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NRL Report 5043

# THE MAINTENANCE OF FRACTIONAL DEGREE PHASING BETWEEN TWO SEPARATE AC VOLTAGES OR ROTATING SHAFTS

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November 29, 1957

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## ABSTRACT

A method is often required whereby two or more sources of electrical potential may be automatically maintained not only in frequency synchronism but also in phase synchronism to a very high degree of accuracy. Occasionally, the same high degree of phase accuracy must be maintained between the instantaneous shaft positions of two or more rapidly rotating devices such as electric motors. A system has been developed that is useful in fulfilling both of these requirements. It consists essentially of treating the problem on a master and slave basis whereby the voltage of the one or more slave sources of potential is maintained under continuous phase comparison with that of the master. When any small phase change develops, an error signal is produced that actuates a servo system, automatically correcting the phase of the slave station. For the maintenance of mechanical phase alignment, the shaft positions of the master and slave devices are translated into ac electrical potentials whose phases are compared in a similar system, and any necessary correction effected through a servomechanism. Performance data indicate that phase accuracy to plus or minus one minute of electrical or mechanical phase difference can be obtained.

## PROBLEM STATUS

This is an interim report; work on this problem is continuing.

## AUTHORIZATION

NRL Problem R06-05
Project NE 070-154-6, 7
Bureau No. S-1431

Manuscript submitted October 2, 1957

# THE MAINTENANCE OF FRACTIONAL DEGREE PHASING BETWEEN TWO SEPARATE AC VOLTAGES OR ROTATING SHAFTS

## INTRODUCTION

There are many instances in the design of electronic systems in which it is necessary to maintain the operation of two or more remotely located pieces of equipment in exact phase synchronism, i.e., within several minutes of arc. Such synchronism requirements may refer either to two or more rotating devices operating at relatively high speeds, in which case the term phase connotes the instantaneous angular relationship between similar points on their respective shafts, or to two or more electrical circuits where the electrical phase between their respective voltages is involved.

The common practice of employing synchronous motors operating on a common power source serves admirably in the maintenance of speed synchronism, but such devices will not remain in phase synchronism for any appreciable period of time, nor will they always start and lock into synchronism in the proper phase. However, synchronous motors are such simple and useful tools in obtaining speed synchronous operation of a multiplicity of rotating devices that the development of means for accurately controlling and maintaining their phase synchronism would simplify an otherwise complicated problem. The purpose of this report is to describe the principles of operation of such a system.

It should be realized, however, that the requirements and performance details of the many different applications of synchronized systems are so varied and numerous that any attempt to discuss them all would be futile. Accordingly, this report will describe the operation in terms of a system designed and developed to maintain electrical phase synchronism between a single-phase source of potential and a remotely located three-phase source. In addition, a description is given of the adaptation of the system to the maintenance of mechanical phase synchronism between two rotating devices located at a distance from each other, specifically, devices employed for radio direction finding purposes.

## BACKGROUND

In connection with an investigation of a more extensive problem, it became necessary to provide a three-phase source of potential that could be maintained in exact phase synchronism with a single-phase reference potential, transmitted at low level over a considerable distance. Unattended operation and a high order of accuracy under the usual variations in line voltage, temperature, humidity, etc., were paramount requirements. Because a three-phase circuit was involved, an additional requirement was the maintenance of similar accuracy between the respective phases.

Amplifying and static phase-splitting techniques were investigated both theoretically and experimentally but were found unsuitable from both a stability and a distortion viewpoint. Accordingly, the use of a motor-driven three-phase generator was investigated. The use of such a generator was obviously a simple solution to the problem of obtaining a three-phase potential source with the required low distortion and stable intraphase accuracy. The only problem was to maintain this source in exact phase relationship with the remotely located reference potential. The solution of this problem resulted in the development of the system herein described.

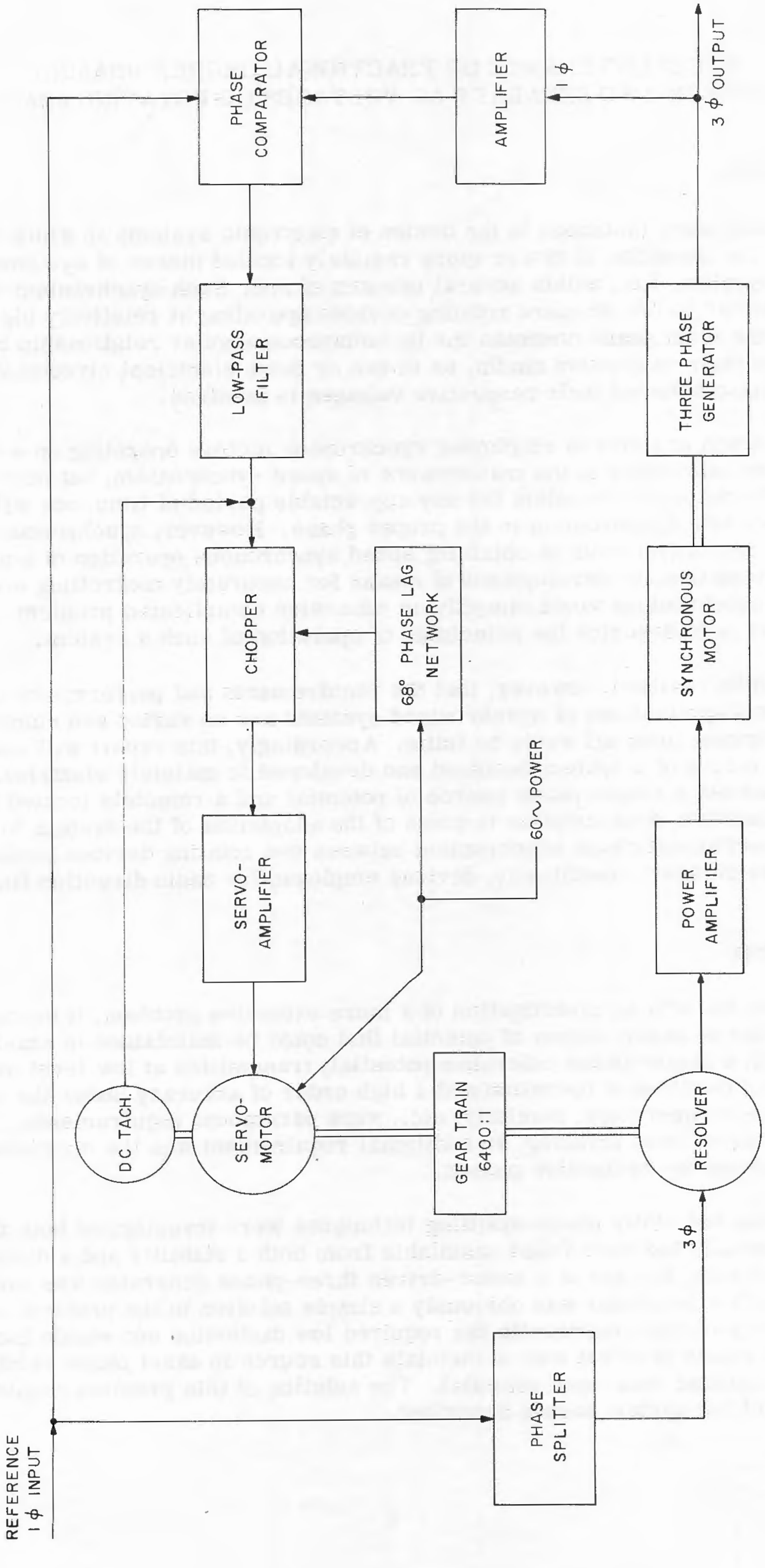


Fig. 1 - Block diagram of the system

## DESCRIPTION OF THE SYSTEM

Figure 1 is a block diagram showing the operating principles of the system. The single-phase reference frequency connects to a static phase splitter having a three-phase output. These three phases energize the stators of a Navy Standard #1 control transformer which will hereafter be designated as the resolver. The phase of the output voltage from the resolver is variable through 360 degrees, the exact phase depending on the position of its rotor. Its output connects to a power amplifier having sufficient gain and output capabilities to drive a single-phase synchronous motor. Coupled to this motor, through a zero-back-lash coupling, is a three-phase, permanent magent type generator which supplies the desired three-phase output. This part of the system will obviously provide a three-phase voltage from a single-phase input with exactly the same frequency characteristics, but with all possible phase relationships. It is equally obvious that the phase of the generator output can be varied with respect to the input by rotation of the rotor of the resolver. This characteristic is used in the design of the automatic phase correction and maintenance feature of the system.

