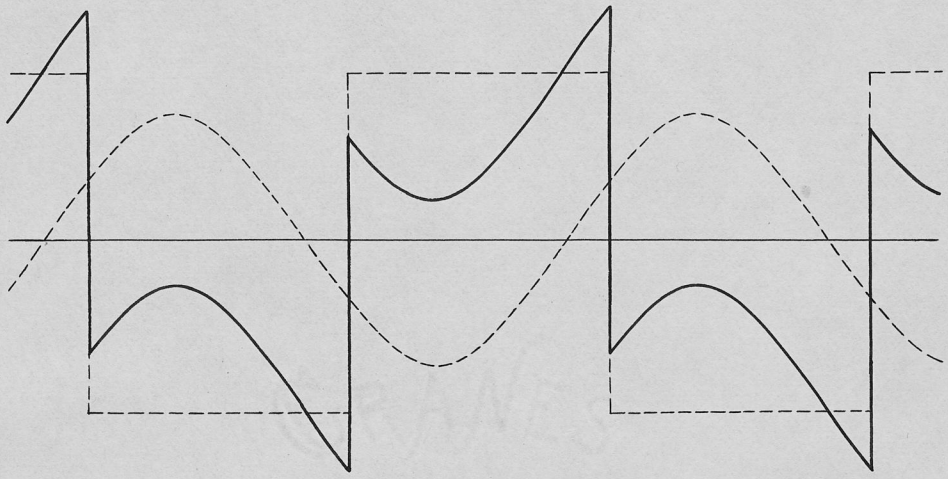

Fig. 15. Theoretical curve of the current flowing in the center coil of a synchronous converter at 30° leading power factor angle.

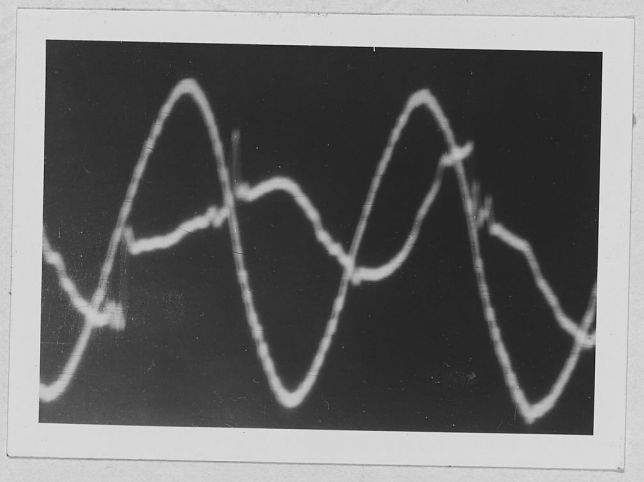

Fig. 16. Actual curve of the current flowing in the center coil of tested synchronous converter at 30° leading power factor angle.

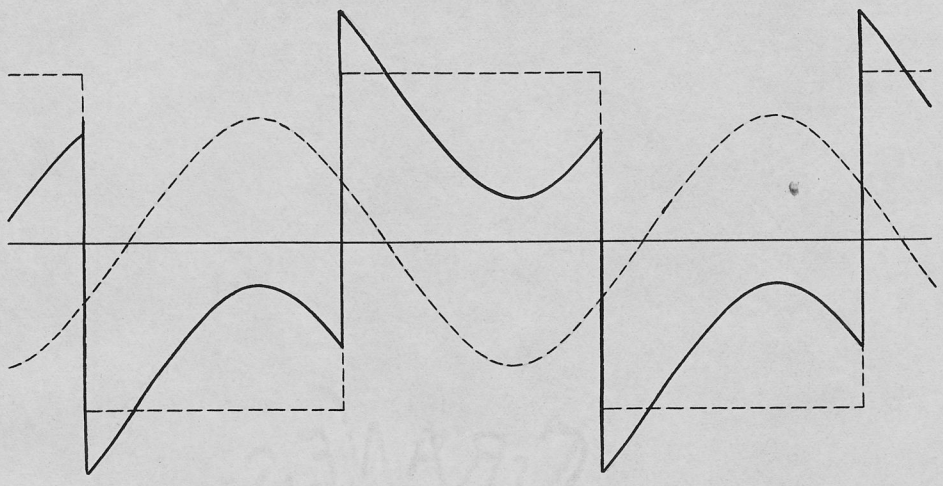

Fig. 17. Theoretical curve of the current flowing in the leading tap coil of a synchronous converter at 30° leading power factor angle.

