SYNCHRONIZATION AND SYNCHRONOUS DEVICES

A Thesis Submitted to the Graduate Committee for

the Degree of

MASTER OF SCIENCE

in

Electrical Engineering

Submitted by

N. L. Gregg, Jr.

R. W. Watson

J. S. Jarvis.

H. E. Naylor, Jr.

Approved:

____
Head of Department

____
Dean of Engineering

____
Chairman Graduate Committee

Virginia Polytechnic Institute

1934

PREFACE

It has been our aim to provide the Virginia Polytechnic Institute's electrical laboratory with a portable synchroscope which would be particularly adapted to the laboratory needs. We have put forth an honest effort in our work, and although nine months is a short time to make a study of any subject of this nature, we feel that we have accomplished a great deal and it is with a feeling of pride that we submit the results of our work.

In order to thoroughly understand the meaning of this thesis we suggest that the reader pay particular attention to the diagrams and sketches.

We wish to make grateful acknowledgement to all those who, by their generous counsel and constructive criticism, have helped us in obtaining our objective. We especially wish to thank Professors Claudius Lee, C. W. Hoilman, and B. M. Widner of the department of Electrical Engineering and Mr. Phillips of the Electrical Engineering laboratory for their advice and assistance.

TABLE OF CONTENTS

PLATES

Introduction

The principle of the synchroscope is not essentially a modern development. However, although it is not as common as some other electrical instruments and meters, it is a very necessary piece of apparatus to every power plant and electrical laboratory.

Since the beginning of the use of alternating current machinery it has been necessary to provide some method of tying in a new alternator to the bus bars without shutting down the operation of the whole system. This created the need for some device for determining when synchronization* between the incoming and running alternators was reached. The synchroscope has provided a means for tying in a new alternator to the bus bars without interrupting the service. There are many types of synchronizing devices, but time does not permit us to make a complete study of each type; accordingly, we are endeavoring only to deal with what we consider to be the most important types.

(*) Two circuits are in synchronism when they have the same frequency and their voltages are in phase.

Description of the Operating Principles

A synchronism indicator is essentially like a small bi-polar, two-phase, synchronous motor. Its component parts are: a rotor, an electromagnetic stator, an external resistance, and an external inductive reactance. The stator is built from laminated iron and it is excited by a continuous winding supplied with a single-phase current from the station bus. The rotor is mounted on bearings and it carries two windings separated from each other by ninety degrees, and joined together at the middle. The outside end of each coil, and the junction of the inside ends are connected directly to slip rings. The junction of the rotor coils is connected directly to one line of the incoming alternator. The outside end of one rotor coil is connected through the external resistance to a second line of the incoming alternator, and the outside end of the other rotor coil is connected through the external inductive reactance to the same line of the incoming alternator. The reactance coil is as near free from resistance as possible and its impedance is equal to the impedance of the pure resistance coil. This enables the current in the reactance to lag the current in the resistance approximately ninety degrees. It is impossible to construct an impedance coil which is absolutely free from resistance, and, therefore, the current will lag slightly less than ninety degrees.

When in operation the stator sets up an alternating field around the rotor. This flux lags about ninety degrees behind the electromotive force of the bus bars, because the exciting current has that lag due to the comparatively high inductance of the field windings. The windings B and D of the rotor (Fig. 1A) each set up a field too. That generated by coil B (which is in series with the external resistance) is practically in phase with the electromotive force of the incoming alternator, because the impedance of that circuit is principally pure resistance. That generated by the coil D (which is in series with the external reactance) lags practically ninety degrees behind the electromotive force of the incoming alternator, because the impedance of that circuit is largely inductive.

The operation of the indicator (Fig. 1A) under different possible conditions is as follows:

(1) Assume the case wherein the incoming alternator's frequency is the same as that of the bus bars, and also the electromotive forces of each machine are in phase (i.e., the synchronizing switches can be closed providing the two voltages are equal). The stator flux is ninety degrees behind the electromotive force; the flux of coil D is also ninety degrees behind the electromotive force, and, therefore, in phase with the stator flux. The coil B flux is in phase with the electromotive force and, therefore, ninety degrees ahead of and out of phase with the stator flux and that of coil D. Under these conditions the rotor will take a set position as illustrated in figure 1A, because the stator

