Sept. 12, 1933.

H. NYQUIST

1,926,169

PHASE AND FREQUENCY CONTROL

Filed March 11, 1931

3 Sheets-Sheet 1

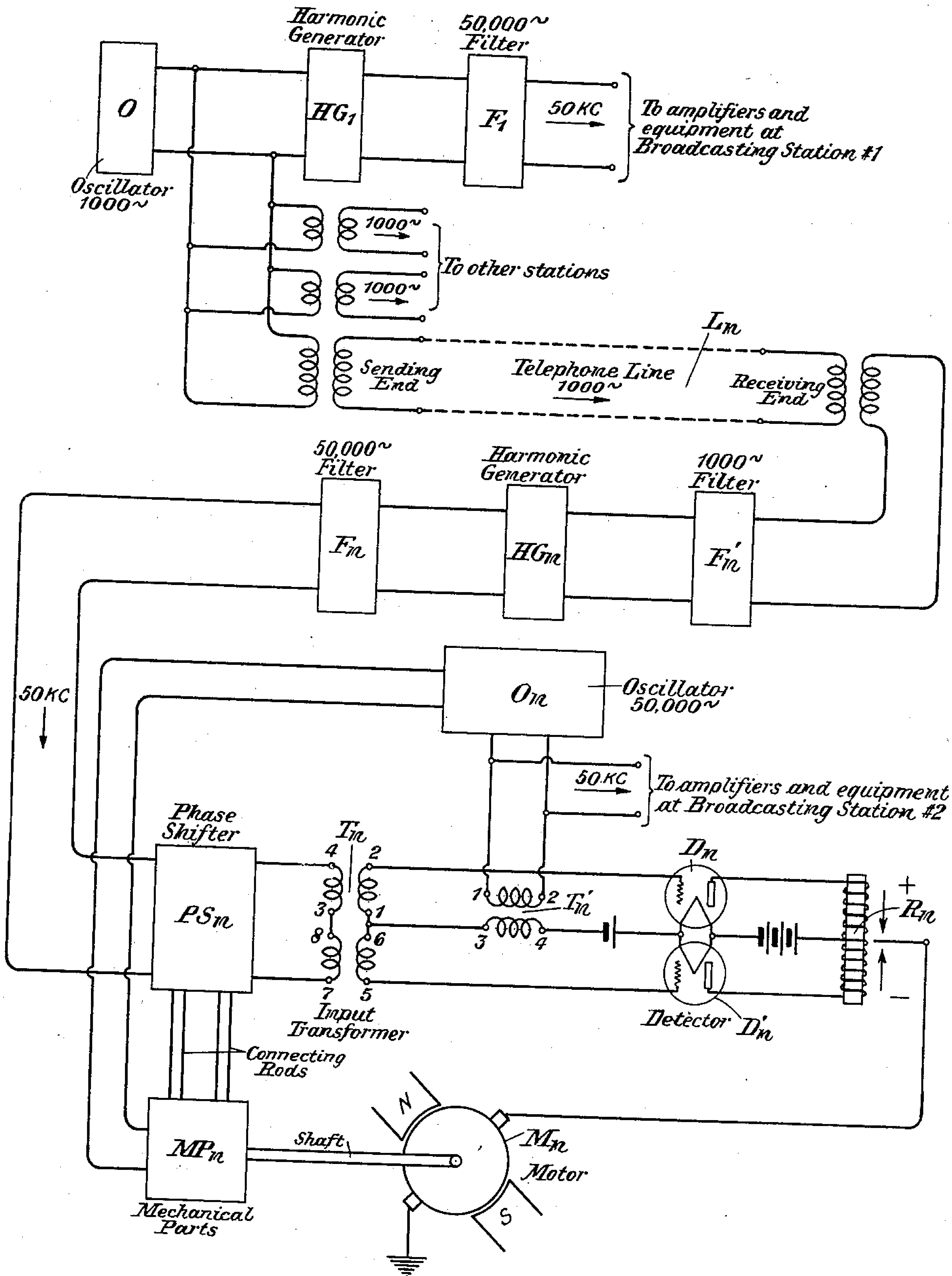


Fig. 1

INVENTOR
H. Nyquist

BY G. E. Folk

ATTORNEY

Sept. 12, 1933.

