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ELECTRO-MECHANICAL PHASE SHIFTER

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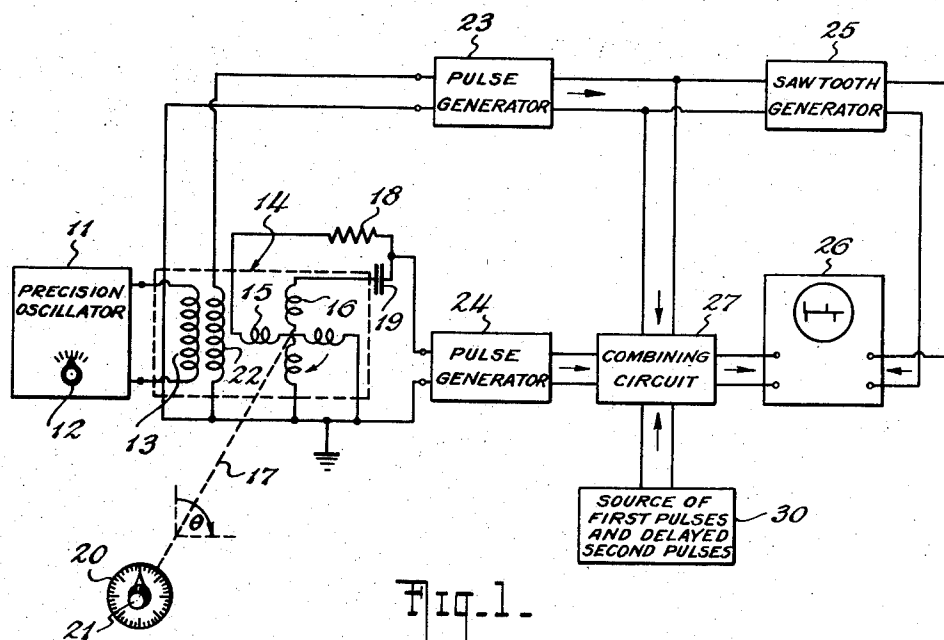


Fig. 1.

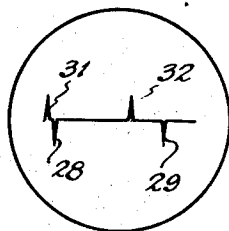


Fig. 3.

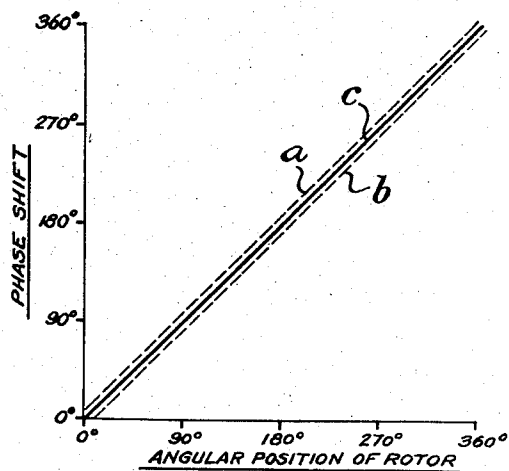


Fig. 2.

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1

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ELECTRO-MECHANICAL PHASE SHIFTER

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13 Claims. (Cl. 324—83)

The present invention relates to phase shifting circuits, and in particular to improvements in electro-mechanical phase shifters employing synchros.

It is well known that a synchro may be used as a phase shifter by applying a single-phase sinusoidal alternating voltage to the primary or single winding of the synchro and combining the alternating output voltages from the crossed-field secondary windings in a reactive phase-shift network. Patent 2,627,598, assigned to the same assignee as the present invention, describes and claims an electro-mechanical phase shifter of this type. A similar phase shifter is described on page 498 of the book "Waveforms" published by the McGraw-Hill Book Company, 1949.

While electro-mechanical phase shifters of this type possess good linearity of phase shift as a function of angular rotation of the rotor winding, they have been found to possess undesired variations of phase shift with changes in temperature. This variation of phase shift restricts the use of the synchro phase shifter, especially in equipments designed for military service. It has been found that these variations in phase shift with temperature are unpredictable and are different with synchros of the same type and manufacture.