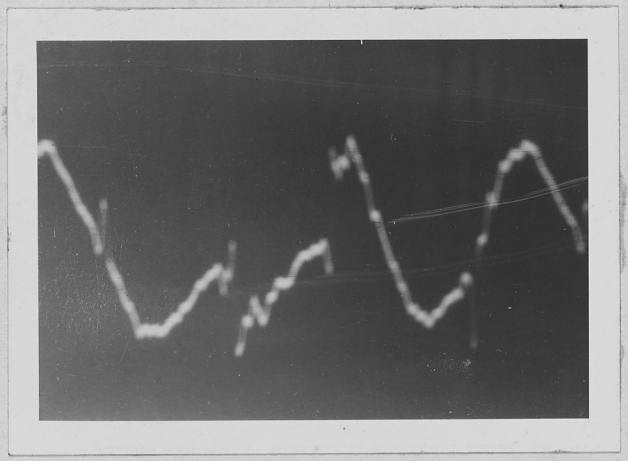

Fig. 18. Actual curve of the current flowing in the leading tap coil of tested synchronous converter at 30° leading power factor angle.

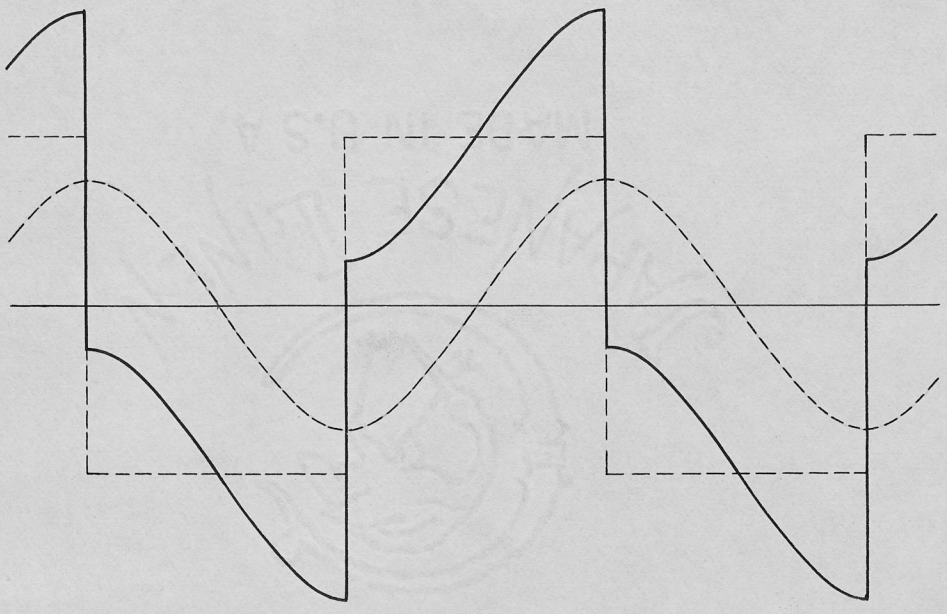

Fig. 19. Theoretical curve of the current flowing in the lagging tap coil of a synchronous converter at 30° leading power factor angle.