This feature involves, fundamentally, a phase-critical servomechanism. The rotor of the resolver is driven by a small (5-watt) servomotor through a double worm reduction gear having an overall ratio of 6400:1. The exact value of this ratio resulted from the use of gears that were immediately available and has no particular significance except that the higher it is, the more accurate the possible phase maintenance — at the expense of slower action. The 6400:1 ratio provides for a phase variation of just under 3.4 minutes for a complete revolution of the servomotor, so that correction and maintenance to better than one minute is entirely possible.

In Fig. 1, it will be noted that one of the three phases of the generator connects to a comparator amplifier. This amplifier, which has a very high impedance input, serves the purpose of providing sufficient power to energize one side of the comparator without distorting the waveform or phase relationship of the three generator voltages.

Next in the servo loop is the phase comparator. This is a three-circuit device that will be described in detail in a later section. One of its two input circuits connects to the generator through the comparator amplifier, and the other to the reference source. These two sources provide the voltages to be phase compared.

Assuming that the mechanical connection between the servomotor and the resolver through their gearing is mechanically perfect, the heart of the system lies in the method of controlling the servomotor. The basic requirement is that the input and output voltages of the system be maintained in exact phase synchronism at all times. To assure this, all that is necessary is to compare the two voltages in question in a sensitive phase-critical device that will produce an error signal for operating the correcting servomechanism when the relative phase of these voltages varies by the slightest amount. This is accomplished by a ring-type phase comparator. This device, when fed with the two ac voltages under comparison, produces an output consisting of even harmonics of the input frequency and a dc component whose amplitude and polarity vary with the phase difference between the two input voltages. In operation, the ac components are filtered out and the dc component is used as the error signal to control the correcting servomechanism. When the two voltages under comparison are exactly 90 degrees or 270 degrees out of phase, this dc component is zero, but it increases rapidly (as a cosine function) as the phase difference departs from these reference points. The polarity or sign of the voltage depends on whether the departure is positive or negative, thereby providing "sense" to the error signal. While a zero voltage exists for two phase angles (90 and 270 degrees), only one is effective as the reference error signal. This arises from the fact that a departure from one of these two phase relationships (depending on the initial connection) will tend to drive the system back toward zero while the other will drive it away from the incorrect zero, through 180 degrees to the correct one.

The output of the phase comparator, as has been mentioned, contains a very high second-harmonic frequency of the voltages under comparison as well as being relatively rich in other even harmonics. To eliminate these and obtain a "clean" dc voltage, the phase comparator output is passed through a multisection low-pass filter with an end section consisting of a bridged-T network to affect the necessary high attenuation of the second harmonic.

The filter output is connected to the contacts of a 60-cycle vibrator-type chopper to convert the dc output of the comparator to ac suitable for driving the servomotor that effects the phase correction in the resolver. The chopper is driven from the power line that also energizes the fixed phase of the servomotor. Since there is a phase lag of 22 degrees between the chopper contacts and the driving source, a 68-degree phase lag network is included between the power line and the chopper actuator winding in order to obtain the required 90-degree phase difference between the fixed and controlled inputs of the two-phase servomotor.

The output of the chopper is connected to the input of a servoamplifier which raises the level of the error signal to a sufficiently high power level to drive the servomotor.

To eliminate hunt and oscillations in the system, the servomotor is provided with a built-in dc tachometer, the output of which is fed to the chopper contacts together with the dc error signal from the comparator filter.

## OPERATION OF THE SYSTEM

Figure 2 is a schematic diagram of the system. It should be borne in mind that this diagram applies to the particular system constructed for a specific application within a larger system; therefore no attempt was made to consolidate the components of this diagram into one having a minimum number of functional units.

When power has been applied to the equipment so that its various units are activated and the reference signal is applied, the synchronous motor will start and lock into frequency synchronous operation. However, it is unlikely that the generator output connected to the amplifier will be exactly 90 degrees out of phase with this reference voltage. As a result, a dc voltage will be present at the output of the low-pass filter. This dc is converted by the chopper to a square-wave ac that energizes the servoamplifier, causing the servomotor to operate. This will rotate the rotor of the resolver, which will change the phase of the voltage driving the synchronous motor. As this changes, the instantaneous angular position of its rotor together with the rotor of the generator also changes, thereby changing the phase of the generator output voltage with respect to the reference input voltage. This will continue until the input and output voltages are exactly 90 degrees out of phase, whereupon the dc component of the comparator output will drop to zero, the servomotor will stop, and the correcting system will become quiescent and remain so as long as the two voltages stay 90 degrees out of phase. If, however, this phase relationship varies slightly, such as would result from a variation in the phase lag of the synchronous motor, the servomotor will again operate until the necessary phase correction is effected.

## COMPONENT PERFORMANCE CONSIDERATIONS

In order to permit application and design variations of the system to be considered, the characteristics of major importance for each of the component units will be treated individually.