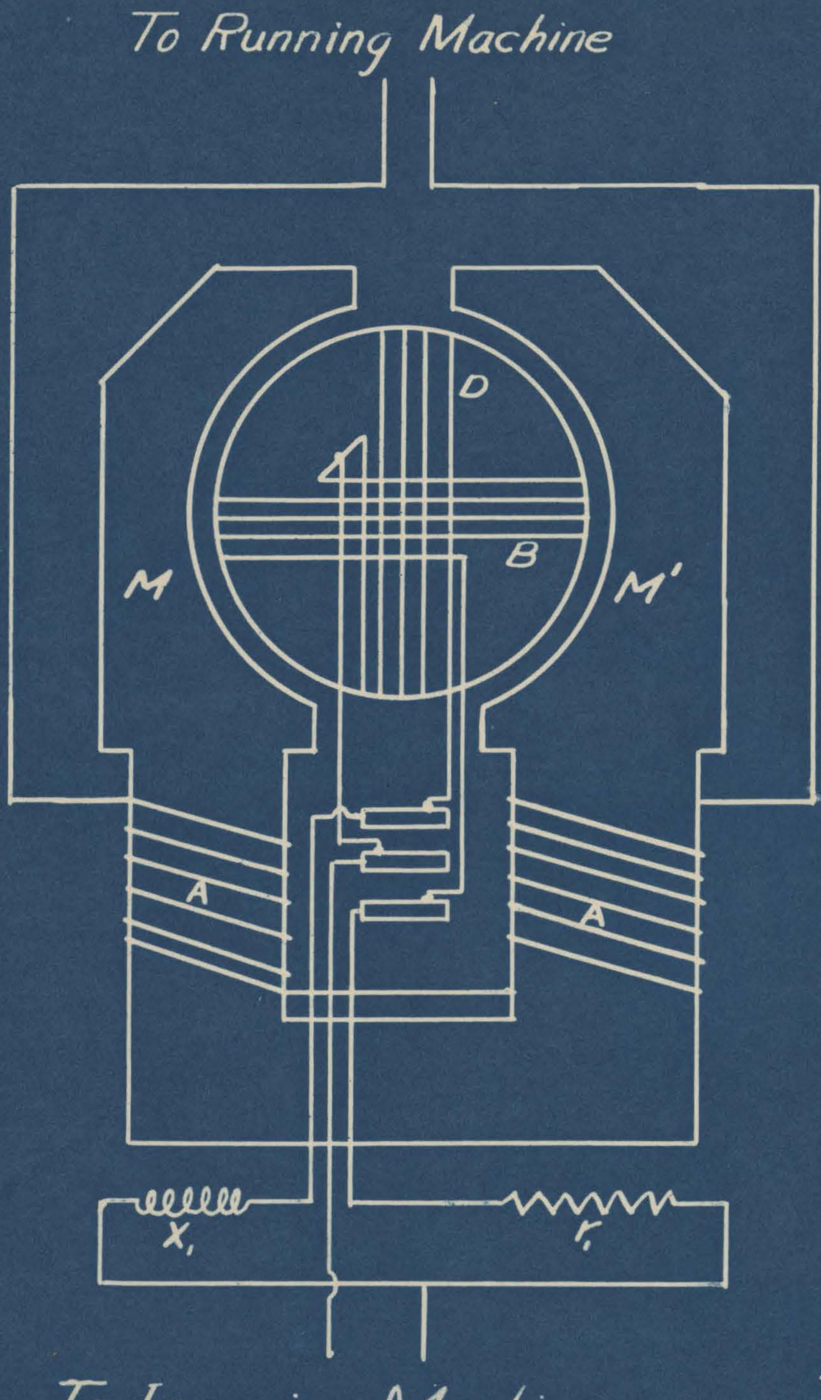


Fig. 1 A

Wiring Diagram of Lincoln Type Synchroscope.

exerts a torque on coil D, but not on coil B. When the rotor is in this position the dial pointer points straight down (vertically). This position indicates that the two machines are in synchronism.

(2) When the electromotive force of the incoming machine and that of the bus bars (running machine) have the same frequency, but the electromotive force of the incoming machine is say twenty degrees ahead. The pointer on the dial will then turn twenty degrees in a clockwise direction.

(3) When the frequency of the incoming machine is higher than that of the bus bars. The pointer will then rotate clockwise.

(4) When the electromotive force of the incoming machine is twenty degrees behind that of the bus bars, but both machines have the same frequency. The pointer will then turn twenty degrees in a counter-clockwise direction.

(5) When the frequency of the incoming machine is lower than that of the bus bars. The pointer will then rotate in a counter-clockwise direction.