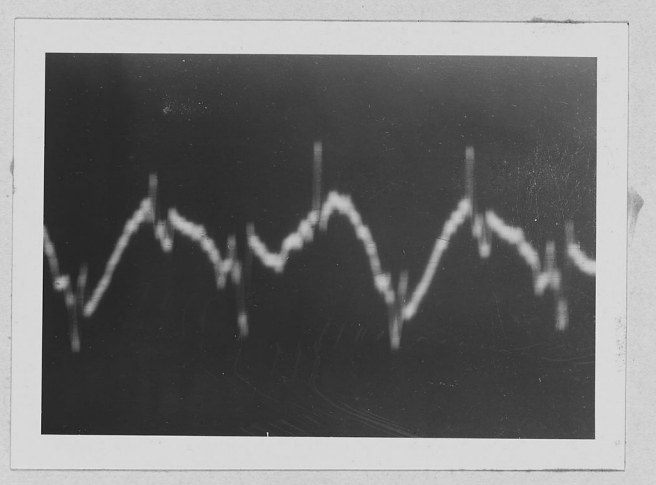

Fig. 20. Actual curve of the current flowing in the lagging tap coil of tested synchronous converter at 30° leading power factor angle.

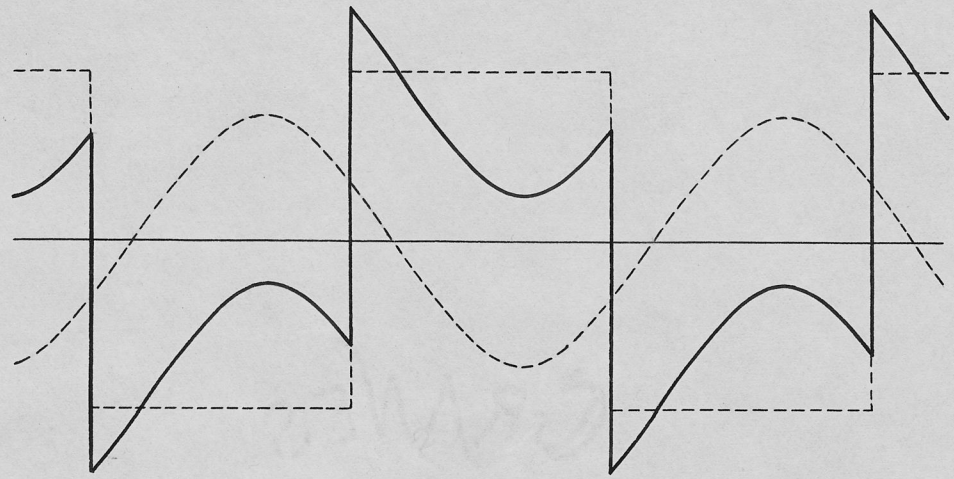

Fig. 21. Theoretical curve of the current flowing in the center coil of a synchronous converter at 30° lagging power factor angle.

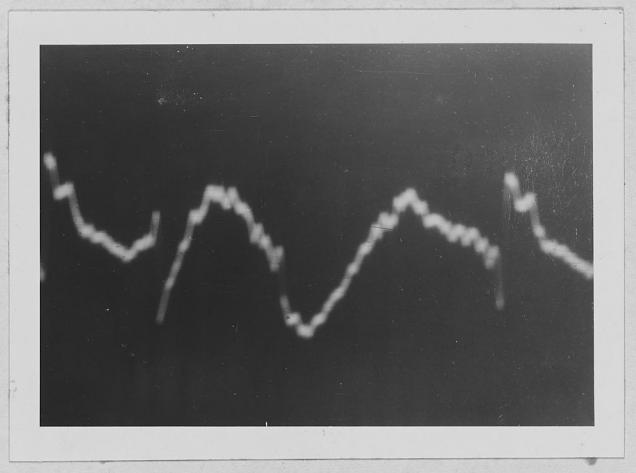

Fig. 22. Actual curve of the current flowing in the center coil of tested synchronous converter at 30° lagging power factor angle.