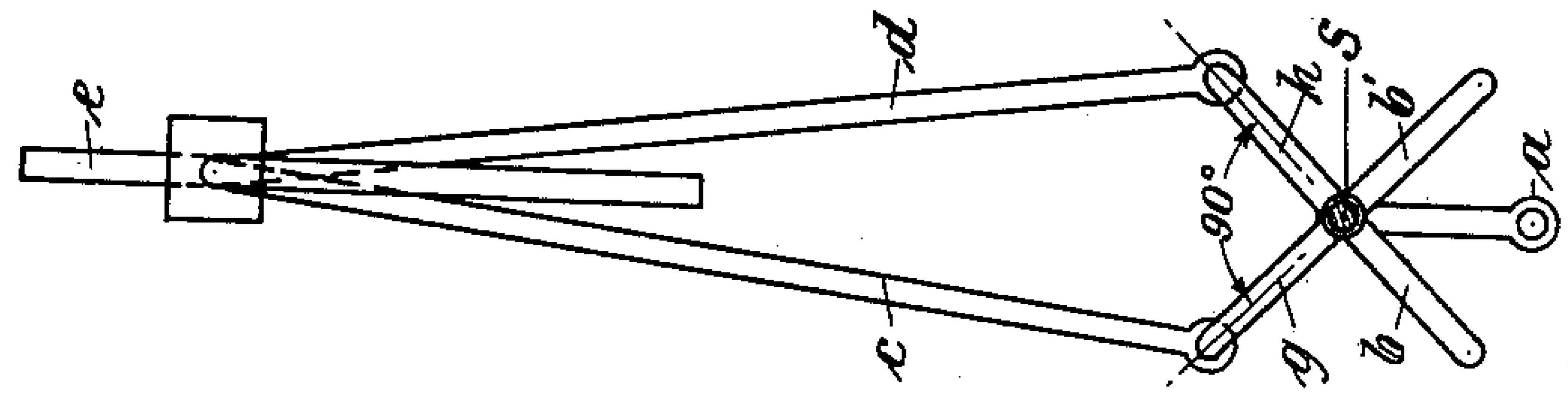
H. NYQUIST

1,926,169

PHASE AND FREQUENCY CONTROL

Filed March 11, 1931

3 Sheets-Sheet 2



Section A-A
Fig. 2a

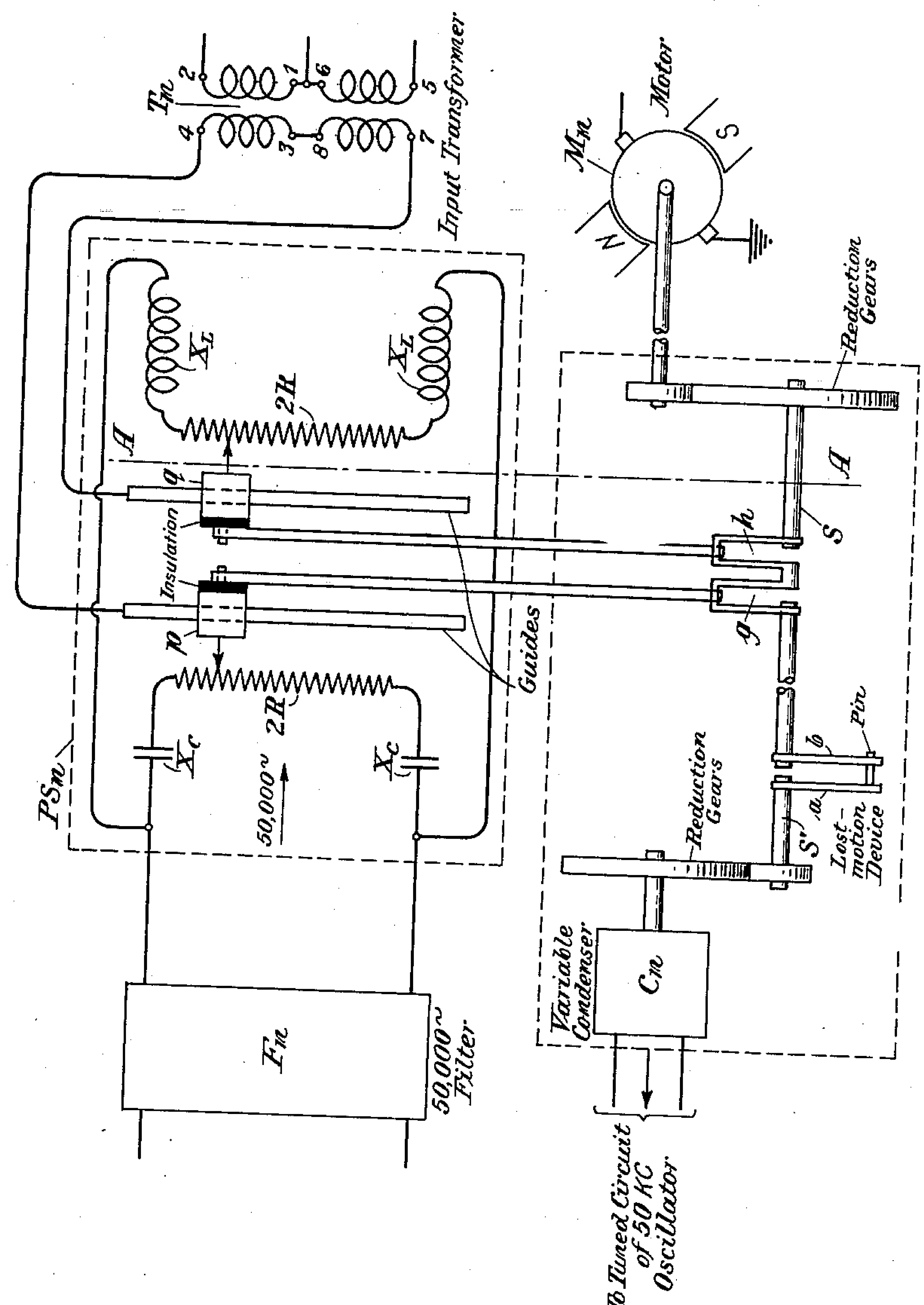


Fig. 2

INVENTOR
H. Nyquist
BY
G. E. Folk
ATTORNEY

Sept. 12, 1933. H. NYQUIST 1,926,169

PHASE AND FREQUENCY CONTROL

Filed March 11, 1931 3 Sheets-Sheet 3

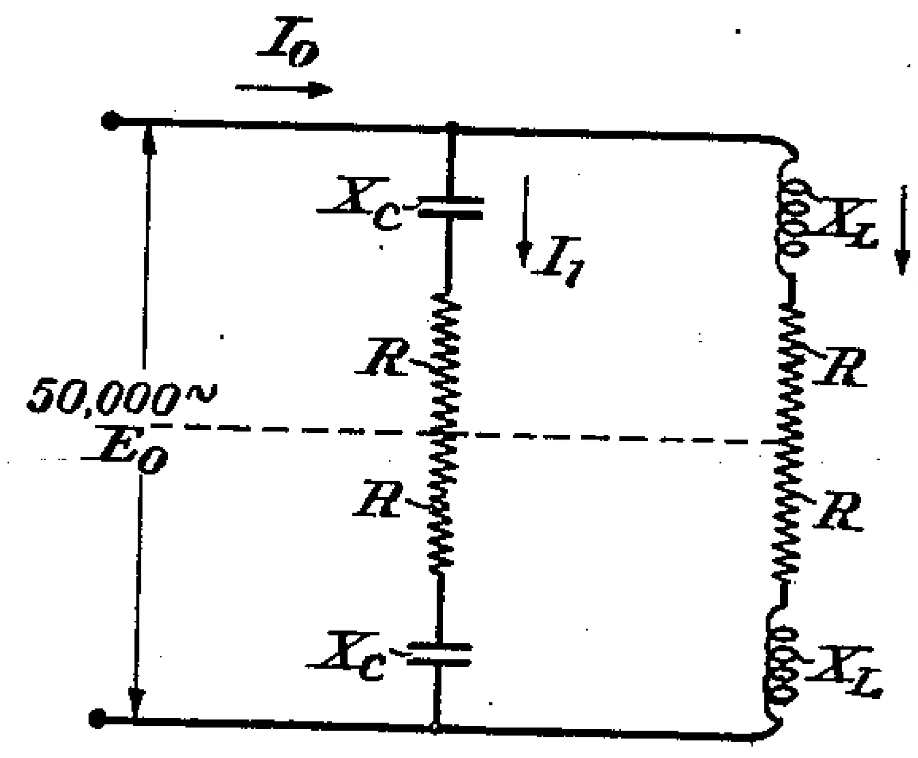


Fig. 3

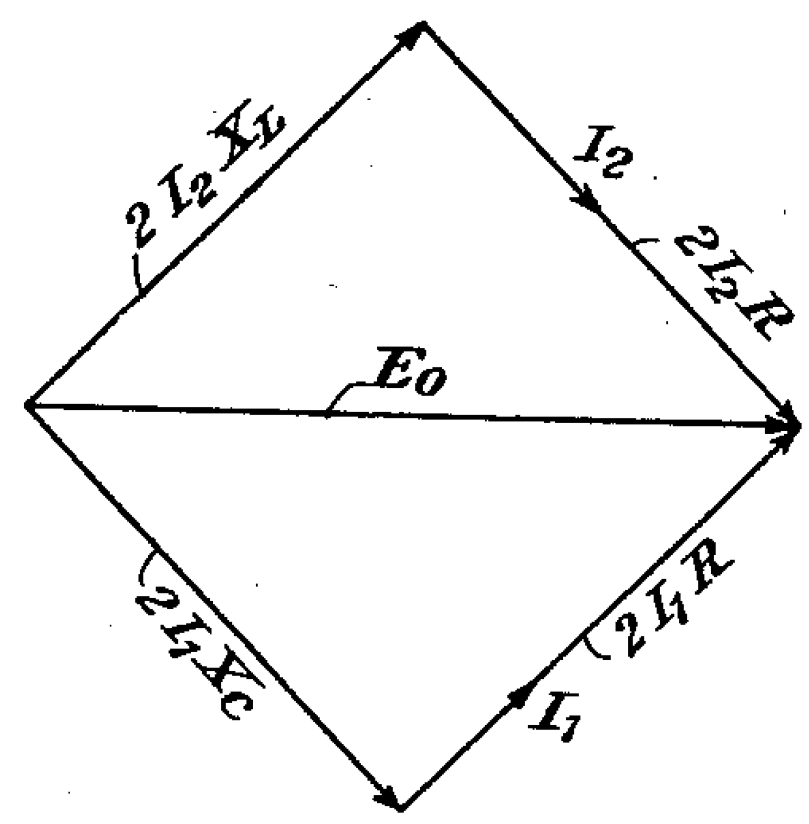


Fig. 4

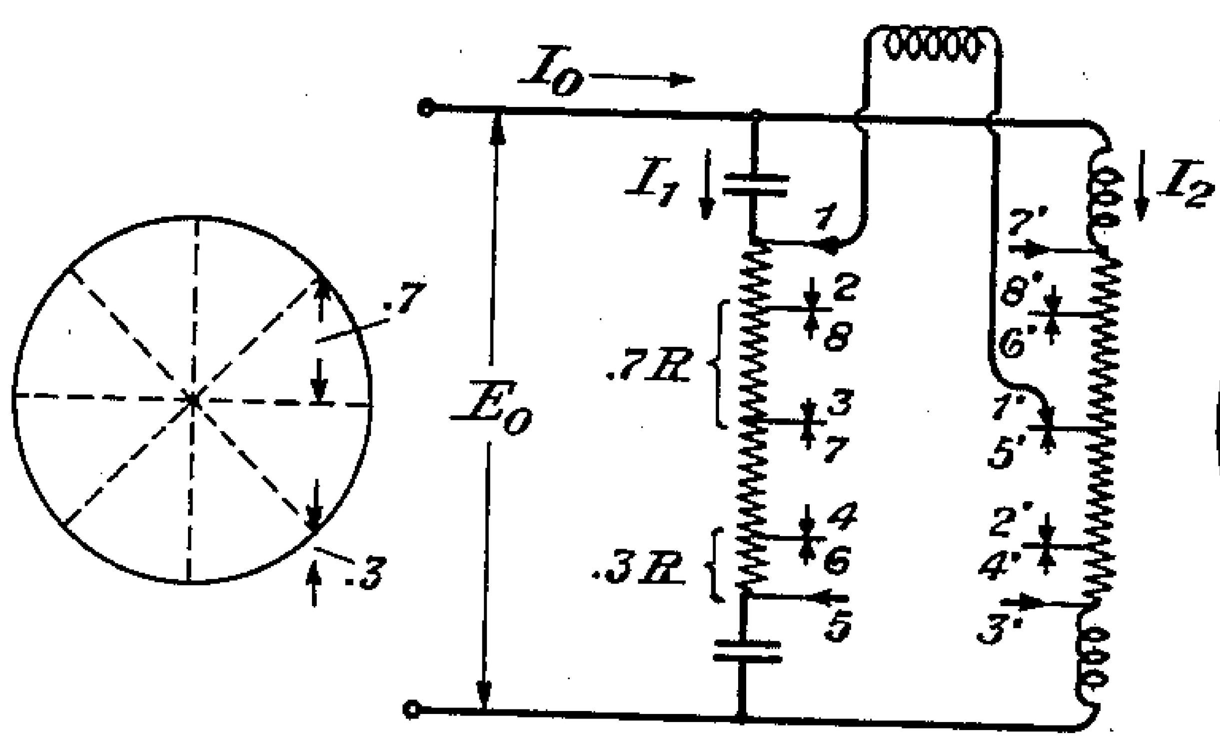


Fig. 5

Position 1-1'