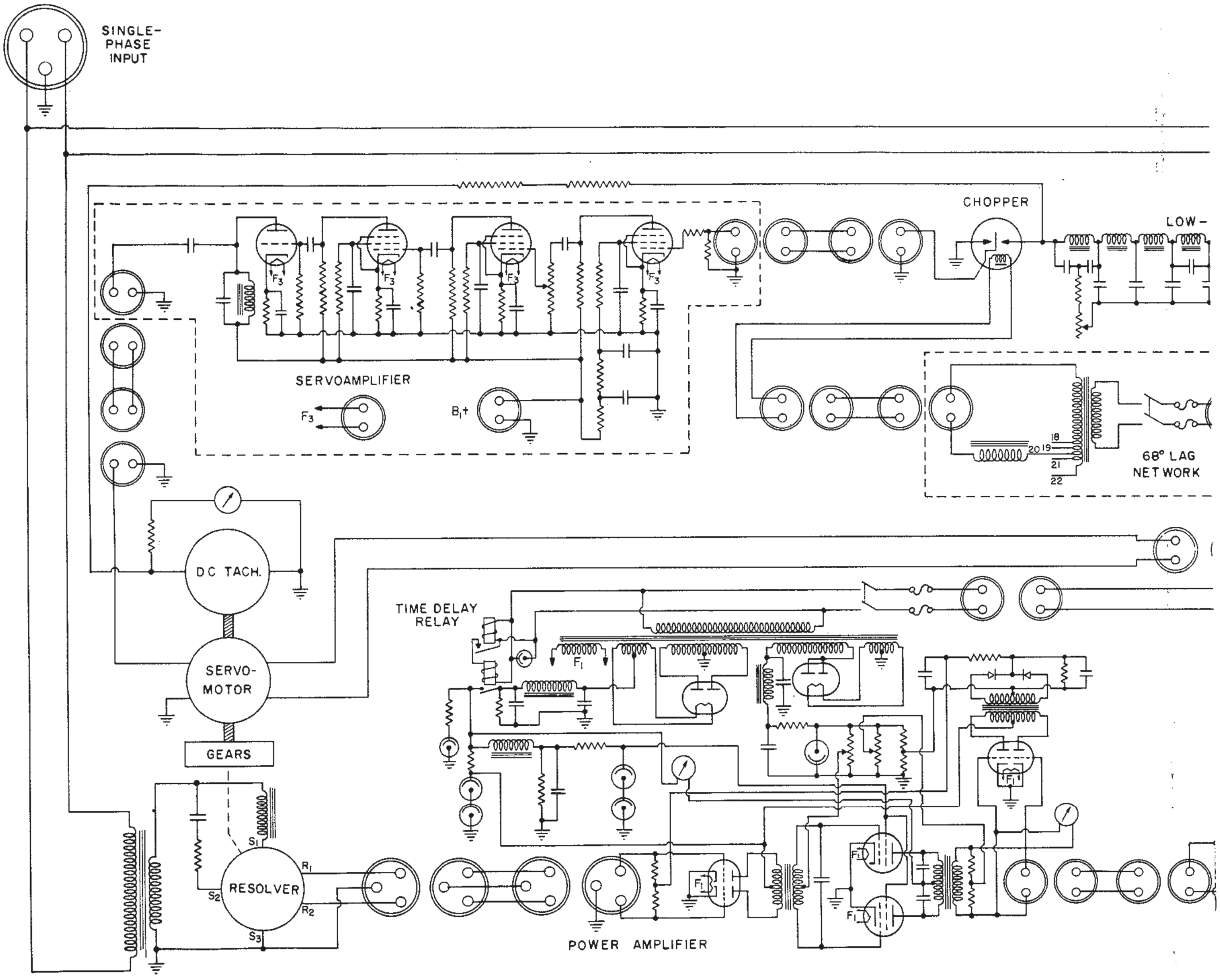
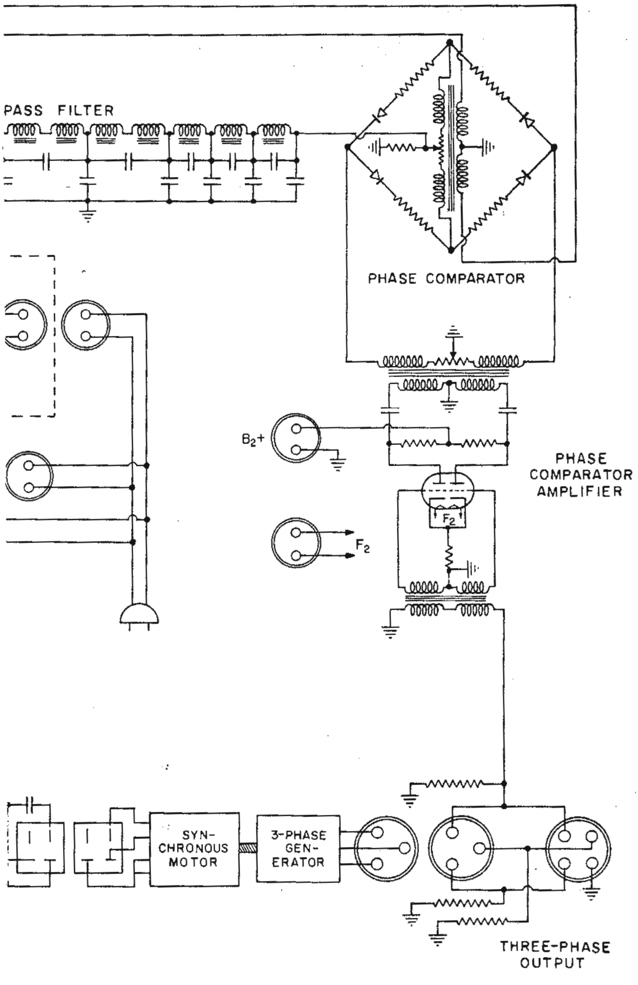


**Fig. 2 - System schematic wiring diagram. (Components not shown in Fi in dotted lines and connected into system through connectin**



gs. 6 and 8 are enclosed
g cables.)

## The Phase Splitter

The three phases from the output of the phase splitter should not depart from the normal 120-degree relationship by more than plus or minus 10 degrees. While any inaccuracy will be corrected by the automatic correcting feature of the system, too great an inaccuracy will cause sections of the phase versus rotation curve of the resolver to have a steep slope, thereby making the corrective action more critical than is desirable. The impedance of the phase splitter is determined by the type of resolver used and, should the phase splitter excessively load the reference line across which it is connected, a power amplifier should be inserted between it and the line.

## The Resolver

Almost any resolver or synchro control transformer designed and marketed for their normal use will have sufficient angular accuracy for this application inasmuch as any inaccuracies in this device are automatically corrected in the operation of the system. There are, however, four requirements:

(a) The rated stator voltages must be at least as high as the maximum voltages obtained from the reference line through the phase splitter.

(b) The stator and rotor impedances should preferably be high. The former simplifies the design of the phase splitter and reduces the reference line loading, and the latter increases the voltage applied to the power amplifier and reduces the required gain in this unit.

(c) Ball bearings should be used and should be easy running with sufficiently close tolerances to produce the very minimum of shaft play. This is of extreme importance because the accuracy of phase regulation is directly proportional to the accuracy to which the resolver rotor can be set and maintained.

(d) The collector rings and brush assembly should be of high quality, inasmuch as any chattering or other circuit interruptions caused by them will result in a chatter of the driving motor and a subsequent phase chatter in the output.

## The Servomotor

This should be of the conventional two-phase type with a top speed of approximately 3600 rpm and with a built-in dc tachometer having an output of about 6 volts per 1000 rpm. The greater the number of commutator bars, the more satisfactorily the tachometer will perform its function. The rotor inertia of the combined motor and tachometer should be as low as possible. However, the most important considerations, again, are well-fitted but easy-running ball bearings and a straight shaft to permit a gear fit without binding or play.

## The Gear Train

The gear ratio chosen should be a compromise between the rapidity required for the phase correction and the accuracy. Between 5000:1 and 10,000:1 may be considered reasonable limits. The use of spur or worm gears is a design choice, but if spur gears are employed they should be of the spring-loaded split type, except for the first and possibly the second gear adjacent to the servomotor. In either case, however, the feature of paramount importance is that the train must be entirely free running, with no tight spots at any point of mesh of any of the gears, but at the same time must be devoid of any tooth lash. The accuracy with which phase match can be maintained can be no better than the angular accuracy between the movement of the servomotor shaft and the movement of the resolver rotor. It is recommended that all gearing other than the split type be fitted slightly tight and then "run in" with a polishing agent. All bearings should be of the ball type, as well fitted and easy running as those in the resolver and the servomotor.

### The Power Amplifier

This unit should be designed for continuous duty and have sufficient gain and power output to operate the motor at full speed on the voltage obtained from the output of the resolver. It obviously must be designed for the frequency on which the system is to operate. Since it might appear that the sole duty of this amplifier is to operate a motor, filtering to remove residual 60-cyle and 120-cycle hum would be relatively unimportant. However, on the contrary, there are some cases where this factor might assume considerable importance. If the reference frequency under control (or any of its lower harmonics) should be close to the power line frequency (or any of its harmonics) used by the power amplifier and the hum level is high, these two frequencies will produce "beats" of a slow periodicity which may make the synchronous motor "hunt" at a rate too fast for the corrector to operate, with a resultant phase hunt in the system. Therefore, the voltage amplifier stages should be electrostatically shielded, and sufficient filtering of the dc power supply feeding these stages should be provided to keep the output hum level at least 40 db below the maximum output level.

### The Motor-Generator

The design, size, and specifications for the motor-generator will obviously depend on the service to which it is to be put. For this reason it is impossible to state any positive detailed requirements. There are, however, a few details that should be considered in choosing the motor and generator. First, both machines should have well-fitted bearings (preferably ball bearings) in order to preclude any uneven running or chattering. Second, the size of the motor should be chosen with respect to the load of the generator but should not be excessively oversized, since a motor loaded too lightly will have a tendency to produce small phase "wobbulations." Third, the coupling between the motor and generator should be completely devoid of play or backlash. Fourth, a salient pole motor should be used, since hysteresis motors have been found to have serious phase excursions when excited by voltage transients.

### The Phase Comparator Amplifier

This amplifier may be of any conventional design with both its gain and its input and output impedances suitable for the circuits to which they connect. In general, a very high impedance input is desirable to preclude loading the generator. Under all operating conditions, the amplifier should have a minimum (five degrees or less) inherent phase shift. This requirement is necessary to insure that any variations in phase caused by component instability will be negligible with respect to the desired accuracy of the overall system, since the amplifier is within the correcting servo loop and any phase change introduced by it will be reflected as an uncorrectable error in the phase relationship between the two voltages that are to be maintained in a matched condition. One of the sources of phase shift variation, even when using a push-pull amplifier, arises from changes in the differential plate current (although small) flowing through the transformer primary. To eliminate this, the amplifier uses resistive load impedances and is capacitively coupled to the comparator transformer as shown in Fig. 2.