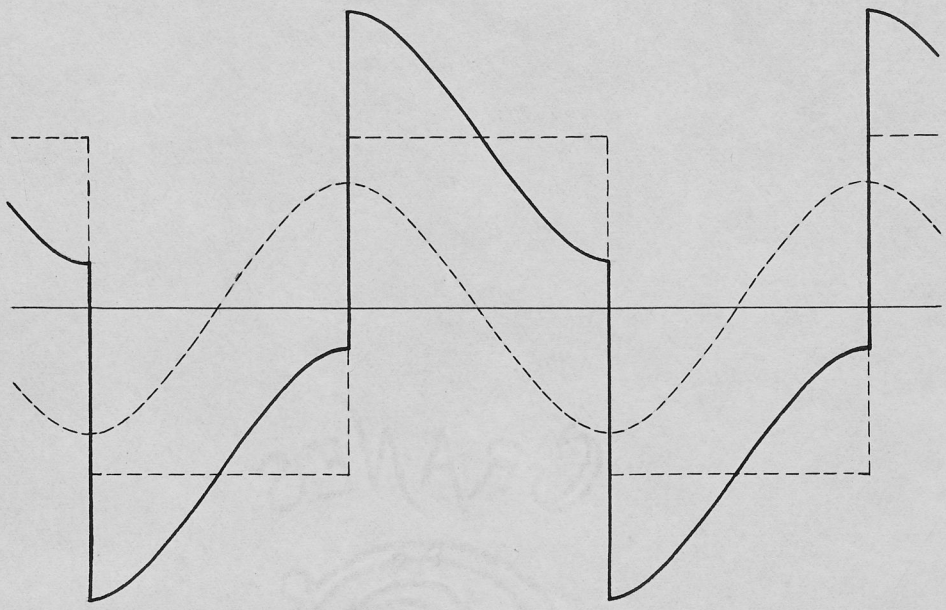

Fig. 23. Theoretical curve of the current flowing in the leading tap coil of a synchronous converter at a 30° lagging power factor angle.

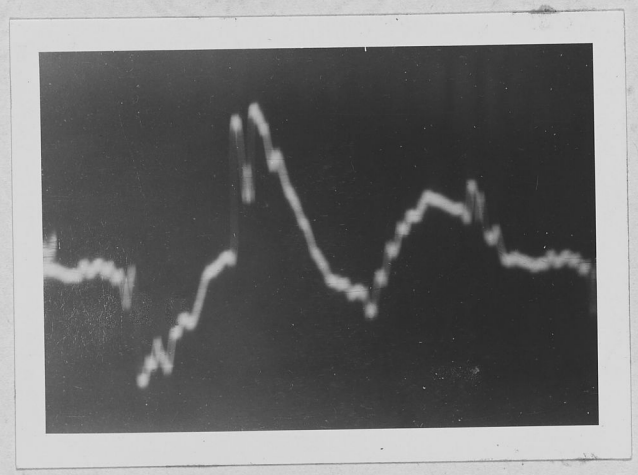

Fig. 24. Actual curve of the current flowing in the leading tap coil of tested synchronous converter at 30° lagging power factor angle.

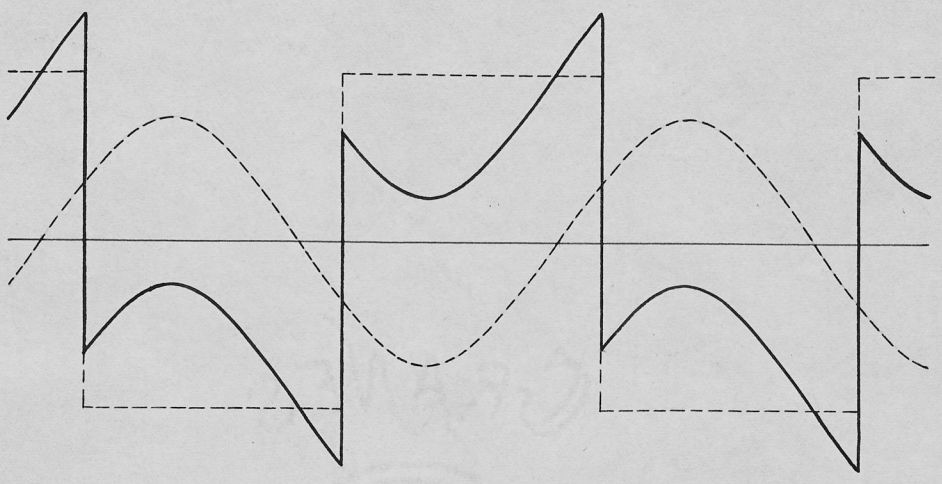

Fig. 25. Theoretical curve of the current flowing in the lagging tap coil of a synchronous converter at a 30° lagging power factor angle.