Accordingly, the principal object of the present invention is to provide an electro-mechanical phase shifting system having improved accuracy and phase stability.

Another object is to provide an electro-mechanical phase shifter whose phase shift characteristic is substantially independent of changes in temperature.

In accordance with the present invention there is introduced an improved electro-mechanical phase shifter employing a synchro having an auxiliary winding with fixed mutual coupling with the primary winding of the synchro. The alternating voltage applied to the primary winding induces a voltage in the auxiliary winding, and this induced voltage is employed as the reference voltage instead of the voltage applied to the primary winding. The phase difference between the phase shifted output voltage from the synchro phase shifter and the induced reference output voltage from the auxiliary winding is substantially independent of changes in temperature.

The above objects of and the brief introduction to the present invention will be more fully understood and further objects and advantages will become apparent from a study of the following detailed description in connection with the drawings, wherein,

Fig. 1 is a combination block and schematic diagram of the improved electro-mechanical phase shifter of the present invention as employed to measure the phase difference between applied first and second recurrent pulses.

Fig. 2 illustrates the phase shift versus angular position of the rotor winding of the improved electro-mechanical phase shifter of the invention for different values of temperature.

Fig. 3 is a representation of the pulse waveforms appearing on the face of the cathode-ray tube phase indicator of Fig. 1.

2

Referring to Fig. 1, a precision oscillator 11 having a fine frequency control knob 12 supplies an alternating voltage to the primary winding 13 of a synchro 14. The synchro includes crossed-field secondary windings 15 and 16 mutually coupled to the primary winding 13. The mutual inductive coupling between the primary and secondary windings is controlled by shaft 17 coupled to the rotatable secondary windings. In certain synchros, the primary winding instead of the secondary windings is designed as the rotor. The word synchro is a universal term applied to devices such as the selsyn, control transformer, resolver, and other similar variable magnetic coupled devices.

The alternating voltage applied to the primary winding 13 induces alternating voltages in the secondary windings 15 and 16 whose magnitude depends upon the amount of mutual coupling between the primary and secondary windings, and whose phase is fixed relative to the applied alternating voltage. The voltages induced in the secondary windings are combined in a reactive phase-shift network comprising resistor 18 and condenser 19 to form an electro-mechanical phase shifter as taught in the aforesaid Patent 2,627,598, or on page 498 of the aforementioned book "Waveforms." The resistor 18 and condenser 19 are coupled in series between one terminal of secondary winding 15 and one terminal of secondary winding 16. The other two terminals of the secondary windings 15 and 16 are coupled to a common ground terminal. The single alternating output voltage between the junction of resistor 18 and condenser 19 and the common ground terminal varies in phase with respect to the applied voltage across the primary winding linearly according to the angular position θ of shaft 17, as shown in Fig. 2. The angular position of shaft 17 in degrees may be indicated on the calibrated dial 20. The angular position of the shaft is controlled by knob 21.

The phase of the alternating voltage at the output of the phase shifter with respect to the applied alternating voltage across the primary winding 13, while varying substantially linearly with respect to the angular position of shaft 17, is not independent of changes in temperature. At low temperatures the phase shift characteristic is as shown by the broken line *a* of Fig. 2, while for high temperatures the phase shift characteristic is as shown by the broken line *b*. Accordingly, the absolute calibration of the phase shifter, according to the calibrated dial 20, is subject to error if the temperature of the electro-mechanical phase shifter is susceptible to wide variations.

The temperature variation of the phase of the alternating voltage at the output of the phase shifter with respect to the alternating voltage applied to the primary winding 13 is largely due to the variation of primary resistance with temperature. The phase of the primary current relative to the applied primary voltage depends on the primary resistance and leakage reactance, so that this phase will change as temperature changes. The magnetic flux linking the secondary windings 15, 16 depends, in turn, on the primary current. Consequently, voltage induced in the secondary windings due to this magnetic flux will bear a phase relative to the applied primary voltage that changes with temperature.