Electrostatic Synchronism Indicator

The electrostatic instrument consists essentially of an electrostatic glower, metallic condenser hood, switch for cutting the glower in and out of the circuit, and a hook for suspending the indicator from the line and leading the current to the glower. One terminal of the glower is connected to a spark gap and then to the lower terminal of the suspension hook. The other terminal is connected to the condenser hood. The loop in the suspension hook enables the indicator to be hung over the line by means of the ordinary type of switch hook used for operating disconnecting lever switches. The glower lamps are operated by the charging current of suspension insulators used as condensers; one set of insulators being required for each phase of the incoming and operated lines. The lamps are mounted in a case and project through holes in the cover to permit observation from the sides as well as from the front. The instrument is mounted on a panel with two three-pole switches, which connect it to the incoming and operating lines. The suspension insulators have an insulating strength greater than the maximum voltage used on the line. The glower lamps when not excited have the appearance of ordinary spherical,frosted,incandescent lamp bulbs. When the proper difference of potential is supplied across the lamps they glow with a reddish hue, due to the special gas that they contain.

One of the glowers is connected to the line of the incoming and running machines so that the glower will be short-circuited by one of the poles of the switch when the lines are connected together. The other two glowers have their connections to the line through the insulators reversed, so that at synchronism they are connected across the two remaining phases of the lines with one connection on each glower on the other side of the synchronizing oil circuit breaker.

When the lines are in synchronism, the glowers will indicate in an order similar to that of ordinary synchronizing lamps the apparent direction of rotation, denoting whether the incoming machine is running too fast or too slow. When synchronism is reached there will be no rotating effect and the glower which is connected to the corresponding lines will be dark while the other two glowers will indicate at about one-half brilliancy, which is the condition for throwing the machines together.

The instrument will give satisfactory indications on circuits of as low pressure as 13,200 volts and it can be applied to lines of any higher voltage by connecting in an adequate number of insulators.

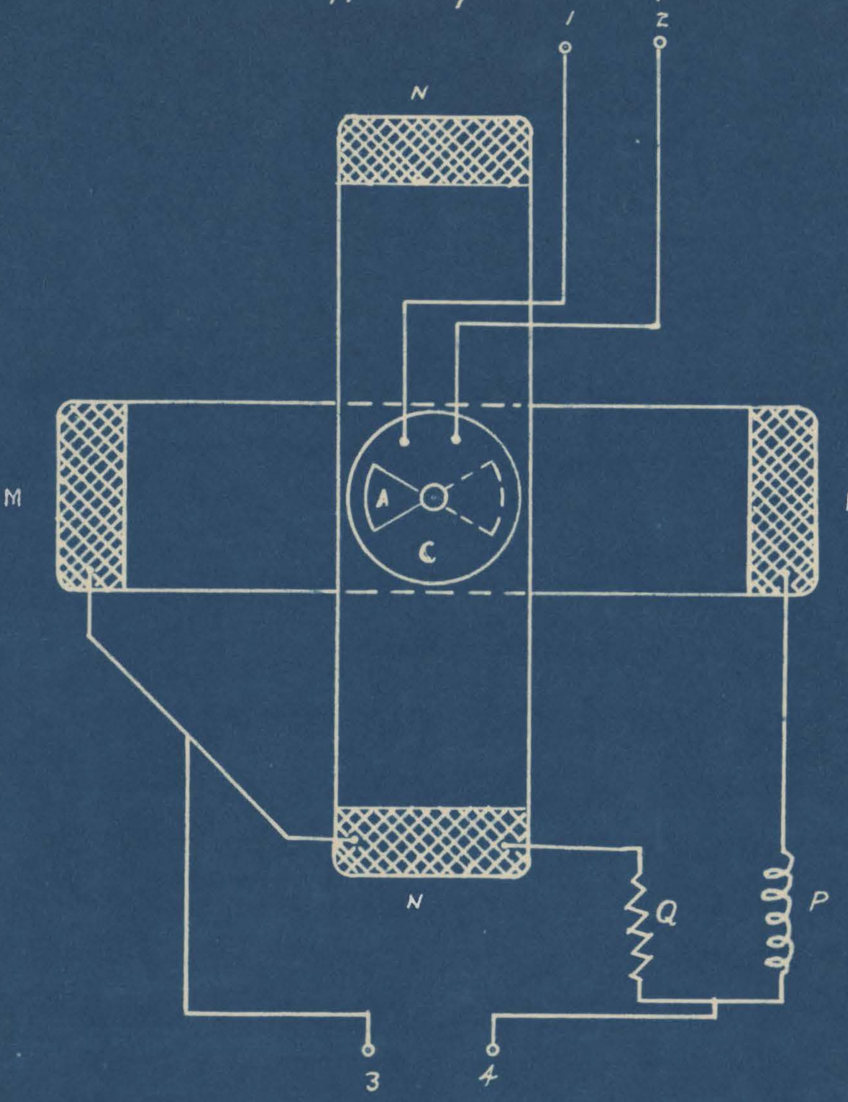
The electrostatic type of indicator is suitable primarily for indicating synchronism between high tension circuits where the voltage and current are measured on the low tension side. It consists of a few simple and inexpensive parts, and can be used to advantage in main stations, switching stations, line junction stations, and some substations. The usual method of indicating when machines may be synchronized by use of a synchronous indicator or lamps, employs also as a rule, potential transformers. This arrangement is very satisfactory but when it is desired to connect two systems together where transformers are not needed for indicating or measuring purposes the electrostatic type of indicator is satisfactory and comparatively inexpensive. The higher the voltage the more does this apply. The General Electric Company manufactures an electrostatic synchronizer which requires for operation only the charging current of the line.