Fig. 26. Actual curve of the current flowing in the lagging tap coil of tested synchronous converter at a 30° lagging power factor angle.

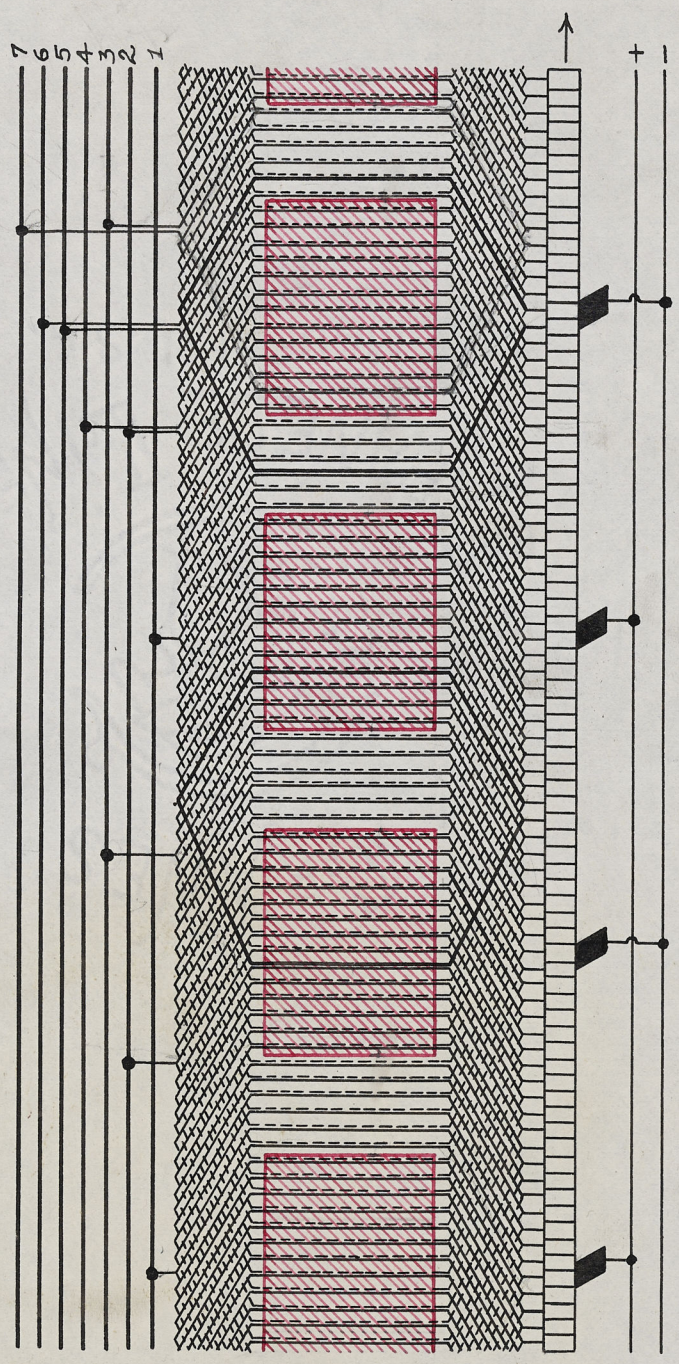

Figure 27. Armature Winding Diagram Showing Rings and Connections for Testing.