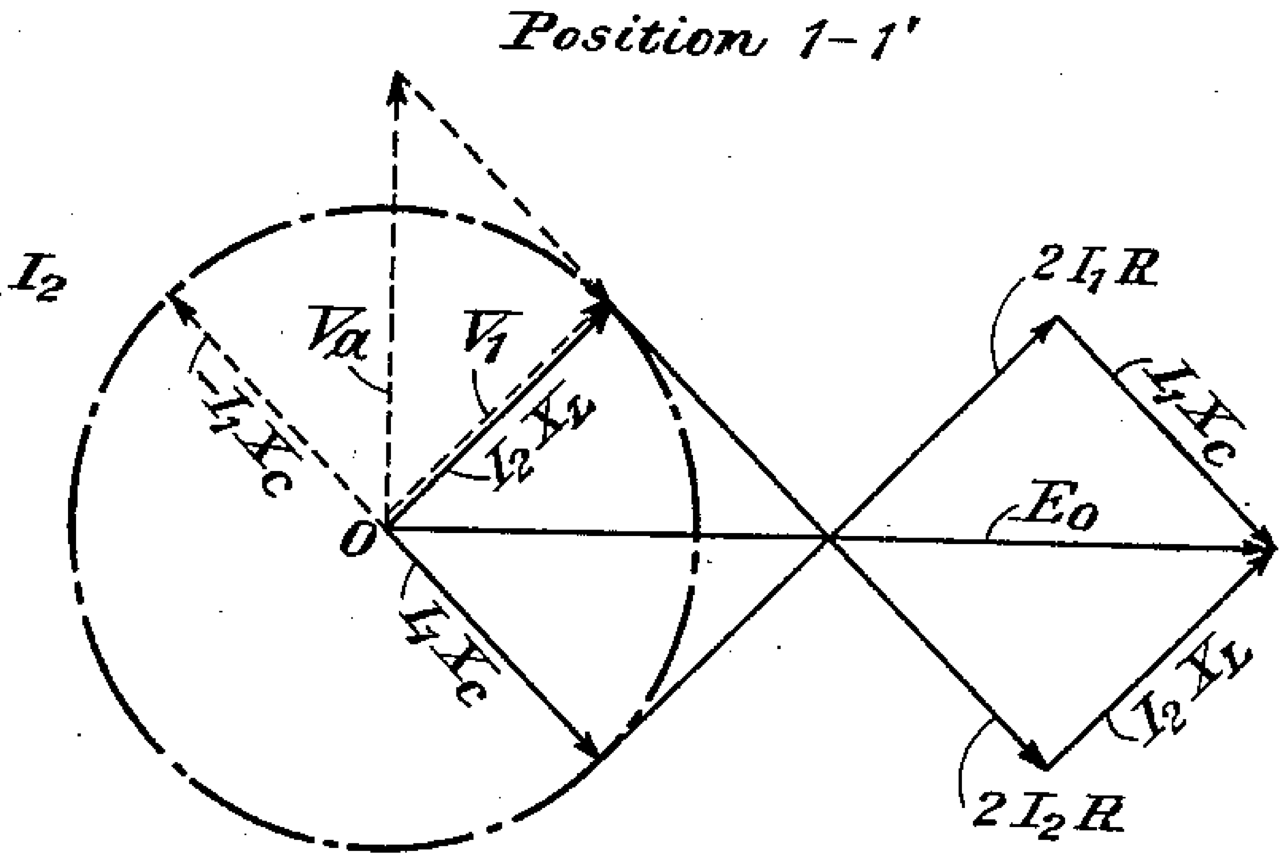


Fig. 6

Position 2-2'

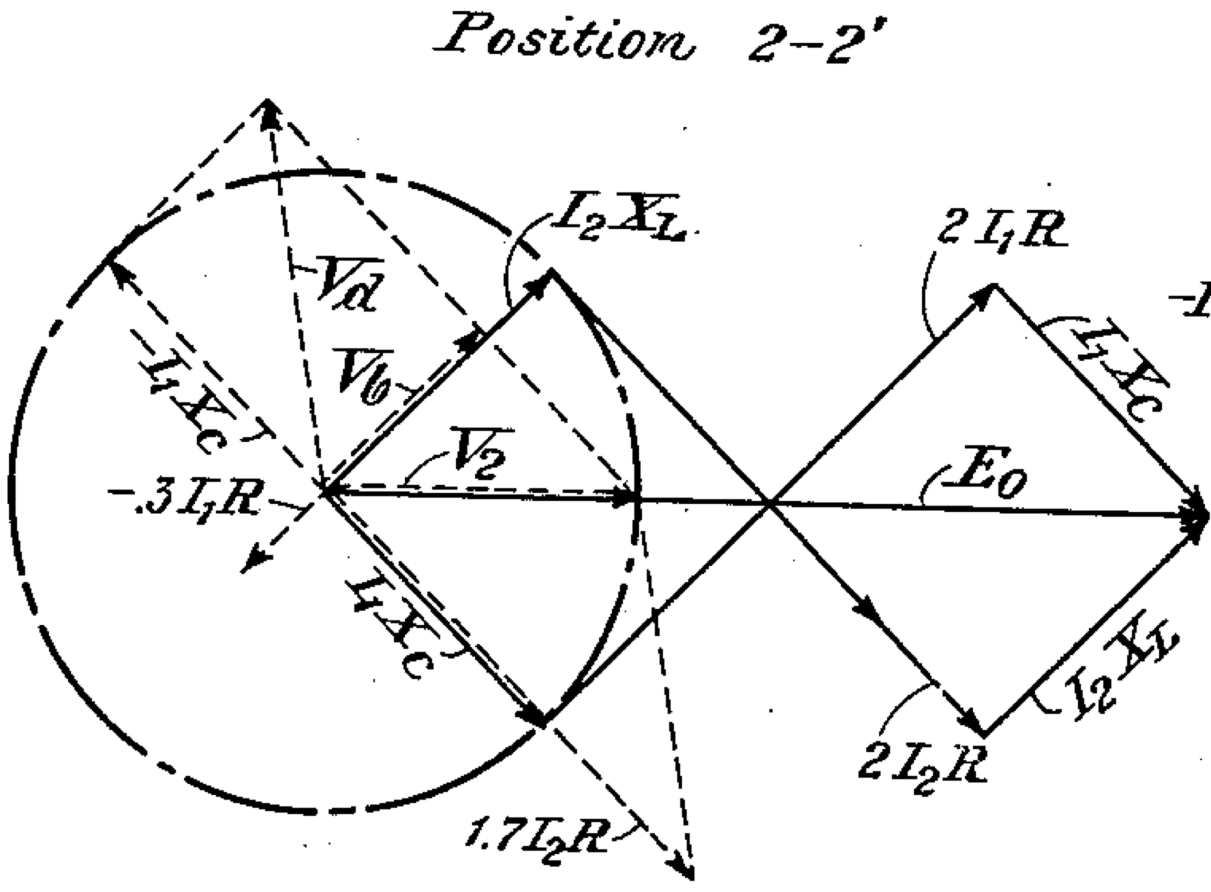


Fig. 7

Position 8-8'