The electrostatic synchronism indicator can also be used as a ground detector by connecting one terminal of each glower to the ground and the other terminals to the line. A lighted glower will indicate that the line is at a potential higher than that of the ground, that is, not grounded.

Induction Type Instrument

Construction: (see Fig. 2) The inductor type of synchroscope consists of three stationary coils N, M, and C, and a moving system consisting of an iron armature A rigidly attached to a shaft S which is suitably pivoted and mounted in bearings. The moving system is balanced and is not subject to any restraining force or spring such as a gravity control. The coils

Inductor Type Synchroscope



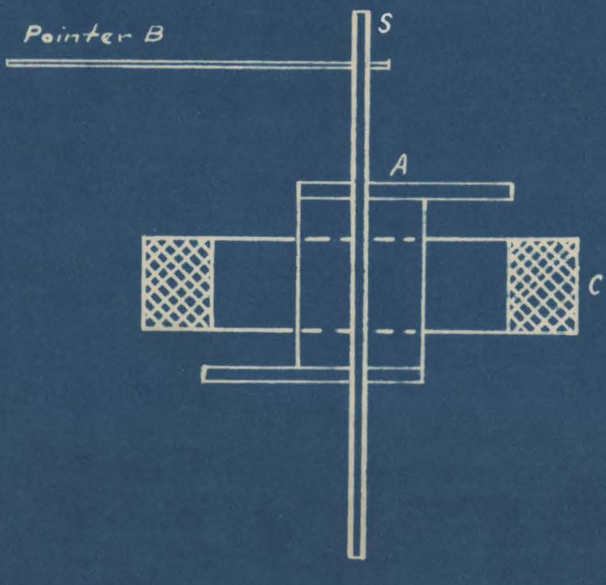


Fig. 2

N and M have their axes in the same vertical plane but ninety degrees apart, while coil C has its axis in a horizontal plane. N and M are connected in split-phase relation through an inductive reactance P and a noninductive resistance Q, and the two circuits are paralleled across the bus bar terminals 3 and 4. Coil C is connected through a noninductive resistance across the upper or machine terminals of the synchroscope.

Principle of Operation: Current in the coil C magnetizes the iron core carried by the shaft and the two projections. There is, however, no tendency to rotate the shaft. If current be passed through one of the other coils, say M, a magnetic field will be produced parallel with its axis. This will act on the projection of the armature causing it to turn so that the positive and negative projections assume their position in the field of M. A reversal of the direction of the current in both coils will obviously not affect the position of the armature, hence alternating current of the same frequency and phase relation in coils C and M cause the same directional effect as if direct current was passed through the coils. If current lagging ninety degrees behind that in coils C and M be passed through N it will cause no rotating effect upon the armature because the maximum value of the field which it produces will occur at the instant when the pole strength is zero. The two currents in the coils N and M produce a shifting magnetic field which rotates about the shaft as an axis. As all currents are assumed to be of the same frequency, the rate of rotation of the field is such that its direction corresponds with that of the armature projections at the instant when the poles induced in them by the current in the coil C are at a maximum value and the field shifts through 180 degrees in the same interval as is required for the reversal of the poles. This is the essential feature of the instrument; namely, that the armature projections take a position in the rotating magnetic field which corresponds to the direction of the field at the instant when the projections are magnetized to their maximum strength by the current in the coil C. If the frequency of the currents in the coils which produce the shifting field is less than that in the coil which magnetizes the armature then the armature must turn in order that it may be parallel with the field when its poles are at maximum strength; consequently a rotation of the armature indicates a difference in frequencies, and the rate and direction show which has the higher frequency and the amount of difference.

Lincoln Type Synchroscope

The Lincoln type of synchroscope has been developed for use in large stations where it is necessary that the instrument be visible from each prime mover.

Construction: (See Fig. 1A, page 5a) As may be seen by inspection of the figure, this instrument consists of an alternating current bi-polar motor with a laminated iron field M and M' and a core on which is wound a distributed two-phase winding B and D and which is connected in split-phase relation through a noninductive resistance r_1 and an inductive reactance x_1. The resistance consists of two stationary illuminating lamps located on the glass, dial, and movable lamps are attached to the indicating pointer.