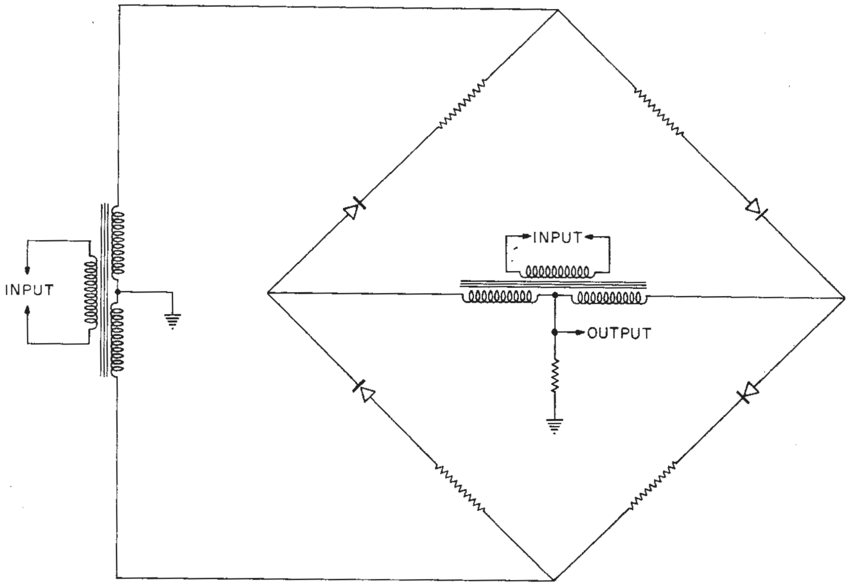


Fig. 3 - Schematic diagram of a ring-type phase comparator

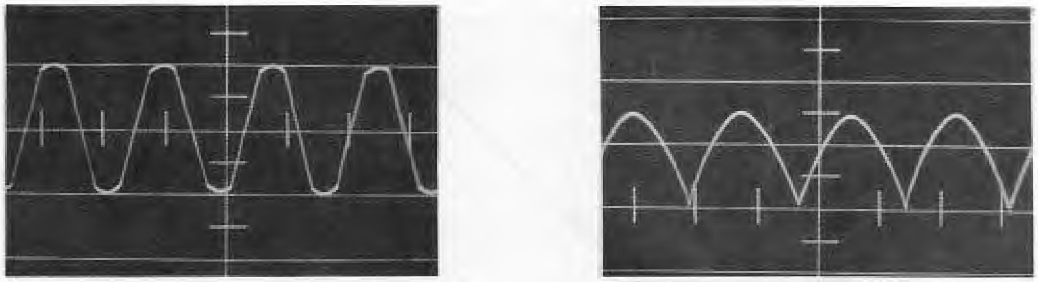
## The Phase Comparator

Design Considerations — The phase comparator is the heart of the system and as such requires special consideration. As shown in Fig. 3, it is fundamentally a bridge circuit and, as such, symmetry in the two arms of the bridge is of extreme importance. In the interest of clarity the various elements will be discussed individually.

Although commercial plate-to-grid transformers and external potentiometer balances were employed in the experimental equipment described herein, this is not recommended for optimum stability and results. It is preferable that the transformers be especially designed and constructed for this purpose. The primary and secondary impedances should be suitable for matching the plates of the amplifier tube(s) and the bridge arms respectively; but the important factor is that of balance between primary and secondary and between the secondary and ground. For optimum performance, a grounded shield should be included between the primary and secondary, and the secondary should be pie wound so that, insofar as possible, the same capacitance is maintained between any two similar voltage points on either side of the center tap and ground, identical to a small fraction of a percent. Similarly, the voltage between the two outside terminals of the secondary and the center tap should be identical to better than 0.1 percent. With such construction, the two balancing potentiometers shown in Fig. 2 may be advantageously omitted with an improvement in stability and elimination of the fundamental frequency in the output.

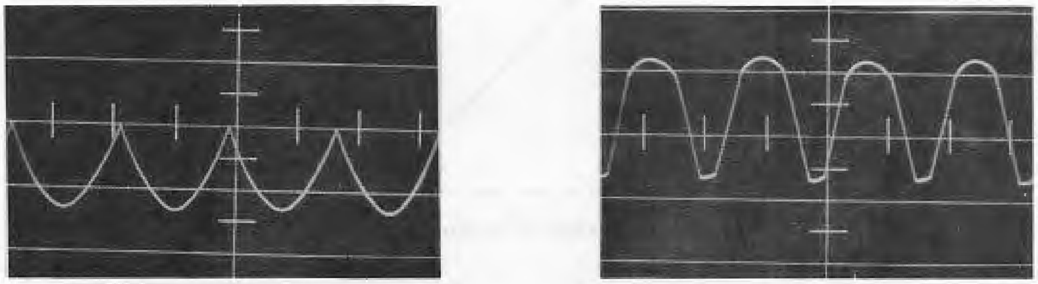
The resistors employed should be of the precision wire-wound type with a low temperature coefficient and matched to at least 0.1 percent.

Although thermionic diodes may be employed for the four rectifiers, their use is not recommended because of the existence and variability of their contact potential, which reduces the stability of the balance point of the bridge circuit. Germanium crystal diodes, TI type 622 C, having a very high front-to-back ratio, are employed in the experimental model and appear to perform very satisfactorily.



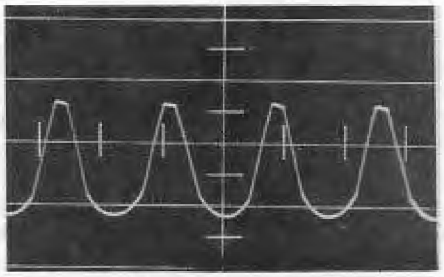
(a) 90 or 270 degrees

(b) In phase



(c) 180 degrees

(d) 45 or 315 degrees



(e) 135 or 225 degrees

Fig. 4 - Oscillograms showing the ouput of the comparator prior to filtering under various phase relationships of the two inputs

The following generalities may be made about the values of the resistors in the comparator circuit. The output load resistance should be approximately twice the value of the resistance in each arm of the bridge. The latter should be chosen with respect to the characteristics of the crystal diodes employed. They should be as high as possible in order to minimize the effects of mismatches in the crystals, but should not exceed approximately one percent of the back impedance of the crystals.

Functioning of the Comparator — Figures 4a to 4e inclusive are oscillograms showing the output waveform of the comparator (prior to filtering) under various phase relationships between the two inputs. When the two inputs are exactly 90 degrees or 270 degrees out of phase (Fig. 4a), a strong ac component (mostly the second harmonic of the input frequencies) exists in the output, but this is symmetrically disposed around the axis so that the dc component is exactly zero. This is the phase maintenance condition for which the correcting mechanism is quiescent. When the inputs are in phase (Fig. 4b), the ac component still has a strong second harmonic, but the zero axis has moved down so that the maximum dc component exists. In the 180-degree phase condition (Fig. 4c), the ac and dc components are numerically the same as for the in-phase condition except that the polarity of the dc component has reversed. Under any phase conditions other than that shown by Fig. 4a, the servomotor will operate, gradually correcting the phase between the two comparator inputs (which represent the input and output voltages of the system) until the exact 90-degree relationship is restored.

## The Low-Pass Filter

The output of the phase comparator contains, in addition to its dc component, a multiplicity of even harmonics. The odd harmonics are relatively small, and if the comparator were perfect, they would be nonexistent. Since the comparator is a "null" operating device and under null conditions the dc voltage is substantially zero regardless of the magnitude of the maximum dc voltage, and since the ac component to be filtered is at its maximum value when the dc voltage is zero, it is obvious that the attenuation characteristics of the required filter will depend on the magnitude of the maximum comparator ac output, i.e., the greater the maximum comparator ac output, the greater the filter attenuation required. As an indication of the required filter attenuation, it has been found, on the basis of a maximum dc level of 15 volts, that for all harmonic frequencies of the operating frequency other than the second, an attenuation of 40 db is sufficient. Since the second harmonic has a peak value slightly greater than the dc output, it must be attenuated at least 80 db.