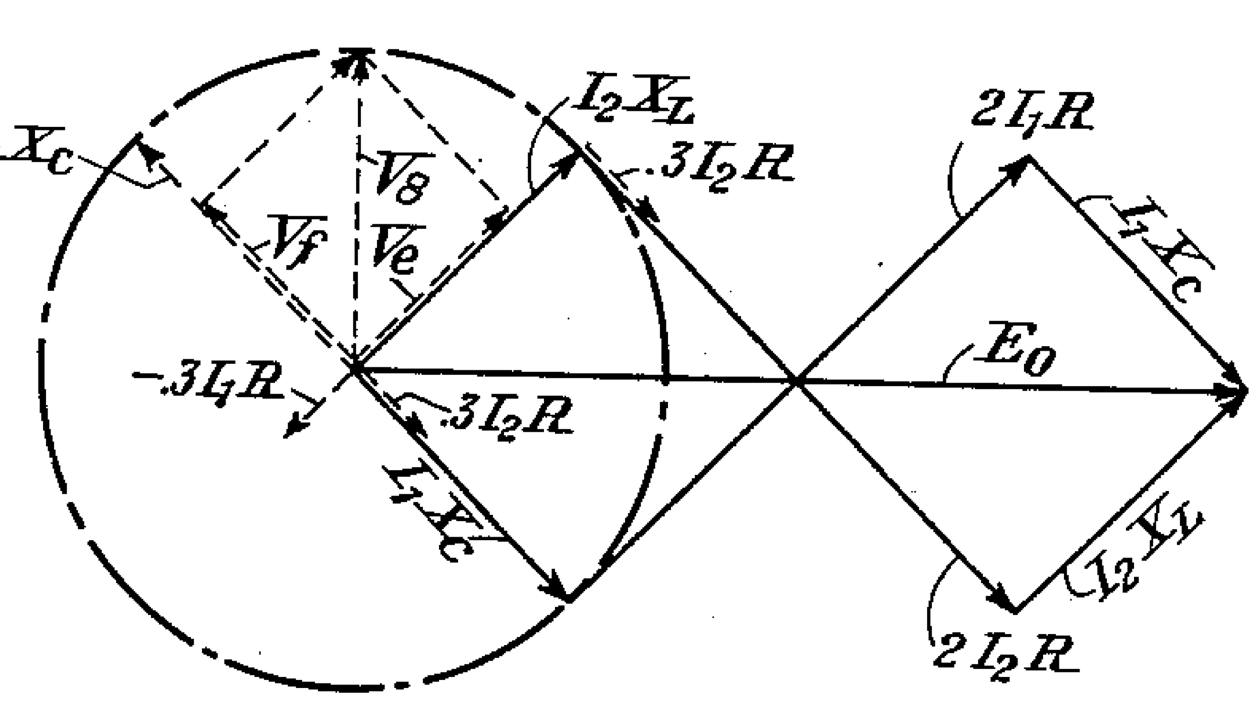


Fig. 8

INVENTOR
H. Nyquist
BY [signature]
ATTORNEY

Patented Sept. 12, 1933

1,926,169

UNITED STATES PATENT OFFICE

1,926,169

PHASE AND FREQUENCY CONTROL

Harry Nyquist, Millburn, N. J., assignor to American Telephone and Telegraph Company, a corporation of New York

Application March 11, 1931. Serial No. 521,851

21 Claims. (Cl. 250—2)

This invention relates to an arrangement for maintaining distant sources of current substantially in phase and at approximately the same frequency. One embodiment of the invention is described herein in connection with an arrangement for controlling the phase and frequency of the carrier waves of a chain of broadcasting stations.

When two or more distant radio stations are connected by telephone lines in order to broadcast the same program, it is desirable that all broadcasting stations use the same carrier frequency so that the number of frequency channels required for one program may be a minimum. Unfortunately, slight changes in the relative phase of the radio frequency carrier currents from the various broadcasting stations affect the field strength in certain intermediate localities, thus causing received signals to vary in amplitude and in some cases to vanish completely.

If two radio broadcasting stations are to operate on the same nominal carrier frequency, it is necessary, if the service furnished is to be satisfactory and at the same time reasonably economical, that the nearness the actual frequencies come to being the same be considered with some care. It would obviously be ideal, from the point of view of the service rendered, to require the actual frequencies to be identical. If this were the case the phase relation would be invariable and at any given receiving point there would be a fixed phase relation between the fields received from the two broadcasting stations.

In practice, however, it would be sufficient to merely specify that the phase angle between the carrier waves of the two stations should not change by more than a certain number of degrees, and to specify in addition that the rate of phase drift should not exceed a given value. A slow phase drift merely causes gradual fading at the receiver, which may be taken care of by a gain adjustment in the receiving set itself. Rapid phase drift, however, would obviously ruin the reception, either by causing fading which is too rapid to be compensated for at the receiver or by causing such a rapid fluctation of the signal strength that the signal would be distorted. It is absolutely essential, therefore, that the rate of phase drift be limited. If, however, the rate of phase drift be held within sufficiently small limits, it is not so important to limit the maximum phase angle which may be permitted between the stations.

It has heretofore been proposed to maintain the desired constancy of frequency and phase relation by transmitting a control current from a master station over wire lines to the various radio stations. At each radio station the carrier wave from the station is generated by means of a local generator, such as a high frequency oscillator. The frequency of this oscillator is automatically adjusted whenever the normal relation between the generated carrier wave and the received control wave is changed more than a given amount, and this adjustment is automatically made regardless of the cause of the variation.

In such a system differences in the phase and frequency of the carrier waves of different radio stations will depend upon two general sources of error: (1) errors due to the oscillators used for generating the carrier waves at the radio stations or errors due to the oscillator used for generating the control wave at the master station, and (2) errors due to variations in the transmission line used for transmitting the master control wave.

The errors of oscillators are usually classified for convenience into (*a*) the long time error in the rate or frequency of the oscillator and (*b*) the short period errors or differences in period of successive cycles. The characteristics of oscillators of course vary, but in most cases particular attention is paid to reduce the long time error because it is cumulative, and it is assumed that the short period errors are less important because in general they are not cumulative. However, the short time errors in some instances may be so relatively large as to become important. Where such is the case, it is now possible, by the use of modern methods, to so design crystal-controlled oscillators that both the long time error and the short time error may be kept very small.

As to the errors due to the line itself, it should be noted that if a current of given frequency is transmitted over a line, the impulses at the receiving end as compared with those at the sending end will, of course, show no long time error. Short time errors may occur, however, and will be manifested as changed in phase. These are due to variations in the elements going to make up the line caused by such things as temperature changes, repeater steppings and (if this particular channel is amplified in repeaters common to other channels) overloading of repeaters by signals on other channels.

It should also be noted that the phase shift between two oscillators which is caused by difference between their long time frequencies, is cumulative with the first power of the time. The phase shift caused by short period errors, if these are random, is cumulative with the square root of the time. The short period errors causing phase shifts between the two ends of a line are not entirely random, however, so that although for a short time the phase shift may accumulate as the square root of the time, over a long period it will practically accumulate to zero. In other words, the phase shift due to changes in the line will not accumulate over a long period but in general the phase will be advanced or retarded with respect to an average phase relation, and the amount of this phase advance or phase retardation with respect to this average will not exceed a given maximum for a given line.

With these conditions in mind, it becomes evident that a master control system such as above outlined will suppress long period differences in frequency by not allowing the phase shift to accumulate. Also, the short period difference between the resultant of the short period errors in the master oscillator and the controlled oscillator, and the error in the line, is taken up by varying the controlled oscillator. Such a method of control will be satisfactory where the resultant of the short period errors in the two oscillators is of the same order of magnitude or greater than the short period errors in the line. However, if oscillators are available which are constructed to be so steady in their operation that their short period fluctuations are substantially negligible when compared with the corresponding fluctuations in the line, this method forces the controlled oscillator to conform to the vagaries of the line and wastes the valuable property of the steadiness in the oscillators.

In accordance with the present invention it is proposed to take advantage of the fact that the frequency of the oscillators may be held within narrow limits so that the cumulative long period error may be relatively small as compared with the error due to fluctuations in the line. To this end it is proposed, in effect, to loosen the coupling between the receiving end of the line and the controlled oscillator at the radio station so that the oscillator will not be adjusted in response to the short period variations of the line but will be adjusted when long time variations occur. This is accomplished by introducing between the line and the control element a phase compensating device by which changes in phase within limits corresponding to the phase changes introduced by the line itself will be compensated for without causing any adjustment of the controlled oscillator. When the phase change exceeds this limit, however, as will be the case when cumulative long time error is introduced by any difference of the frequencies of the two oscillators, the mechanism for adjusting the oscillator will be brought into play to bring the frequency of the oscillator back to its normal relation to the control wave.

More specifically, the invention involves transmitting a control frequency (preferably a voice frequency) from a master station over a line to the radio station and at the radio station stepping up the control frequency to a frequency equal to that of the local oscillator for generating the carrier wave of the radio station. Some of the energy from the local generator or oscillator at the radio station is applied to a push-pull detector circuit, together with energy from the telephone line. The currents in the two output branches of the push-pull detector will be balanced at a certain optimum phase relation of the two input waves. Any departure from this phase relation produces an unbalance in one of two senses, depending upon the direction of the phase shift. This principle is utilized to control two separate mechanisms one of which is a phase changer which may be connected in the telephone line and the other of which is a variable condenser or other device for changing the frequency of the controlled oscillator. The control exercised over these two devices is such that for small changes of phase of the order of those produced by variations in the telephone line itself, the phase changer may be operated to compensate therefor without causing any change in the frequency of the oscillator. The variable condenser of the oscillator is connected to the control mechanism by a lost motion device to permit of this operation of the phase changer without adjusting the frequency of the controlled oscillator. If the frequency of the controlled oscillator changes, it results in a continuous or cumulative shifting of the phase of the carrier wave with respect to the control wave so that the push-pull arrangement causes an adjustment of the phase shifter and (after the lost motion is taken up) of the variable condenser. The adjustment of the condenser results in bringing the frequency of the oscillator back to normal.