On M and M' are wound two field coils connected to the two bus bar leads 3 and 4. Current is carried to and from the armature by means of a set of three collector rings and corresponding brushes. The armature shaft also carries an indicating pointer supporting the moving indicating lamps.

Principle of Operation: In a motor, as shown, the armature tends to take a position such that the current in its coils produces a magnetic field in the same direction as the magnetic field produced by the stationary field coils. If a direct current be passed through the field coils and also through the armature coil D, then the armature will assume a position as shown in the figure. If the direction of the current be simultaneously reversed in both coils the position of the armature is obviously unaffected. Hence, if alternating current be substituted for the direct current the position of the armature will remain unchanged provided the alternating currents have the same frequency and the same phase relation. A second current having a difference of phase of ninety degrees may be passed through the coil B of the armature. This will cause the position of the armature to shift for the reason that the magnetic field it produces is a maximum when that produced by the stationary field coils is zero; hence there is no effective torque produced. The two currents in the armature produce a progressive shifting of the direction of the magnetic field and (as all the currents are of the same frequency) the rate of rotation of this magnetic field is such that its direction coincides with that produced by the stationary field coils at the instant that the latter are at a maximum value. This is the essential feature of the instrument; namely, that the rate of physical rotation of the magnetic field produced in the armature must be such that it coincides in direction with the field produced by the stationary field coils when the latter are at their maximum value. As above described, if the frequency of the current in all the coils is the same the armature takes the position as illustrated in the figure. Suppose the frequency of the armature current is less than that of the current in the stationary field coils; then the rotating field does not shift quite 180 degrees while the stationary field reverses, hence a torque is produced and the armature turns. It tends to rotate at such a speed that its shifting field moves through a physical angle of 180 degrees during the reversal of the field current; that is, the speed of the armature rotation equals the difference in the magnetic rotation. The speed of the armature and the pointer attached to it, therefore, shows the difference in frequency between the alternating current in the armature and that in the stationary field.

It is advisable to use lamps as an additional check because the synchroscope cannot follow in differential frequency when synchronizing is begun with a great difference in speed of the generators. Synchronizing lamps should be used until the speed is within ten per cent of the speed of the running machine, and then the synchroscope will fall in step and indicate by the direction of its rotation the speed relation between the incoming machine and the bus bars.

A synchronizing device is sufficient in single-phase for paralleling machines after the correct permanent connections have been made to the synchronizing switches.

Automatic Synchronizer

The automatic synchronizer is primarily intended for use in stations operating large capacity machines, and where it is essential that synchronizing be done rapidly and safely.

A successful automatic synchronizer should close the circuit when all conditions are suitable for closing, and it should prevent the closing of circuits until these conditions are reached. This involves the following requirements:

(1) It should permit the coupling of the machines as soon as the difference of speed is within safe limits, and it should prevent the coupling of the machines at all other times.

(2) It should permit the coupling of machines when the electromotive forces are within the proper limits, and it should prevent the coupling of the machines when their electromotive forces are too far out of phase.

(3) It should permit the coupling of the machines when their electromotive forces are equal, and it should prevent the coupling of the machines when their electromotive forces are too widely divergent.

(4) It should close the relay circuit for coupling these machines on the first occasion when the three foregoing conditions occur.

(5) It should close the relay contacts in advance of the period for coupling by a sufficiently large interval to allow the switch to act at the exact moment of synchronism; the greater the difference in speed the greater should be the advance in angle in order to make the time allowed constant. As

different types of switches require different amounts of time to close, the time of advance should be adjustable.

(6) It should be certain and safe in its operation and if anything in the mechanism fails it should prevent coupling.

The automatic synchronizer is especially well adapted for use in power stations of large railway systems. When accidents occur which entirely shut down one or more substations, it is exceedingly important to start up again with the least possible delay. With alternating current motors for starting, and an automatic synchronizer for each rotary converter, this can be done very quickly. Unless the voltage of the system has been disturbed it is simply necessary to close the starting motor switches and the automatic synchronizer will do the rest.

With the incoming machine in phase with the running machine, as in synchronism, the magnetic fields induced by the currents in the left hand solenoid oppose each other, then neutralizing the pull of their core at the same instant, the magnetic fields induced by the currents in the right hand solenoid assist each other, thus giving a maximum pull on their core and drawing it to the bottom of the solenoid. When the incoming machine is not in synchronism the magnetic fields induced by the currents in the left hand solenoid assist each other and exert a maximum pull on their iron core. When the incoming machine and the running machine are in ninety degree phase relation the solenoids exert equal pulls on their iron cores, which take up equal distances from the bottom of each solenoid. The displacement of the beam from the first synchronizing position (due to a differenc in phase relations between the two machines) imparts to it a walking-beam action, and this movement up and down corresponds to the dark and light periods of lamps, or to the pointer rotation of the regular dial synchroscope.