The choice of the type of filters to be employed is optional and could be influenced by the operating frequency of the system. Their insertion loss for zero frequency should be low but they can begin their cutoff close to zero, inasmuch as the correctional operation is so relatively slow that any sideband frequencies close to zero are negligible. In some cases a "brute force" filter will be adequate for all but the second harmonic, or, because only discrete frequencies are involved and harmonics above the sixth are quite low, tuned networks with a relatively poor "brute force" filter for the higher harmonics can be employed. However, because of the high attentuation required for the second harmonic, it is suggested that a bridged-T network be employed for this purpose.

## The Chopper

The chopper may be of any type that will operate synchronously with the power line frequency and with a relatively constant phase displacement. Its make and break periods should be relatively the same so as to maintain as high a duty cycle as possible. Its paramount requirements are with respect to its spurious output level and its contact reliability. With respect to the former, its hum or other spurious output level when operating (with no input) into a high impedance load should not exceed 1000 microvolts. The contacts should operate with a minimum of bounce or imperfection in contact at very low voltage levels and should be capable of giving at least 5000 hours of continuous operation. Inasmuch as the voltage and current broken by these contacts is extremely low (except for short periods of time when starting), the use of gold contacts on the chopper is recommended.

## The Servoamplifier

This unit, like the power amplifier, should have sufficient power output (when saturated) to supply the rated voltage to the servomotor employed. It should have sufficient filtering to reduce the output hum level (at full gain) to at least 60 db below its maximum output. The required gain is difficult to specify quantitatively because of the many variables involved. It would be desirable to have the maximum gain considerably above the minimum required and to incorporate a gain control that would reduce the hum and spurious outputs in direct proportion to the signal so that an optimum can be obtained. The minimum gain is a function of three factors: (1) the maximum comparator output voltage, (2) the minimum voltage required to initiate servomotor rotation, and (3) the phase accuracy desired of the system. A quantitative example of the manner in which these factors may be applied in determining the minimum gain is included in the discussion of insufficient dc voltage from the comparator as a cause of servo system inaccuracy. The values used therein are somewhat representative of the experimental system described in this report.

## INSTRUMENTATION

Figure 5 is a panel view of the alternator phase control chassis. The controls are well identified by the engraving and need no explanation except for the unidentified meter. This is a refinement that was added to indicate when the corrector was operating and the direction of the correction. It is merely a zero center dc voltmeter connected across the tachometer and thus indicates the direction of rotation of the servomotor.

Fig. 5 - Panel view of the alternator phase control chassis

Figure 6 is a top view of the alternator phase control chassis. The synchronous motor and the generator may be seen near the rear, while immediately behind the panel on the right of the chassis is the resolver unit with its gearing and servomotor drive. The chopper is the cylindrical object having the appearance of an oversized metal vacuum tube. It should be noted that Mumetal shields are used where magnetic pickup would otherwise interfere with proper operation.

Figure 7 is a panel view of the power amplifier for driving the synchronous motor, and Fig. 8 is a top view of the chassis. This unit is entirely orthodox in design and construction.

Photographs of the servoamplifier and rectifier power units have been omitted inasmuch as they are parts of the complete basic equipment, of which the system described herein is only a small part. However, they are completely orthodox in character and their design and construction are unimportant with respect to the operation of the system.

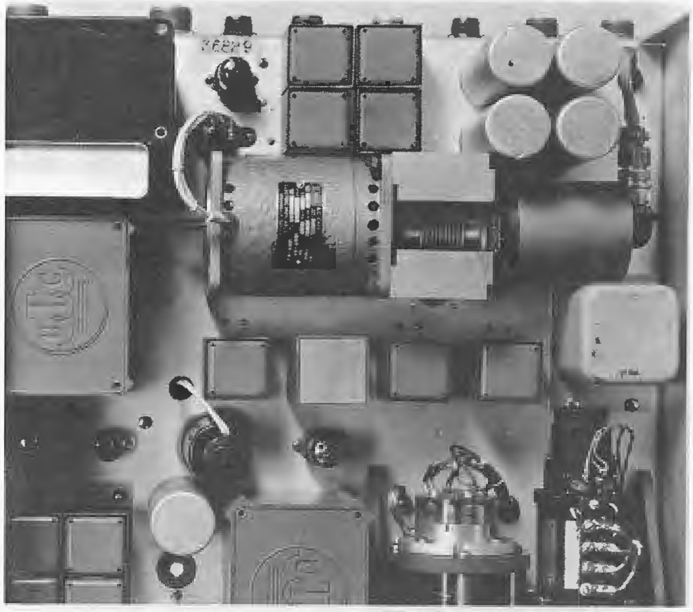


Fig. 6 - Top view of the alternator phase control chassis

Fig. 7 - Panel view of the power amplifier

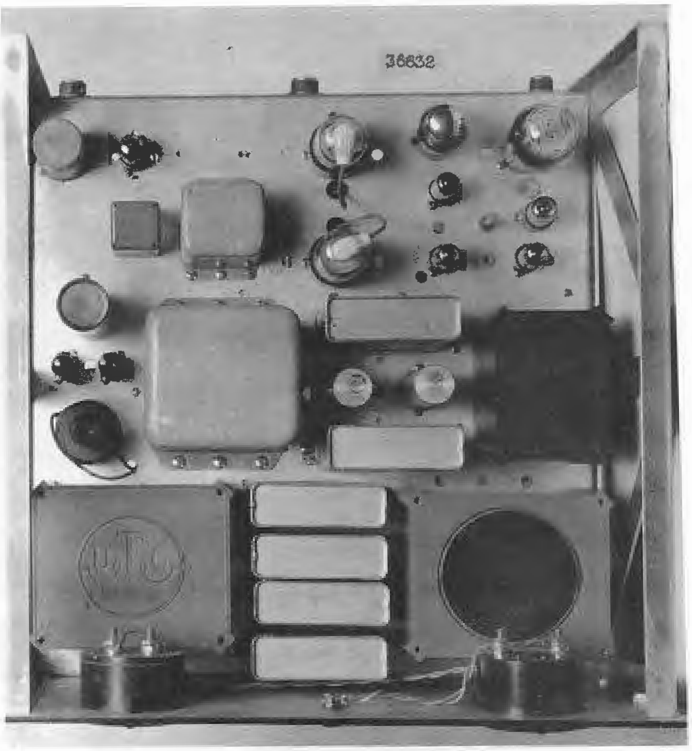


**Fig. 8 - Top view of the power amplifier chassis**

Most of the instrumentation can be modified to suit particular applications. For example, the size of the synchronous motor, being a function of the load it must drive, determines the size of the power amplifier, which, in turn, determines the size of its dc supply and the possibility of taking from this supply the other dc voltages required, thus eliminating the need for two or three separate supplies. A similar treatment applies to the servomotor and servoamplifier. Their power requirements are determined by the size of the resolver.

The type of chopper chosen depends on the servomotor used, since their operating frequencies must be the same, but the choice of one from a particular type is determined by its spurious output level.

The low-pass filter between the comparator output and the chopper must be designed for the frequency at which the system is to operate and can be of any type provided it has suitable attentuation characteristics.

In summation it may be said that all the components of the system are subject to great latitude in their choice and design with the exception of the phase comparator and its amplifier, these being the critical items on which the successful operation of the system depends.

## ADVANTAGES OF THE SYSTEM

In order for a system of this type to be a useful tool, it is necessary that phase stability be maintained at all times.

In this system, phase variations caused by voltage changes or other factors in any of the units except the phase comparator and its amplifier are innocuous because they are outside the comparison and error signal loop, and thus any change they might attempt to effect in the phase angle of the generator is automatically corrected as it is introduced. It is for this reason that it is possible to employ a passive-type phase splitter for this use even though, as has been stated previously, it is not stable enough for direct application. For the same reason, the resolver need not have a high order of accuracy nor the power amplifier a high order of phase stability.

The phase comparator and its amplifier although not outside the comparison and error signal loop, will, when properly designed and once properly adjusted, remain phase stable over long periods of time, not being affected by voltage variations or changes in temperature, humidity, or other external factors.