With this arrangement the phase shifter takes up the short shifts (except those so short as not to be able to effect a change in the setting of the device) between the receiving end of the line and the controlled oscillator on the assumption that the latter is more steady. If these phase shifts start accumulating to an appreciable amount, however, an adjustment is made on the frequency of the controlled oscillator on the assumption that it is the latter which is beginning to drift. This is accomplished by means of the lost motion device. The optimum adjustment of the lost motion device depends upon the relative errors to be expected from the line and the oscillators. If the line is bad the lost motion should be large; if it is good the lost motion should be small.

If the adjustment of the lost motion device is such as to take care of the maximum phase shift due to the line, it is evident that an adjustment of the controlled oscillator will never occur unless cumulative drift due to change in frequency of the oscillator, occurs. If, however, the adjustment of the lost motion device is not sufficient to take care of the maximum phase changes which may occur in the line, occasionally the oscillator will be adjusted due to a large phase change in the line. This, however, will soon be corrected, as the resultant cumulative drift in phase between the oscillator and the control frequency will cause re-setting of the oscillator.

One more point should be noted. With this arrangement the maximum phase change between any two radio stations may exceed the maximum phase shift introduced by the line (which is cared for by the lost motion device). This is due to the fact that the phase compensator is adjusted simultaneously with the adjustment of the oscillator in addition to the adjustment introduced to take care of the line shift. The amount of this additional adjustment of the phase compensator may be kept small, however, by introducing suitable gearing or other means so arranged that a very slight change in the control mechanism over and above that necessary to take up the lost motion will bring the adjustment of the oscillator back to normal.

The invention may now be more fully understood from the following description, when read in connection with the accompanying drawings, in which Figure 1 shows schematically a circuit arrangement embodying the invention; Fig. 2 shows in somewhat more detail the arrangement of the phase changer and the mechanism for adjusting the phase changer and the variable condenser for frequency control; Fig. 2 (*a*) is a sectional view of part of the apparatus of Fig. 2; Fig. 3 illustrates the electrical elements of the frequency changer; Fig. 4 is a vector diagram corresponding to the arrangement of Fig. 3; Fig. 5 is a diagram similar to Fig. 3 but showing various positions of adjustment of the phase controller; while Figs. 6, 7 and 8 are vector diagrams corresponding to definite positions of the phase controller of Fig. 5.

Figure 1 shows the essential features necessary for maintaining distance sources of current in phase and at the same frequency. In these drawings an oscillator O, which may generate a voice frequency of, say, 1,000 cycles per second, is connected to an harmonic generator HG_1 to step up the frequency to correspond with the wave length of a local broadcasting station. In the case assumed, the frequency is 50,000 cycles per second, and a filter F_1 is provided to select the desired harmonic from the other harmonics in the output of the harmonic generator HG_1. Some of the energy of the control wave from the oscillator O is also connected through parallel repeating coils to various telephone lines such as L_m leading to other broadcasting stations. The apparatus associated with the distant terminal of line L_n only is shown, it being understood that the apparatus associated with the other lines will be similar. In the case of the line L_m the 1,000 cycle control frequency passes through a transformer into a selecting filter F'_n and is impressed upon an harmonic generator HG_n to generate the carrier wave for the broadcasting station associated with the distant end of the line L_m.

The carrier wave in this instance also has a frequency of 50,000 cycles per second. Accordingly, the harmonic of this frequency is selected by means of the filter F_n and is passed through the phase shifter PS_n, symbolically indicated, and by means of a transformer T_n is applied to the grid circuits of a push-pull detector circuit comprising detectors D_n and D'_n whose output circuits are oppositely connected through opposing windings of a polar relay R_n. The carrier wave supplied to the broadcasting station is generated by means of a local oscillator O_n. In order that the phase and frequency of this oscillator may be controlled with respect to other similar oscillators at other broadcasting stations associated with the control station, some of the energy from the output of the oscillator O_n is connected to the common branch of the grid circuits of the push-pull detector arrangement through a transformer T'_n.

The relationship of the various elements of the push-pull circuit is such that when the waves transmitted through transformers T_n and T'_n are 90 degrees out of phase with respect to each other, equal opposing currents will flow through the two windings of the polar relay R_n and its armature is held in neutral posiiton. A phase shift of the two waves in one direction results in an increase in the direct current flowing in the output of the one detector and a decrease of the direct current flowing in the output of the other detector, thereby producing an unbalance which causes the polar relay to attract its armature toward one contact. If the shift in phase is in the opposite direction the two detectors will be unbalanced in the opposite sense so that the polar relay will attract its armature to its opposite contact.

When the armature of the polar relay rests upon one contact, the circuit of the control motor M_n is closed to cause the motor to rotate in one direction. When the armature of the polar relay is upon its opposite contact the motor rotates in the opposite direction. The shaft of the motor controls certain mechanical parts symbolically indicated at MP_n, whereby the phase shifter PS_n may be adjusted and a frequency control arrangement such as the variable condenser associated with the oscillator O_n may be adjustable.

The details of the mechanical parts MP_n and the phase shifter PS_n and their relationship are shown in Fig. 2. Before explaining these details, it is desirable, however, to have an understanding of what is required in order that the circuit shall function properly. Bearing in mind that the push-pull arrangement of Fig. 1 is so arranged that a very small departure from the proper phase relation of the two input waves results in an operation of the polar relay, and hence, of the control mechanism, it is desirable that some provision should be made whereby short time changes in phase, arising from abnormal conditions (such as temperature changes, repeater steppings, repeater overloading, etc.,) of the telephone line over which the control frequency is transmitted, should be compensated for without adjusting the frequency control arrangement for the oscillator O_n. Furthermore, since any change in the frequency of the oscillator results in a cumulative phase shift of the carrier wave with respect to the control wave it becomes desirable to have the control mechanism so arranged that in response to such a cumulative phase shift the oscillator O_n will be adjusted to bring its frequency to normal.

These requirements are met in the present instance by connecting the phase shifter PS_n so that it may be adjusted by the motor M_n whenever a shift in phase occurs between the control wave and the carrier wave regardless of the amount of said shift. The variable condenser C_n for controlling the frequency of the local oscillator O_n, however, is connected to the motor drive through a lost motion device. This permits the phase shifter PS_n to be adjusted over a small range to compensate for the small changes in phase which arise in the telephone line itself without disturbing the frequency of the oscillator. When the frequency of the oscillator does change with the consequent cumulative shifting in phase between the control wave and the carrier wave, the lost motion is taken up and the phase shifter PS_n and the variable condenser C_n are adjusted together until the normal phase difference between the control wave and the carrier wave is again established. When this occurs the frequency of the oscillator will be back to normal. As has been previously pointed out, the phase shift due to the line is advanced or retarded with respect to an average phase relation. The lost motion is as proportional with respect to the maximum change of phase due to the line as to cause no adjustment of the oscillator in response to ordinary line changes. A phase change greater than that for which the loss of motion is designed is assumed to be due to cumulative error in the oscillator and causes adjustment of the phase shifter PS_n until the loss of motion is taken up, and thereafter the phase changer PS_n and condenser C_n are adjusted together until the frequency of the oscillator is restored to normal. The mechanism is so geared that any adjustment of the condenser C_n necessary to take care of the largest expected cumulative phase shift, will produce a small adjustment of the phase changer PS_n in excess of that resulting from taking up the loss of motion.

These results are accomplished by connecting the shaft of the motor M_n (through reduction gears, if desired) to a shaft S having two cranks *g* and *h* which are normally 90 degrees apart, as shown in Fig. 2*a*. The shaft S is also provided with two arms *b* and *b'*. A corresponding arm *a* is carried by a shaft S' and a pin upon the arm *a* may be engaged by one or the other of the arms *b* and *b'* when the shaft S is rotated through a suitable arc. The shaft S' drives the variable condenser C_n (through a suitable reduction gear, if desired) and the arrangement of arms *a*—*b*—*b'* provides a lost motion arrangement so that the cranks *g* and *h* may be driven through a suitable range of adjustment without any change of the variable condenser C_n.