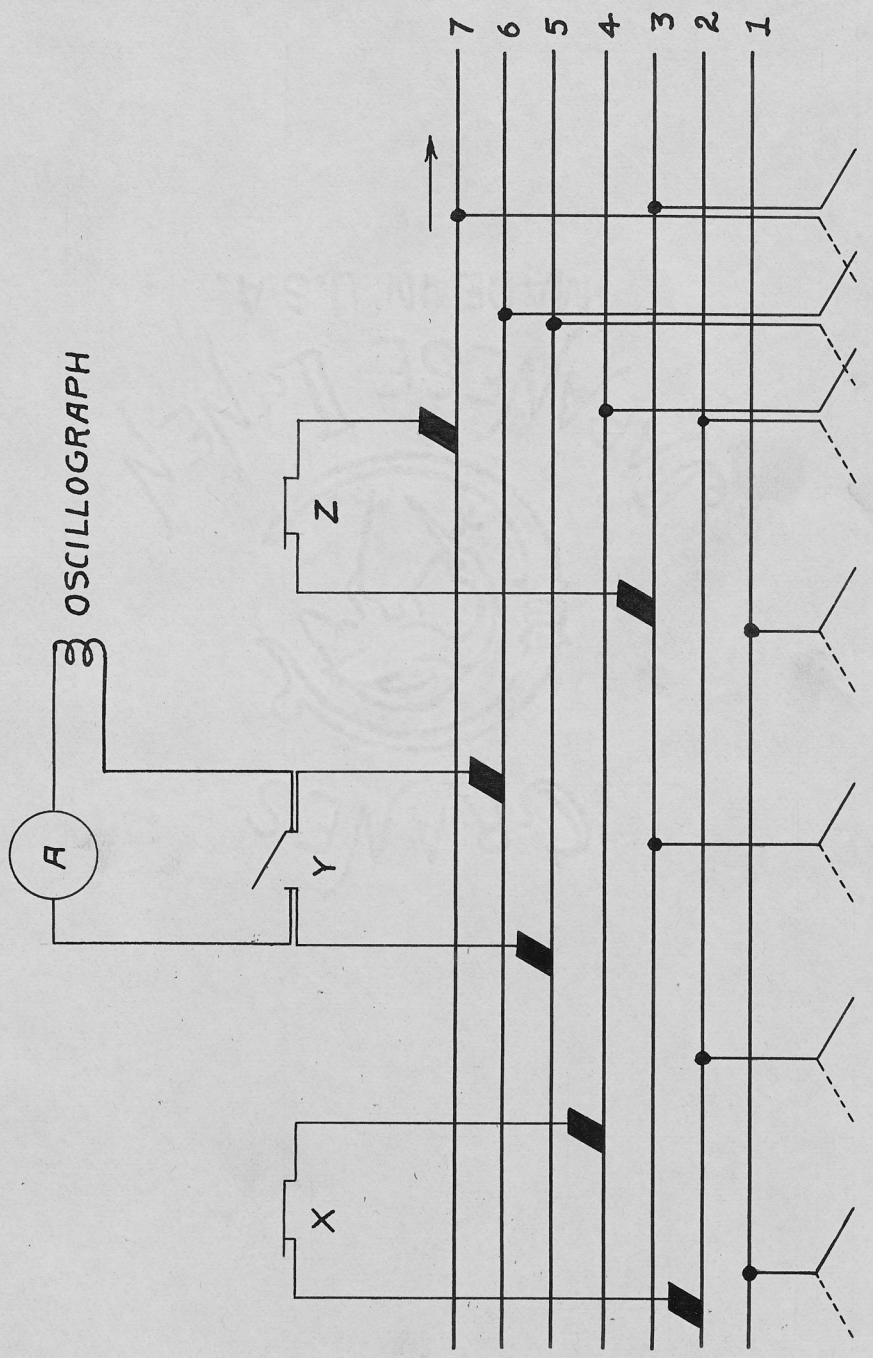

Figure 28. Diagram of Connections to Ammeter and Oscillograph.

BIBLIOGRAPHY

Croft, Terrell. Practical Electricity. New York: McGraw-Hill Book Company, 1923.

Dawes, Chester L. Electrical Engineering. New York: McGraw-Hill Book Company, 1934. Volume 2.

Gray, Alexander, and Wallace, G. A. Principles and Practice of Electrical Engineering. New York: McGraw-Hill Book Company, 1933.

Lawrence, Ralph R. Principles of Alternating Current Machinery. New York: McGraw-Hill Book Company, 1921.

Standard handbook for electrical engineers; edited by Frank F. Fowle. Sixth edition. New York: McGraw-Hill Book Company, 1933. Section 9.

Tarboux, J. G. Alternating Current Theory. Norman, Oklahoma: University Litho Publishers, 1933. Volume 2.

Tarboux, J. G. Electric Power Equipment. Second edition. New York: McGraw-Hill Book Company, 1932.

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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