Low Energy Synchroscope

The increasing variety of phase angle measurements requiring low burden instruments has created a need for a phase angle meter having low power consumption. This is especially desirable for synchronizing power circuits when only potentials from condenser bushing devices are available. However, a low energy instrument is desirable for all applications.

A new iron-vane synchroscope has been developed with a burden of about four volt-amperes per circuit, which is about one fourth of the energy consumption of previous types. The rotating field of this synchroscope is set up in an efficient magnetic path of low reluctance by coils connected to the incoming machine. The magnetic circuit is practically all iron except for the gap between the moving iron-vane and the stator.

The moving element is made of a light-weight, rugged, duralumin shaft to which are attached iron vanes. The vanes are of hipernik, a low-loss iron. Hipernik has high permeability at low induction, making it especially suitable for this case.

The same mechanism is being used with different windings in power factor meters with a 360 degree scale. Such instruments are useful on circuits subject to power flow reverses in direction, as on tie lines. The ordinary dynamometer power factor meter scales necessitate switching the instrument transformer connections, but this is avoided in the meter with a 360 degree scale.

The synchroscope element fits into the case which has been developed as a standard for switchboard instruments. This permits interchangeable case and cover parts as well as good appearance. The mechanism can also be used as a position indicator by using a three-phase winding on the stator for connections to a controller motor of the duplicate position type. The scale is more uniform and accurate than on previous indicators. The low energy consumption makes it possible to operate more indicators from a given size controller, or to operate indicators at a greater distance.

Experimental Procedure

Object: To construct a synchroscope for use in the Electrical Engineering Laboratory. This synchroscope is to be small and a very compact unit, which will be portable and of such sturdy construction that it will not be damaged by the frequent handling of inexperienced students.

Method of Procedure: After a thorough research of the existing types of instruments, a synchroscope of the Lincoln type was chosen as best suited for the given object. The construction of this type of synchroscope is essentially that of a wound rotor induction motor. This involves the construction of pole pieces, field coils, and a wound rotor.

The pole pieces were cut from laminated sheet steel to the desired size and shape and then bolted together (see Figs. 3 & 4)

As the instrument was to be used on 110 volt, 60 cycle circuits the number of turns on the field coils was calculated as follows:

Assuming 40,000 lines per square inch to be the flux density of the laminated iron poles, the number of turns was determined from the relation—

$$e = 4.44 \, f \, N \, \phi \, 10^{8} \text{ volts}$$

where; f is the frequency in cycles per second

N is the number of turns

ϕ is the flux

e is the impressed voltage

The required number of turns was found to be 1,100 for both coils, or 550 turns per coil. The largest wire which could be placed into the available space was found to be number 19 B.& S. enameled, single cotton covered, copper wire. Wooden coil forms were then constructed, upon which the coils were wound. The coils were next wrapped with insulating tape and soaked in black insulating varnish; and,after being allowed to dry, were then placed on the field poles.

The armature was wound on a frame taken from an old Thomson watt-hour meter. This frame was first cut down so that it would be of the proper diameter for the field poles. The two armature windings were then placed on the core at right angles to each other and leads were brought out to the collector rings. Each winding was composed of 60 turns of number 32 B.& S., enameled, single cotton covered, copper wire. The complete armature was of very light construction, due mainly to the fact that it was of the air core type.

Brass frames (Fig. 3) were attached to the field poles to provide bearings for the armature shaft, and supports for the brush holders. The field coils, poles, and armature were then assembled (Fig. 4) and mounted in a small wooden box.

The instrument,as it is,is not a complete unit because it is necessary to provide a phase splitting device for the windings on the armature. Practically all commercial units have the phase splitting device as a separate unit from the instrument itself.