Two drive rods *c* and *d* are connected from the crank throws *g* and *h* to insulated portions of suitable sliders *p* and *q* which move over a pair of guides *e* with a travel approximately proportioned to the sine and cosine of the angular positions of their respective crank throws. These sliders make contact with the uniformly wound resistances 2R and also with the metallic guides which are connected to the terminals of the primary of the input transformer T_n. The resistances 2R are connected in two parallel circuits bridged across the terminals of the telephone line. In the series branch with the one resistance are two capacities X_C, one arranged on either side of the resistance. In series with the resistance in the other branch are two inductances X_L, the inductances being arranged on either side of the resistance. By making $X_L=X_C=R$ at the frequency of transmission, which in this case is 50,000 cycles, the resultant voltage across the primary on the input transformer can be shown to have a substantially constant amplitude, with phase shifted at either direction, depending upon the direction of rotation of the motor M_n. As shown on the drawings, the sliders will pass each other moving in opposite directions at approximately 0.707R from the middle of the resistance 2R when the connecting rods are long.

In order to understand the operation of the phase shifter PS_n, let us refer to Figs. 3 to 8, inclusive. Fig. 3 shows the circuit arrangement of the phase shifter in simple form. If we imagine a voltage E_O applied to the terminals of the network in Fig. 3, currents I_1 and I_2 will flow through the branches. Since the elements R, X_C and X_L have impedances whose numerical values are equal, the numerical values of the currents I_1 and I_2 will be equal. If we consider the impedances of the two capacities in the one branch as being combined in one, and the impedances of the two inductances in the other branch likewise combined, and represent the drops through the elements of each branch due to the currents I_1 and I_2 flowing therethrough, respectively, the resultant vector diagram will be as represented in Fig. 4. The vectorial drop through the capacities and resistance must be equal to the applied voltage E_O. The drop $2\,I_1\,R$ through the resistance 2R will be 90 degrees out of phase with the drop $2\,I_1\,X_C$ through the total capacity of the branch and the drop through the resistance will be numerically equal to that through the capacity of the branch since the impedances of the resistance and capacity are numerically equal and the same current flows through both. Applying the same principles to the drops through the resistance and inductance of the second branch, we get the two vectors $2\,I_2\,X_L$ and $2\,I_2\,R$.

With the mechanical arrangement previously described the two contacts will be simultaneously moved over the side wire resistances 90 degrees out of phase with each other. In order to show that the resultant drop between the contacts is always numerically of the same value but rotates in phase, let us consider eight contact positions on each resistance. These contact points are indicated in Fig. 5 in which the number opposite each arrow indicates the numerical order in which the contact point is reached in a cycle of movement of the contact and the direction of the arrow indicates the direction of movement of the contact as it approaches each contact point. Corresponding contact positions on the two resistances are indicated by the same numeral, primes being added in the case of the resistance in the right-hand branch.

First, let us suppose that the contacts are in positions 1 and 1'. Let us see what is the effective drop between these two points. Referring to the vectorial diagram of Fig. 6, the vectorial drops through two branches are as shown in full lines. Here the drops through each of the two condensers are shown as separate vectors, and likewise, the drops through each of the two inductances are shown by separate vectors. The result is that the applied voltage E_O instead of being subtended by two vectors for each branch so as to form two triangles as shown in Fig. 4, is subtended by three vectors in such manner that the resultant vector diagram forms two pairs of triangles.

Now, in order to obtain the drop between 1 and 1' in Fig. 5, let us determine the vectorial drop through the upper condenser of the first branch, through the upper inductance of the second branch, and through the resistance R between points 7' and 1' of the second branch. The drop between points 1 and 1' will be the vectorial resultant of these drops. It will be noted that the circuit traced from the point 1 to the point 1' passes through the upper condenser of the first branch in the direction opposite to the direction of current flow so that in taking the vectorial sum of the drops, the drop through the condenser must be reversed.

As shown in full line in Fig. 6, the vectorial drop through this condenser has the value $I_1\,X_C$. Let us draw the drop through this condenser in the opposite direction as shown by the dotted vector $-I_1\,X_C$. The drop through the upper inductance of the second branch will be $I_2\,X_L$ as shown in full line in Fig. 6. If we obtain the resultant of this drop with the drop $-I_1\,X_C$, we obtain the vector V_a. It remains to combine this vector with the vectorial drop through the resistance R between the points 7' and 1'. This drop through the resistance R will have a value of one-half of the vector $2\,I_2\,R$ of Fig. 6 and will be in the same direction. Drawing this vector in dotted lines at $I_2\,R$ and obtaining the resultant of the vector thus drawn and the vector V_a, we have as the vectorial drop from the point 1 to the point 1′ the dotted line vector V_1. This vector, it will be noted, is numerically equal and in phase with the drop $I_2 X_L$ through the upper inductance of the second branch.

If, now, similar diagrams are drawn for the various other positions which the two sliding contacts may assume in Fig. 5, it will be found that the resultant vector is always of the same numerical value (that is, has the same length) but rotates about the point O of Fig. 6. This will be clear by considering two other positions of the sliding contacts. Let us first consider the case where the sliding contacts are in positions 2 and 2′, respectively, which are the next positions in order of rotation of the crank shaft. Due to the sine relation that exists between the motion of the cranks and the motion of the sliding contacts, the left-hand sliding contact only passes over about .3 R in passing from position 1 to position 2. The right-hand sliding contact, on the other hand, passes over approximately .7 R in going from point 1′ to point 2′.

The method of obtaining the vectorial drop between points 2 and 2′ is shown in Fig. 7. Here we have reverse drops through .3 R between 2 and 1 and also through the upper condenser of the left-hand branch, these drops being in series with the normal drops through the upper inductance of the right-hand branch, through the resistance R and a resistance of approximately .7 R, the latter resistance being between points 5′ and 2′. First let us draw the vectorial drop through the resistance .3 R as shown in dotted line. This drop is opposite in direction to the drop 2 I_1 R in Fig. 7 and has the value —3 I_1 R as shown in dotted lines. Since this vector is opposite in direction to the vector $I_2 X_L$ representing the drop through the upper inductance, these two vectors may be combined to give the resultant vector V_b. Next let us draw the vector representing the drop through the upper condenser as we did in Fig. 6. This vector is shown at $-I_1 X_C$ of Fig. 7, and when combined with the vector V_b gives a resultant vector V_d. There remains to be considered the drop through the resistance between points 7′ and 2′. The vector representing this drop will be in the same direction as the drop 2 I_2 R in Fig. 7 but its numerical value will be only 1.7 I_2 R and this vector is shown in dotted lines at 1.7 I_2 R of Fig. 7. Combining this vector with the vector V_d we obtain the resultant vector V_2, which is indeed the resultant of all the vectors considered. Numerically, the vector V_2 is equal to the vector V_1 of Fig. 6 but is rotated in phase 45 degrees with respect thereto, so that as the result of the 45-degree rotation of the crank shaft, there is a shifting in phase in the drop between the sliding contacts of 45 degrees without any change in amplitude.

Now let us consider the drop for the last positions 8—3′ of the two sliding contacts before coming back to their starting positions. It will be noted that the two contacts are now directly opposite each other but are moving in opposite directions, as shown by the arrows in Fig. 5. The drop between these two points is the resultant of reverse drops through .3 R, through the upper condenser, and normal drops through the upper inductance and the resistance .3 R in the right-hand branch.

This is shown vectorially in Fig. 8. First let us draw the vector —.3 I_1 R for the reverse drop through the resistance in the right-hand branch. This vector is opposite in direction to the vector $I_2 X_L$ for the upper inductance of the right-hand branch and upon combining these two vectors we get the resultant vector V_e shown in dotted lines. Next, let us draw the reverse drop through the upper condenser of the left-hand branch as shown at $-I_1 X_C$. Finally, let us draw the vector .3 I_2 R representing the drop through the resistance between 7′ and 8′ in the right-hand branch. This vector is opposite in direction to the vector $-I_1 X_C$ and when these two vectors are combined we get a resultant vector V_f. If we now combine vectors V_e and V_f we obtain the resultant vector V_8 which represents the vectorial drop between points 8 and 8′. This vector, it will be observed, is of the same length as the vectors V_1 and V_2 already obtained and is 45 degrees behind the vector V_1.

It will be readily understood that if the crank shaft is rotated in the opposite direction the vector representing the drop between the contact points will also be rotated in the opposite direction, and the phase shift introduced by the phase shifter will be correspondingly changed. It will also be clear that if the crank shaft is rotated continuously there will be a continuous rotation or shift in phase introduced by the phase shifter PS_n.

With this understanding of the operation of the phase shifter in mind, let us assume that the arm *a* of Fig. 2 carrying the pin is in some position between the arms *b* and *b′* and that, due to some cause such as change in temperature, the phase of the telephone line is shifted by a small amount. The output circuit of the push-pull detector arrangement will be unbalanced and relay R_1 will set the motor M_1 into rotation in one direction, thereby adjusting the phase shifter PS_n until a compensating phase shift is introduced into the line, thus bringing the two wave components entering the detector again into proper relation, whereupon the armature of the polar relay R_n is restored to neutral position and the motor ceases rotating. The wave entering the detector from the line is now restored to its original phase. Obviously, small changes in phase in either direction may be compensated by the phase shifter PS_n so long as the phase adjustment does not involve rotating the pin carried by the arm *a* outside the arc between the arms *b* and *b′*.