## PERFORMANCE

It is extremely difficult to present quantitative data on the performance of a system of this type because accurate measurement of phase differences in the order of several minutes of arc is very difficult, the system itself probably being a more accurate measuring tool than any that could be used to test it. However, performance measurements were made with what is considered a reasonable degree of accuracy by the following method.

Servomotor shaft rotations were measured by means of a very light pointer attached to the shaft and a large 360-degree scale attached to the motor frame. With the known gear ratio of 6400:1 between this shaft and the resolver shaft, it was possible to determine angular movements of the latter to small fractions of minutes of arc, which are equal to resolver output phase changes. Any errors resulting from nonlinearity of phase change versus angular rotation of this device were negligible over the very small movements employed.

To introduce small but accurately known phase shifts into the system, an adjustable RC phase shifter was used. It consisted of a resistor in series with a large capacitor. The phase shift of this combination (several degrees) was carefully calculated as well as checked by oscilloscopic measurements. Across the large capacitor was placed a small variable vernier capacitor (designated as $\Delta C$), so proportioned that its complete range resulted in a phase shift of slightly over one degree. It was carefully calibrated so that each of its settings provided an equal phase shift.

To measure the performance of the correcting system, this phase shifter was inserted between the resolver and the comparator amplifier, bypassing the power amplifier, the synchronous motor, and the generator (Fig. 9). Small increments of known phase shift (both plus and minus) were produced by varying $\Delta C$, and the corresponding movements of the resolver by the servomotor were noted in terms of minutes of phase. In a perfect system the plot of such data would be a single straight line with a slope of 45 degrees, but, as might be expected, the performance results plotted as a small hysteresis loop for increasing and decreasing phase shifts (Fig. 10). In general the increasing and decreasing curves depart approximately the same amount from the theoretical 45-degree slope, the maximum correction error being approximately plus or minus one minute. The deviation of the points was the result of minute high or tight spots on the gearing which varied in different positions of the servomotor and resolver gears and minute variations of the dc input to the chopper due to a slow beat between power line and reference voltage frequencies.

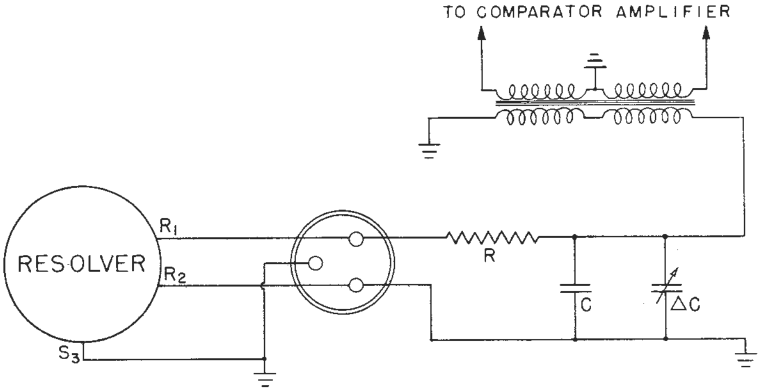


Fig. 9 - Schematic diagram showing phase shifter connections

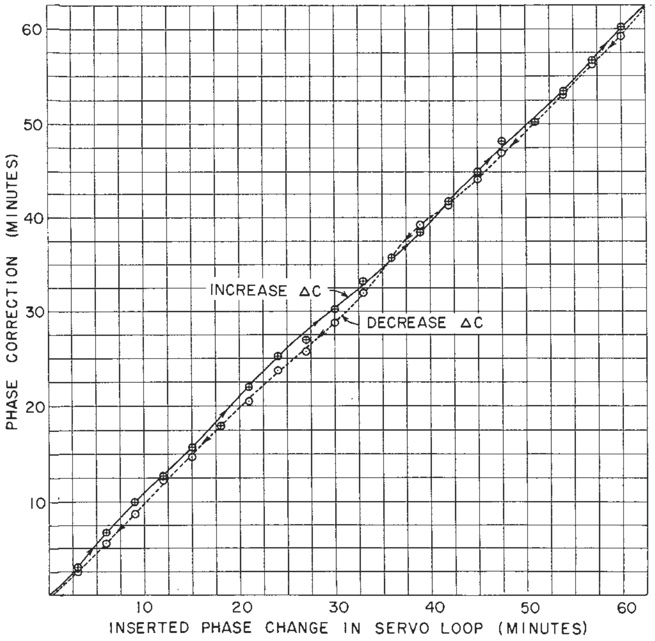


Fig. 10 - System sensitivity characteristic

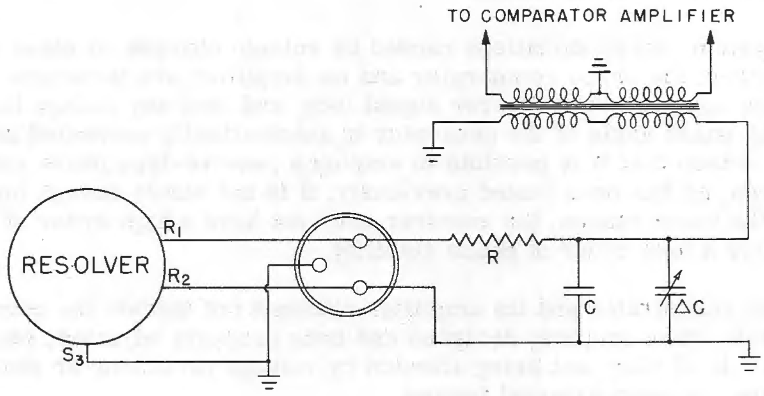


Fig. 9 - Schematic diagram showing phase shifter connections

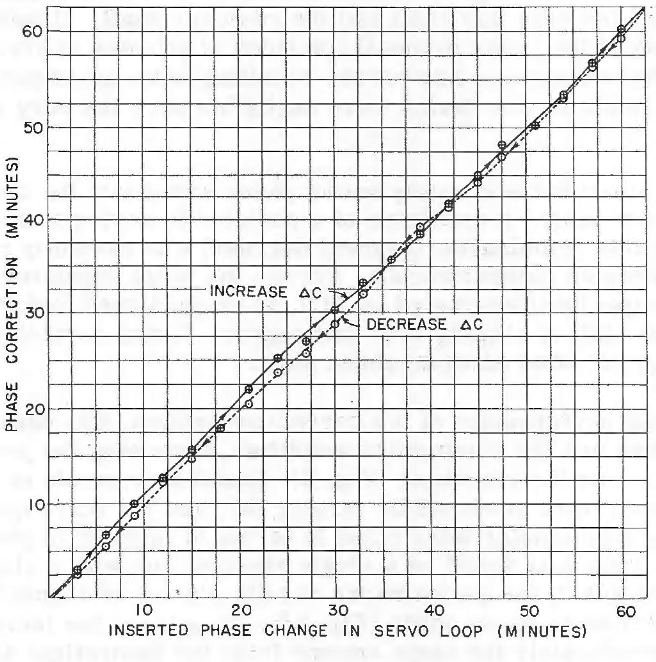


Fig. 10 - System sensitivity characteristic

## CAUSES OF SERVO SYSTEM INACCURACIES

The ultimate attainable accuracy depends primarily upon the quality of the servo system. Therefore, it is necessary to discuss the several causes of servo system inaccuracies which are listed below:

(a) Insufficient dc voltage from the comparator.

(b) Insufficient attenuation in the low-pass filter.

(c) Extraneous output from the chopper (hum, hash, etc.).

(d) Extraneous 60-cycle pickup in the system.

(e) Play or lash in the gear train.

(f) Tightness in the gear train.

(g) Play in the resolver and servomotor shafts.

(h) Instability of the phase comparator.

(i) Phase flutters in the system.

Each of these factors is worthy of individual consideration and will be so treated.

### Insufficient DC Voltage from the Comparator

The voltage required to initiate servomotor rotation is five volts. For a given error signal, this voltage may be obtained by either low comparator output and high amplifier gain or high comparator output and low amplifier gain. Since the signal-to-noise ratio is essentially the same for either comparator output, it is advantageous to use low amplifier gain to prevent spurious operation due to amplifier noise and hum. Therefore, the comparator dc voltage should be limited to the power-handling capabilities of the comparator and low-pass filter.