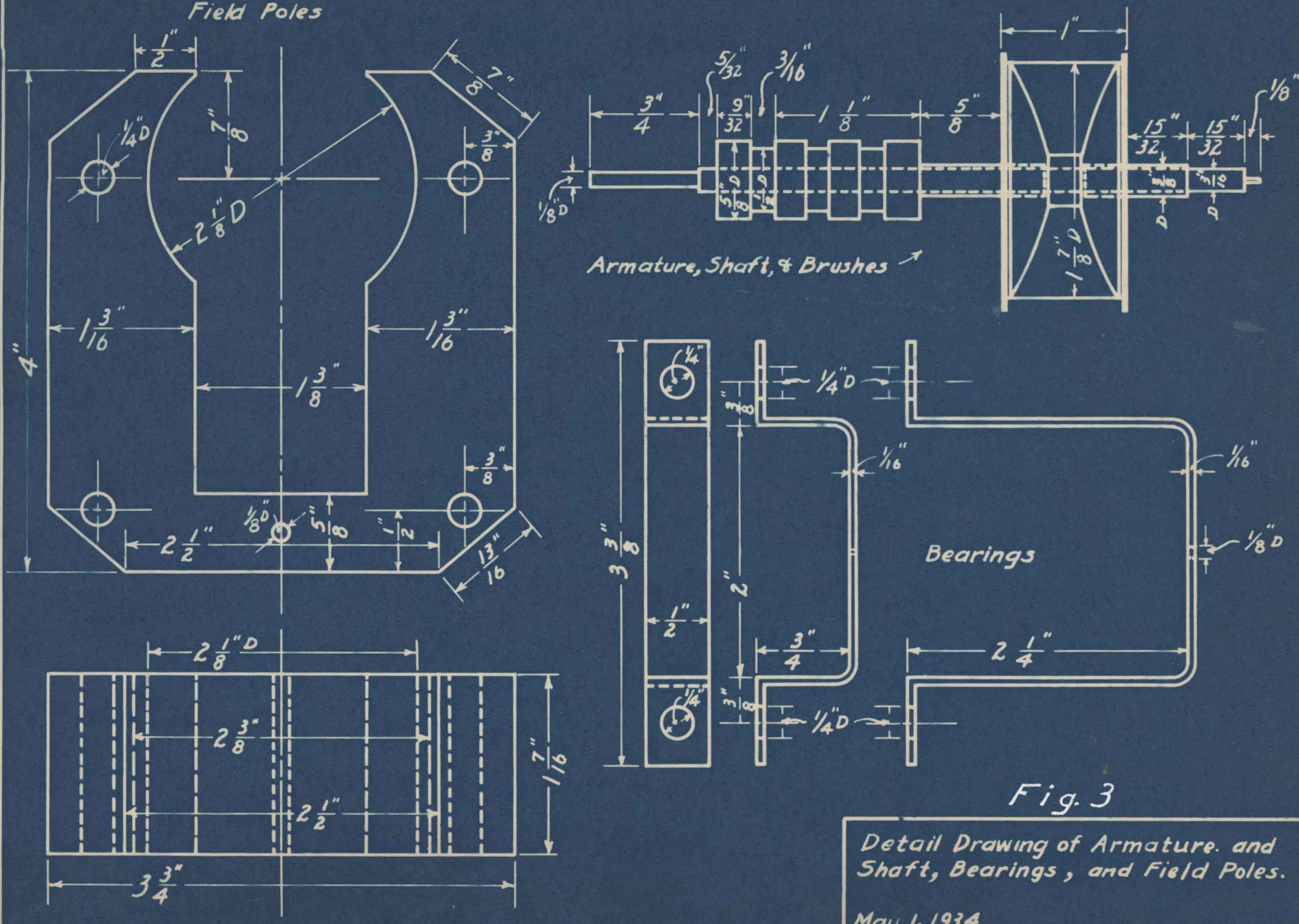


Fig. 3

Detail Drawing of Armature and Shaft, Bearings, and Field Poles.

May 1, 1934

Since it was our original idea to make the synchroscope a compact unit within itself, our next move was to design a resistance coil and a reactance coil so that they could both be placed in the box containing the other mechanism. As the maximum armature current was to be a fraction of an ampere (0.75 amperes), a resistance of approximately 130 ohms was necessary. This resistance also included the resistance of the armature coil which was in series with it. Therefore, in order that the phase should be split as near ninety degrees as possible, a total inductive reactance of approximately 130 ohms was necessary.

A small, circular, laminated, iron core was selected for the construction of the reactance; but before the number of turns necessary to give the required reactance could be determined, the saturation curve of the iron core was determined and the correct flux density was calculated. Then, with the flux density, frequency, and voltage known, the number of turns necessary to give the required reactance was calculated from the relation—

$$e = 4.44 \, f \, N \, \Phi \, 10^{8} \text{ volts.}$$

After having wound the coil it was found that the number of turns was insufficient to give the desired results. Consequently, more turns were added until the total number of turns was 1712, which gave satisfactory results when balanced against the