Let us now consider the case where, without any change in phase in the telephone line, the local oscillator O_n changes it frequency slightly, thus introducing cumulative shifting in phase of the carrier wave with respect to the control wave coming from the telephone line. Again the push-pull circuit is unbalanced and the motor M_n is set into rotation. The actual working of the mechanism will depend upon the position of the pin carried by the arm *a* with respect to the arms *b* and *b′*. Let us suppose that at the time the motor starts to rotate the pin carried by the arm *a* is midway between the arms *b* and *b′*. As the shaft S rotates, the phase shifter may tend to momentarily bring about a balance of the push-pull circuit, the adjustment of the phase shifter tending to compensate for the apparent existing phase difference between the carrier wave and the control wave due to the error in the oscillator. Since where the two waves are not at exactly the same frequency, the effect of the error in the oscillator is cumulative, however, the push-pull circuit is immediately unbalanced and the shaft S continues to rotate until the pin carried by the arm a is brought into contact with the arm b or b' as the case may be.

Up to this point the action of the mechanism has been similar to its action where the difference in phase was due to an error in the telephone line itself. The action is one of attempting to compensate by means of the phase shifter for the apparent difference in phase of the carrier wave and the control wave. As soon, however, as the pin comes in contact with the arm b or b', the cumulative phase difference due to the error of the oscillator causes the shaft S to continue to rotate and the shaft S' begins to rotate with the shaft S, thereby bringing about an adjustment of the variable condenser C_n. There is a simultaneous adjustment of the phase shifter PS_n, and these two actions continue together until a balance is again obtained. The result is that the frequency of the oscillator at the radio station has been changed slightly, tending to bring it back to the same frequency as the control wave. The result of this action is, of course, to bring about an adjustment of the phase shifter PS_n, which was not necessary in order to bring the carrier wave back to the same frequency as the control wave. This adjustment of the phase shifter cannot be avoided, however, because the mechanism for operating the phase shifter cannot distinguish between a phase difference due to the telephone line and a cumulative phase difference due to an error in the oscillator.

As a consequence of this adjustment of the phase shifter, it will be noted that the phase relation between the radio station at which the condenser C_n was adjusted and any other radio station in the chain will to some extent be a function of the correcting condenser. This can be tolerated, however, so long as the shift does not occur too frequently, and it is assumed that a crystal-controlled oscillator of the type now known in the art, is good enough to avoid the necessity of adjusting the correcting condenser too frequently. After the adjustment the mechanism has come to rest with the pin carried by the arm a resting against one of the arms b or b' as the case may be, and with the shaft S shifted an amount corresponding to one-half the lost motion plus the additional amount necessary to bring about the desired adjustment of the correcting condenser C_n. If, with the apparatus in this condition, a maximum phase change should occur in the line in such direction as to cause the shaft S to rotate in the same direction, both the phase shifter and the correcting condenser would be again operated until the condition of balance was restored. Of course, the adjustment of the variable condenser tends to assist the phase shifter in compensating for the phase shift in the line, but the adjustment of the condenser results in an over-correction of the frequency of the oscillator. This will result in a cumulative phase difference between the carrier wave and the control wave in the opposite sense to that which caused the previous correction of the oscillator, and the shaft S will be caused to rotate in the opposite direction until the lost motion is taken up in the opposite direction and the variable condenser and phase shifter simultaneously adjusted until the frequency of the oscillator is corrected. The mechanism will now come to rest with the pin on the arm a resting against the other of the arms b or b' as the case may be. If, in this condition a maximum phase shift in a direction opposite to that previously considered should occur in the line itself, the push-pull circuit will be again unbalanced and the shaft S will be rotated in the same direction as it was last moved until the adjustment of the variable condenser C_n and the phase shifter PS_n compensate for the phase shift in the line. This would also result in over-correction of the variable condenser in the opposite sense to the former over-correction, so that a cumulative phase difference would ultimately result which would cause the mechanism to correct the error as before.

Of course when the pin carried by the arm a lies in an intermediate position between the arms b and b' any phase shift in the line can be corrected by adjustment of the phase shifter PS_n so long as the phase changes in the line (which compensate to zero over a long period) do not require the pin carried by the arm a to move out of the angle between arms b and b'.

It will be apparent from the foregoing description, that the phase relation of the carrier wave of the station illustrated with respect to that of the carrier wave of another station in the chain, may shift by an amount corresponding to a rotation of the shaft S sufficient to take up the complete loss of motion between the arms b and b' plus twice the additional rotation of the shaft S necessary for the variable condenser and phase shifter to jointly compensate for a maximum phase shift in the telephone line, it being assumed, of course, that a greater joint adjustment of the variable condenser and the phase shifter would be necessary to compensate for the phase shift in the telephone line than would be required for compensation of the maximum frequency difference between the generated carrier wave of the station and the control wave.

It is desirable to limit the amount it is necessary to rotate the shaft S over and above the amount required to take up the loss of motion, in order to keep the possible phase difference between the station in question and any other station in the system as small as possible. This may be accomplished by using a gearing to control the operation of the variable condenser C_n, this gearing being so arranged that the maximum adjustment of the variable condenser necessary to compensate for any phase change which brings it into play, will be accompanied by a simultaneous adjustment of the phase shifter PS_n, which is very small as compared with the adjustment of the phase shifter represented by a movement of the shaft sufficient to take up the complete loss of motion. The result is that the maximum of adjustment of the phase shifter which could normally be expected to occur would be but little greater than the adjustment corresponding to a movement of the shaft S sufficient to take up the complete loss of motion between the arms b and b'.

Since the maximum adjustment of the phase shifter PS_n in any given direction from its normal position is a measure of the actual shift in phase of the generated carrier wave of the station with respect to the control oscillator, the carrier wave of the station can only get out of phase with respect to the carrier wave of any other station whose phase relation has not changed, by an amount equivalent to this maximum adjustment of the phase shifter, since the other station may be presumed to be in normal synchronous relation with respect to the common control oscillator. Now the maximum possible adjustment which may be expected of the phase shifter PS_n under any condition being but little greater than the angle between the arms b and b', it becomes evident that even if another station in the chain should have its adjusting apparatus adjusted to the maximum phase, shift of its phase shifter in one direction, and the station here illustrated should have its phase shifter adjusted the maximum amount in the opposite direction, the two stations would only be out of phase by an amount equal to the angle between the arms b and b' plus twice the additional rotation of the shaft S in either direction that would be necessary for the maximum expected adjustment of the condenser C_n.

In other words, if both stations had their carrier waves in normal phase relation, with the pin carried by the arm a at both stations just halfway between the arms b and b', an error causing one of the stations to move its shaft S to its maximum expected adjustment in one direction would merely adjust its phase shifter an amount corresponding to one-half the angle between the arms b and b' plus the additional angle in the same direction corresponding to the maximum adjustment of the variable condenser C_n at that station. If, at the same time an equal but opposite error should occur at the other station, causing its apparatus to be adjusted in the opposite direction, the shaft S at the latter station would be adjusted in the opposite direction by an amount equal to one-half the angle between the arms b and b' plus the additional angle in the same direction corresponding to the maximum adjustment of the condenser C_n.

From the foregoing it will be seen that the arrangement of the invention not only tends to keep the carrier waves of all of the stations of the chain at the same frequency but it limits the maximum amount that the carrier waves of any two stations may get out of phase with respect to each other. By means of the provision of the lost motion device, it provides for a compensating adjustment of the phase shifter alone without any necessary adjustment of the variable condenser controlling the oscillator, where there has been a change in phase due entirely to the line transmitting the control frequency. This renders it unnecessary to make the highly stable oscillator which generates the carrier wave follow the relatively large phase variations due to the line itself.

It will be obvious that the general principles herein disclosed may be embodied in many other organizations widely different from those illustrated without departing from the spirit of the invention as defined in the following claims.

What is claimed is:

1. In a frequency control system, means to generate a wave whose frequency is to be controlled, means to supply a control wave, relay means responsive to certain changes in the normal phase relation of the control and controlled waves, means controlled by said relay means to adjust the frequency of the controlled wave in response to such changes, and means to defeat such adjustment when said relay means operates in response to phase changes of the controlling wave only.

2. In a frequency control system, means to generate a wave whose frequency is to be controlled, means to supply a control wave, relay means responsive to certain changes in the normal phase relation of the control and controlled waves, means controlled by said relay means to adjust the frequency of the controlled wave in response to such changes, and means to defeat such adjustment when said relay means operates in response to small changes from the normal phase relation of the control and controlled waves.