### Insufficient Attenuation in Low-Pass Filter

As explained previously, the output of the phase comparator, in addition to dc, has ac components consisting primarily of even harmonics of the frequencies under comparison. Any voltages at these frequencies remaining after filtering will be fed into the servoamplifier, together with the 60-cycle frequency obtained from the chopped dc. If all these frequencies are well removed from 60 cycles, or harmonics thereof, they will go through the amplifier as "hash" and will do little harm unless excessive, in which case they will completely saturate the amplifier, rendering the whole system inoperative. However, if some of these frequencies are sufficiently close to the 60-cycle frequency, beats or chattering in the servomotor will result when operating at high gain, i.e., with a sensitive system. This will necessitate a reduction in the servoamplifier gain with a subsequent reduction in the overall operating accuracy. Therefore, it is evident that both the relationship of the frequencies under comparison to the power line frequency and the attenuation characteristic of the low-pass filter are factors in predicting the overall accuracy of the system.

## Extraneous Output from the Chopper

Many choppers, through imperfect design, particularly with respect to internal and external shielding, are likely to have a spurious 60-cycle output that, combined with the desired 60-cycle output, will produce an error in the correcting system. However, since a fixed error in the correcting system can be compensated, this condition is not too serious unless the spurious 60-cycle output varies in magnitude.

## Extraneous 60-Cycle Pickup in the System

Systems of this type usually employ a relatively high-gain 60-cycle amplifier operating with a high impedance input circuit. Such a combination is extremely susceptible to pickup due to any stray 60-cycle electrostatic or magnetic fields present in the vicinity of or within the amplifier. This is particularly serious, since a relatively low voltage will operate the servomotor. Such stray pickup will affect the accuracy of the system by introducing a fixed error if they should remain constant, or a variable error should they change in magnitude, and the latter is almost invariably the case.

## Play or Lash in the Gear Train

Mechanical instrumentation will have one of the greatest effects on the accuracy with which the system will function. If there is the slightest perceptible play or lash in the entire gear train between the servomotor and resolver shafts, the accuracy of the system will suffer. Under these conditions the servomotor will chatter or oscillate, and this can be corrected only by reducing the gain. This results in a broad null which is manifested as a phase error.

## Tightness in the Gear Train

This results in a "rubber-band" action of the corrector with an accompanying variable error in the operation of the system. Under these conditions, an excessive error signal from the comparator is required to start the correcting action, which is tantamount to having an insensitive system. Although this in itself is sufficiently undesirable in its affect on the action of the system, the usual condition in any multiple gear train is, unfortunately, one in which high spots or eccentricities exist in the various gears so that the train will have lash in one position and binding in another. Such a gear train not only produces erratic action with regard to accuracy of the system, but also makes the acquisition of meaningful quantitative performance data almost impossible.

An example of this type of operation was encountered while taking data for Fig. 10. For each value of $\Delta C$, as much as fifteen seconds were required for the servomotor to come to rest at the zero signal position. This slow response was due to tight spots between the servomotor worm gear and the gear with which it meshes. The rise and fall of the hash voltage mixed with the signal gradually enabled the servomotor to move the gears from the tight spots and to move the resolver to the position of zero signal. No corrective measures were taken to prevent this type of operation because in actual operation the hash level was of such a magnitude as to cause minute but strong vibrations of the servomotor shaft, and these were sufficiently large to prevent the binding forces from becoming as large as they are when the servomotor rotor is quiescent. However, this type of operation cannot be tolerated in every case; therefore, too much care cannot be exercised in the design and construction of the gear train for an accurate and well-functioning system.

### Play in the Resolver and Servomotor Shafts

Since both devices carry gears on their shafts which mesh with the gear train proper, any play in their shafts would have the same effect as play or lash in the gear train, and the same comments apply. These shafts have been listed separately because, in general, they fit on to the train and are not built into it as are the other gears.

### Instability of the Phase Comparator

The stability of the phase comparator is equally as important as the mechanical instrumentation in the success and ultimate accuracy of the system. Although no long-time stability tests have been made on the experimental model, the probability of obtaining this type of stability is enhanced by the following design considerations:

1. The pair of comparator transformers should have a high order of similarity. This is necessary because only then will equal phase shifts result when equal temperature changes occur, thus cancelling their effects. This permits the problem of phase drifts due to temperature changes to be solved simply by locating the transformers so that their temperatures remain equal.

2. Another factor of concern is the change in transformer characteristics with change in input level. This sould not be serious if it is reasonable to assume that once the input levels are established they will not be subject to appreciable changes. However, in the design of these transformers, it might be desirable to employ either dust cores or an air gap so that any changes in inductance with changes in level will be insignificant.

3. The bridge resistors can be of the precision wire-wound type with a low temperature coefficient, although this is not necessary if they are properly positioned in the chassis to assure equal temperature in each resistor.

4. This leaves the diode rectifiers as the remaining source of concern. The important factor is the variation in the characteristics of any one or opposite pairs of crystals with temperature and time, causing an unbalance in the bridge. However, with proper design, the impedances of the four legs of the bridge can be determined almost completely by the value of the bridge resistors; therefore considerable variation in the crystal impedances can be tolerated with negligible effect on the accuracy of the bridge.

By applying the design considerations given above, it is believed that a high order of stability over long periods of time can be expected.

### Phase Flutters in the System

In order to minimize phase flutters, the system should be capable of responding to relatively high rates of change of phase. However, to attain a high degree of accuracy, there must be a sacrifice in this type of response. This means that the accuracy of the system under operating conditions will be effected, for example, by those phase flutters of the phase-controlled synchronous motor which occur at a rate greater than the maximum correcting rate of the servo-driven resolver.

For example, consider the control system described herein. Assume that the maximum allowable error is plus or minus 2.5 minutes of phase. If the maximum dc output from the phase comparator is 15 volts, the maximum error will produce 15 sin 2.5′, or about 0.01 volts dc, at the output of the phase comparator. According to tests, this voltage will cause the servomotor to rotate at about 700 rpm or 11.7 rps, which is equivalent to about 4200 degrees per second. Reducing this by the gear ratio between the servomotor and the resolver, the maximum allowable phase velocity will be slightly under 0.7 degrees per second. Therefore, combinations of the frequency and magnitude of a phase change resulting in a rate of change of phase greater than 0.7 degrees per second will not be followed by the controller.

Evidently, in designing a system of this type, care must be taken to choose components and voltage sources that do not cause phase flutters, since it is difficult to obtain good response to high velocity phase changes with good sensitivity.

## ADAPTING THE SYSTEM TO MECHANICAL PHASE SYNCHRONIZATION

The main sections of this report have described in some detail the application of the system to the establishment and maintenance of an accurate phase relationship between two alternating electrical potentials. A similar system can be applied to the establishment and maintenance of accurate mechanical phase relationship between two remotely located rotating devices.

In certain types of radio direction-finding equipment, notably those employing fixed antennas and spinning goniometers, the bearing pattern is presented on a cathode-ray tube (generally designated as an Automatic Bearing Indicator or ABI) as a propeller-shaped image. This pattern is obtained by a motor-driven magnetic sweep circuit around the throat of the cathode-ray tube, producing a circular scan that is modulated by the amplified voltage received from the goniometer. The angular position of the goniometer, at which this voltage is zero, is the bearing and appears on the ABI as the ends of the propeller. Accordingly, the goniometer and the ABI scanning coils must be driven in phase synchronism in order to maintain the accuracy of the indicated bearing. In most DF equipments this is accomplished simply by connecting them mechanically to a common driving motor.

It is often desirable, however, to separate the goniometer from the ABI in order to keep the former at the antenna array and the latter in the operating building. This necessitates the provision of some means of rotating these two devices (usually at 1200 rpm) in exact synchronism.

Figure 11 shows a method in which the system previously described may be employed to accomplish this purpose. Here, the ABI scanning coils are driven by an ordinary single-phase induction motor rated at 1175 rpm but likely to vary as much as plus or minus 10 percent around this value with variations in line voltage, temperature, etc. To this motor is also coupled a small two-pole alternator of the permanent-magnet type, having an output of about 30 volts at slightly under 40 cycles. With this arrangement, the phase of the ABI scanning coils is reflected in the phase of the 40-cycle output of the alternator.