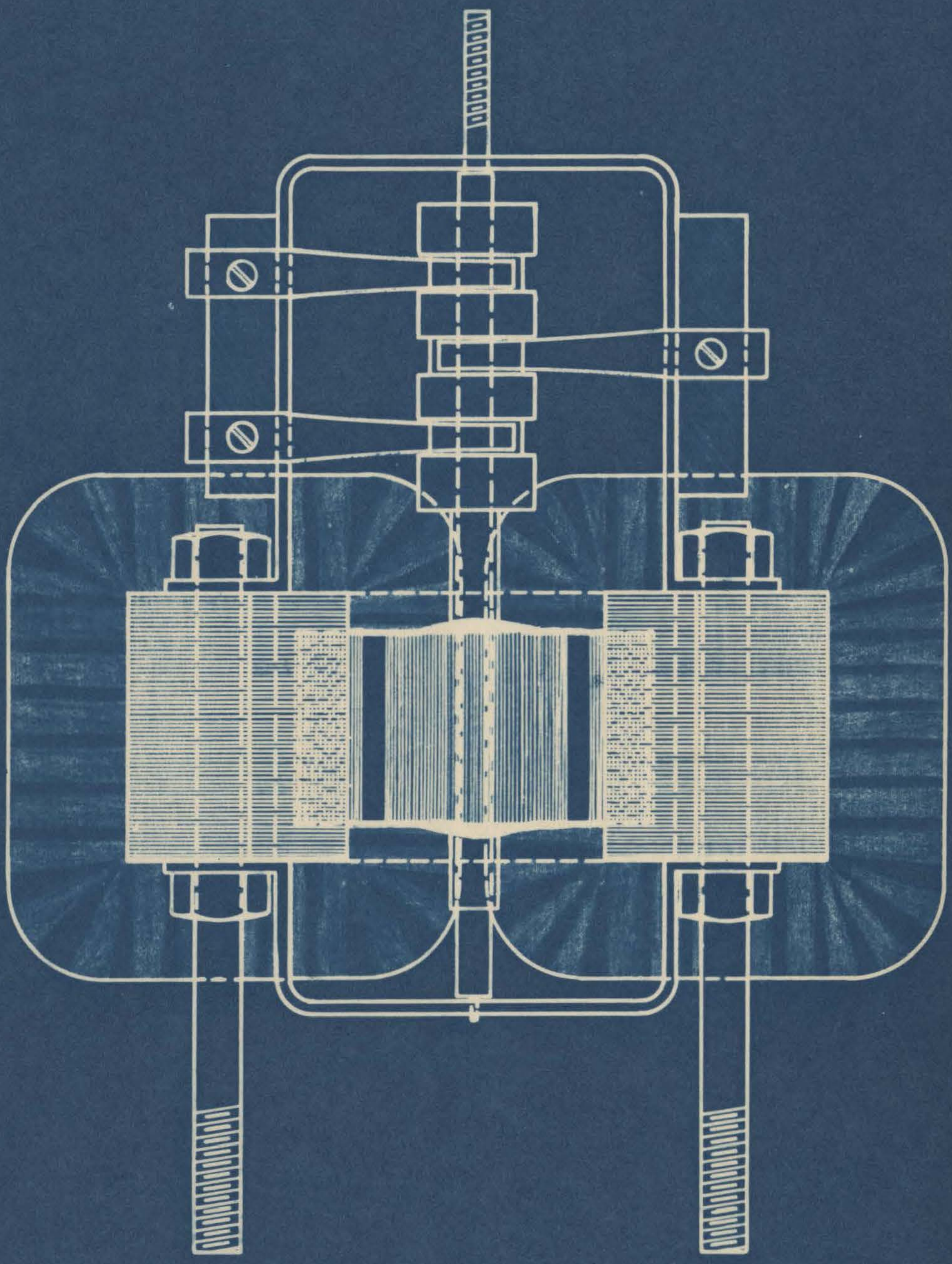


Fig. 4

Top View of Assembled Instrument
Showing Brushes, Field Coils, Core,
Armature and Shaft etcetera.
April 28, 1934

resistance. The reactance coil was wound with number 28 B.& S., enameled, single cotton covered copper wire. It was then taped, soaked in shellac, and mounted in the box with the other parts.

The resistance was made up of forty-seven feet of resistance wire wound in a small spiral and mounted on a sheet of mica. This was then placed in the bottom of the box with an open grill in the front for ventilation and to allow excess heat to escape.

A face was then put on the box with an indicating needle on the armature shaft in front of the face, so that the needle could indicate the point of synchronism.

Conclusions

After the construction of our synchroscope was completed, we proceeded to test it out in the laboratory. We found it gave positive indications of synchronism in every case, and we were more than satisfied with the results obtained. Although our work was comparatively poor in relation to that done by men who have spent their entire life on such subjects, in consideration of the time and the materials that we had to work with, we feel that we have accomplished our purpose and have derived a great deal of benefit from our year of work.

Submitted by:

N. L. Gregg, Jr.

R. W. Watson

J. S. Jarvis

H. E. Naylor, Jr.

Virginia Polytechnic Institute

1934