3. In a frequency control system, means to generate a wave whose frequency is to be controlled, means to supply a control wave, a push-pull detector to which both waves may be applied, means controlled by said detector to adjust the frequency of said control wave in response to certain changes from the normal phase relation of the control and controlled waves applied to said detector, and means controlled by said detector to prevent adjustment of frequency in response to phase changes of the controlling wave only.

4. In a frequency control system, means to generate a wave whose frequency is to be controlled, means to supply a control wave, a push-pull detector to which both waves may be applied, means controlled by said detector to adjust the frequency of said control wave in response to certain changes from the normal phase relation of the control and controlled waves applied to said detector, and means controlled by said detector to prevent adjustment of frequency in response to small changes from the normal phase relation of the control and controlled wave.

5. In a frequency control system, means at a station to generate a wave whose frequency is to be controlled, means to generate a control wave at a distant point, a line to transmit said control wave from said distant point to said station, a controlling device including a relay at said station to which said control and controlled waves may be applied, means controlled by said relay to adjust the frequency of said controlled wave in response to certain changes in the phase relation of the waves applied to said controlling device, and means to defeat such adjustment when said relay operates in response to phase changes in said line.

6. In a frequency control system, means at a station to generate a wave whose frequency is to be controlled, means to generate a control wave at a distant point, a line to transmit said control wave from said distant point to said station, a push-pull detector at said station to which said control and controlled wave may be applied, means controlled thereby to adjust the frequency of said controlled wave in response to certain changes in the phase relation of the waves applied to said detector, and means to prevent such adjustment in response to phase changes in said line.

7. In a frequency control system, means at a station to generate a wave whose frequency is to be controlled, means to generate a control wave at a distant point, a line to transmit said control wave from said distant point to said station, a controlling device at said station to which said control and controlled waves may be applied, means controlled thereby to adjust the frequency of said controlled wave in response to certain changes in the phase relation of the waves applied to said controlling device, a phase changer in said line, said phase changer being controlled by said controlling device, the connections between said controlling device and said frequency adjusting means and said phase changer being such that in response to phase changes in said line said phase changer will be adjusted to compensate therefor without operating said frequency adjusting means.

8. In a frequency control system, means at a

station to generate a wave whose frequency is to be controlled, means to generate a control wave at a distant point, a line to transmit said control wave from said distant point to said station, a push-pull detector at said station to which said control and controlled waves may be applied, means controlled thereby to adjust the frequency of said controlled wave in response to certain changes in the phase relation of the waves applied to said detector, a phase changer in said line, said phase changer being controlled by said detector, the connection between said detector and said frequency adjusting means and said phase changer being such that in response to phase changes in said line said phase changer will be adjusted to compensate therefor without operating said frequency adjusting means.

9. In a frequency control system, means at a station to generate a wave whose frequency is to be controlled, means to generate a control wave at a distant point, a line to transmit said control wave from said distant point to said station, a push-pull detector at said station, means to apply said control and controlled waves to said detector so that they will be differential with respect to the one and cumulative with respect to the other unit of said push-pull detector, a polar relay having an armature, said relay being so connected to the output of said detector as to be neutral when the two waves are applied to said detector in quarter phase relation but to attract its armature to one side or the other depending upon the direction in which said two waves depart from quarter phase relation, an operating mechanism controlled by the armature of said relay, an adjustable phase shifter in said telephone line, a frequency controller associated with the generator whose wave is to be controlled, and means operatively connecting said operating mechanism to said phase shifter and said frequency controller.

10. In a frequency control system, means at a station to generate a wave whose frequency is to be controlled, means to generate a control wave at a distant point, a line to transmit said control wave from said distant point to said station, a push-pull detector at said station, means to apply said control and controlled wave to said detector so that they will be differential with respect to the one and cumulative with respect to the other unit of said push-pull detector, a polar relay having an armature, said relay being so connected to the output of said detector as to be neutral when the two waves are applied to said detector in quarter phase relation but to attract its armature to one side or the other depending upon the direction in which said two waves depart from quarter phase relation, an operating mechanism controlled by the armature of said relay, an adjustable phase shifter in said telephone line, a frequency controller associated with the generator whose wave is to be controlled, and means operatively connecting said operating mechanism to said phase shifter and said frequency controller, said last mentioned means being so arranged as to permit limited adjustment of said phase changer without operating said frequency controller.

11. In a frequency control system, a phase changer, a frequency controller, a drive shaft, connections from said shaft for directly driving said phase changer, and a lost-motion drive between said shaft and said frequency controller.

12. In a frequency control system, a phase changer, a frequency controller, a drive shaft, connections from said shaft for directly driving said phase changer, and means connecting said shaft and said frequency controller, said means including means to delay the operation of said frequency controller after the beginning of rotation of said shaft.

13. In a frequency control system, means to generate a wave whose frequency is to be controlled, means to supply a control wave, a relay jointly controlled by said control wave and controlled wave means operated by said relay to determine the frequency of said controlled wave, and means to defeat a change in frequency of the controlled wave when said relay operates in response to certain changes in the arriving phase of the controlling wave.

14. In a frequency control system, a controlling source of cyclic vibrations, a controlled source of cyclic vibrations, each of said sources having small short period errors, a transmission medium connecting said sources, said medium having relatively large short period errors but substantially no long period error, and means discriminating between short period errors and long period errors for associating said transmission medium and said controlled source to prevent the phase angle of said controlled source from varying more than a predetermined amount, and for preventing the rate of phase drift from exceeding a predetermined value.

15. In a frequency control system, a controlling source of cyclic vibrations, a controlled source of cyclic vibrations, each of said sources having small short period errors, a transmission medium connecting said sources, said medium having relatively large short period errors but substantially no long period error, means discriminating between short period errors and long period errors for associating said transmission medium and said controlled source to prevent the phase angle of said controlled source from varying more than a predetermined amount, and for preventing the rate of phase drift from exceeding a predetermined value, and a phase compensator associated with said discriminating means and controlled thereby to compensate for short period errors in said medium.

16. In a frequency control system, a controlling source of cyclic vibrations, a controlled source of cyclic vibrations, a transmission medium connecting said sources, said medium having short time errors but substantially no long time error, and said controlled source having cumulative long time error, and means discriminating between short period errors and cumulative long period errors for associating said transmission medium and said controlled source to prevent the phase angle of said controlled source from varying more than a predetermined amount, and for preventing the rate of phase drift from exceeding a predetermined value.

17. In a frequency control system, a controlling source of cyclic vibrations, a controlled source of cyclic vibrations, a transmission medium connecting said sources, said medium having short time errors but substantially no long time error, and said controlled source having cumulative long time error, means discriminating between short period errors and cumulative long period errors, said means being interposed between said transmission medium and said controlled source to prevent the phase angle of said controlled source from varying more than predetermined amount and for preventing the rate of phase drift from exceeding a predetermined

value, and a phase compensator associated with said discriminating means and controlled thereby to compensate for short period errors in said medium.

18. In a frequency control system, a controlling source of cyclic vibrations, a controlled source of cyclic vibrations, a transmission medium connecting said sources, said transmission medium having substantially no long time error and having short time errors cumulating practically to zero over a comparatively long period of time, said controlled source having errors cumulating as the first power of time, and means discriminating between short time errors cumulating to zero and errors cumulating as the first power of time for associating said transmission medium and said controlled source to adjust the frequency of said controlled source, said means preventing any adjustment of the frequency unless the phase drift accumulates to a predetermined angle.

19. In a frequency control system, a controlling source of cyclic vibrations, a controlled source of cyclic vibrations, a transmission medium connecting said sources, said transmission medium having substantially no long time error and having short time errors cumulating practically to zero over a comparatively long period of time, said controlled source having errors cumulating as the first power of time, a phase shifter to compensate for short time errors compensating to zero, a frequency adjuster to adjust the frequency of said controlled source, means associated with said medium and said controlled source for operating both said phase shifter and said frequency adjuster and means to prevent the operation of said frequency adjuster until the phase drift accumulates to an appreciable angle.

20. In a frequency control system, means to generate a wave whose frequency is to be controlled, means to supply a control wave, means responsive to certain changes in the normal phase relation of the control and controlled waves to adjust the frequency of the controlled wave and readjust the phase relation between the control and controlled waves, and means to defeat said frequency adjustment while permitting said phase adjustment in response to phase changes of the controlling wave only.

21. In a frequency control system, means to generate a wave whose frequency is to be controlled, means to supply a control wave, means responsive to certain changes in the normal phase relation of the control and controlled waves to adjust the frequency of the controlled wave and to readjust the phase relation of the control and controlled waves, and means to defeat said frequency adjustment while permitting phase adjustment in response to small changes from the normal phase relation of the control and controlled waves.

HARRY NYQUIST.