Its output is fed to a phase splitter at the antenna location and the result is applied to a resolver. The resolver feeds a power amplifier which in turn drives a synchronous motor rated at 1200 rpm. Coupled to this motor is the goniometer and a second alternator rated at 40 cycles, so that the phase of its output reflects the phase of the goniometer rotor.

The voltages from the two alternators (possessing the phase intelligence from the goniometer and the ABI respectively) connect to the phase comparator, which is part of the control system previously described.

When the system is placed in operation, variations in the mechanical phase between the goniometer rotor and ABI scanning coils appear as changes in phase between the two alternator voltages, and are corrected by a suitable rotation of the resolver rotor. Should the synchronous motor rotor lock-in at an incorrect phase position, the correcting system

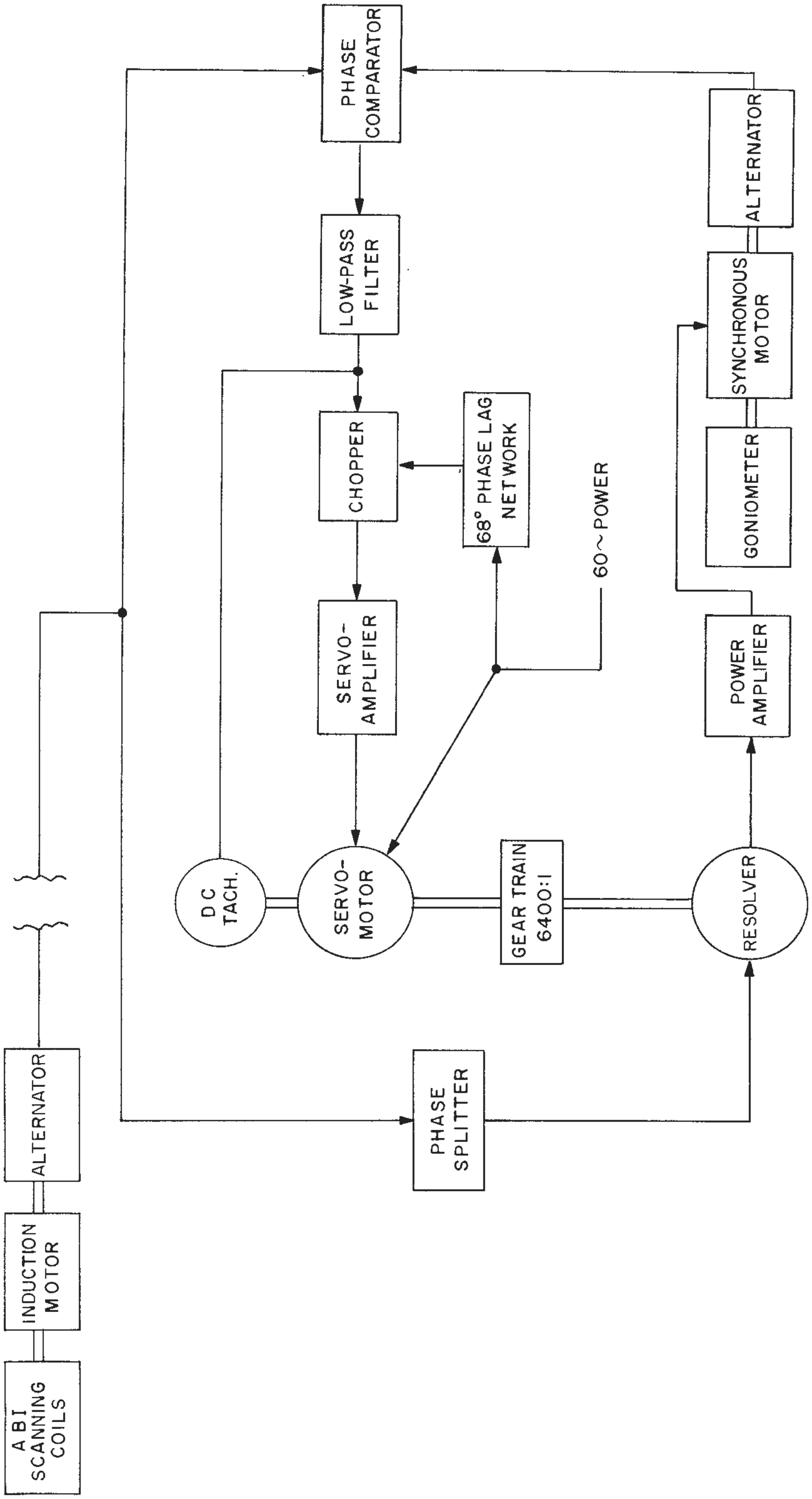


Fig. 11 - Block diagram of the system adapted to the maintenance of mechanical phase synchronism

will bring it to the proper phase, so that the system is entirely automatic for both starting and running. Thus, the goniometer and ABI are kept in phase synchronism to an extremely small fraction of a degree.

The alternators are attached by means of locking-type mountings which allow the alternator frames to be rotated to any angular position so that an initial alignment of the zero settings of goniometer and ABI may be made.

It should be noted that with a system of this type, one of the rotated devices may be of any size, since it may be driven by any size motor which need not be synchronous. Even a dc motor could be used, as long as the limitation on the rate of change of phase between the two rotated devices is not exceeded. A further advantage of this is that the basic system does not and need not operate at any speed fundamentally or harmonically related to the power line frequency. In this application, lack of harmonic relationship with the power line frequency is desirable to avoid stroboscopic modulations of the cathode-ray-tube image.

Figure 12 shows a close-up of the small alternator mounted on the back of the ABI casting of a typical DF equipment, while Fig. 13 shows the goniometer and its alternator connected to its synchronous driving motor. The remainder of the required equipment is the same as shown in Figs. 5 through 8.

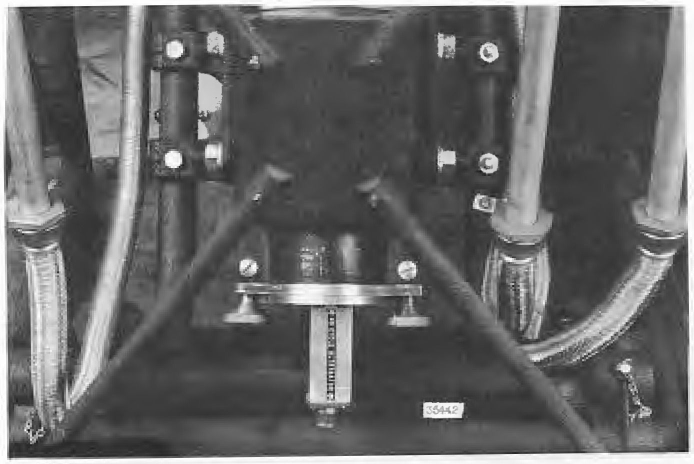


Fig. 12 - Close-up of the small alternator mounted on the back of the ABI casting of a typical direction-finding equipment

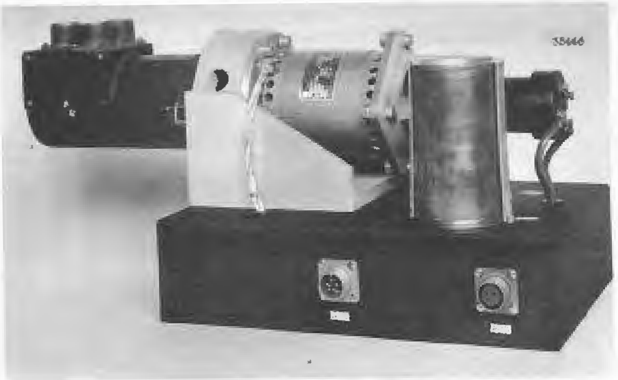


Fig. 13 - Goniometer and alternator connected to the synchronous drive motor

## CONCLUSIONS

It is concluded that phase synchronism of two separate alternating electrical potentials or two remotely located rotating shafts can be maintained to within plus or minus one minute of phase over long periods of time, using the principles and techniques outlined in this report.

## ACKNOWLEDGMENT

The author wishes to express his appreciation to Mr. George W. Kelley, Jr., for his helpful suggestions in the preparation of this report.

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