A paramount improvement in the phase stability of the electro-mechanical phase shifter as a function of temperature can be achieved by providing the synchro 14 with an auxiliary winding 22 having fixed mutual inductive coupling with the primary winding 13. This auxiliary winding 22 may be wound together with primary winding 13 as a bifilar coil, each winding 13 and 22 having the same number of turns and being insulated one from the other. Voltage is induced in auxiliary winding 22 by magnetic flux produced by the current of

primary winding 13. Consequently, the phase between the voltage induced in the secondary windings 15, 16 and that induced in auxiliary winding 22 is dependent only on the relative phase between the respective magnetic fluxes linking these windings and is independent of the value of the primary resistance. When the voltage induced in the auxiliary winding 22 is employed as the reference voltage instead of the voltage existing across the primary winding 13, the phase stability of the phase shifter as a function of angular position of shaft 17 is substantially independent of changes in temperature as illustrated by the solid line c in Fig. 2. One such electro-mechanical phase shifter having an auxiliary winding in accordance with the present invention was found to possess a change in phase shift of less than 0.1 degree at 1000 cycles per second for a temperature change from -40°C. to $+100^{\circ}\text{C.}$

The improved electro-mechanical phase shifter of the present invention may be used in most of the applications where conventional electro-mechanical phase shifters are employed. One such application is illustrated in Fig. 1 where the phase shifter is employed to measure the phase difference or time interval between first and second applied recurrent pulses. The reference alternating voltage induced in the auxiliary winding 22 is applied to a pulse generator 23 for producing recurrent negative reference output pulses. The alternating output voltage from the reactive phase-shift network is applied to pulse generator 24 for producing negative output pulses whose phase or relative time position with respect to the negative reference output pulses is controlled by the angular position of shaft 17. The negative reference output pulses from generator 23 are supplied to the sawtooth generator 25 which produces a sawtooth sweep voltage having the same frequency as the negative reference output pulses. The sawtooth sweep voltage is applied to the horizontal deflection plates of a cathode-ray oscilloscope 26. The negative reference output pulses from pulse generator 23 and the variable phase negative output pulses from pulse generator 24 are combined in the combining circuit 27 and supplied to the vertical deflection plates of the cathode-ray oscilloscope 26. These combined negative pulses appear on the face of the cathode-ray oscilloscope as shown in Fig. 3. The negative reference output pulses appear as the negative pulse waveform 28 and the variable phase negative output pulses appear as the negative pulse waveform 29. The relative phase or time difference between the negative reference pulses of waveform 28 and the variable phase negative pulses of waveform 29 is indicated on the calibrated dial 20.

The first and second pulses whose time difference is to be measured are obtained from the source 30, and these pulses are supplied to the combining circuit 27 and then to the vertical deflection plates of the cathode-ray oscilloscope 26. These pulses appear on the face of the cathode-ray tube as positive pulses 31 and 32, as shown in Fig. 3. The pulse repetition frequency of the applied pulses is substantially equal to the frequency of the negative reference and variable phase pulses obtained from the pulse generators 23 and 24, respectively, and any difference in pulse repetition frequency is eliminated by adjusting the frequency of the precision oscillator 11 by means of a frequency control knob 12. The frequency control knob 12 varies the frequency of the negative reference and variable phase pulses until the time position of the first pulses of waveform 31 are brought into coincidence with the negative reference pulses of waveform 28. Thereafter, the shaft 17 of the phase shifter is adjusted to vary the time position of the variable phase pulses of waveform 29 until they are brought into coincidence with the second positive pulses of waveform 32 on the face of the cathode-ray tube. The phase difference between the applied first and second positive pulses may be read directly from the calibrated dial 20.

The time difference interval between the applied first and second positive pulses is equal to the ratio of the measured phase difference to 360 multiplied by the period of the applied first and second recurrent pulses.

The improved phase shifter of the present invention is not restricted to the application illustrated in Fig. 1, but may be used where it is desired to produce a reference output voltage and a variable phase output voltage whose phase difference is accurately known.

Since many changes could be made in the above construction and many apparently widely different embodiments of this invention could be made without departing from the scope thereof, it is intended that all matter contained in the above description or shown in the accompanying drawings shall be interpreted as illustrative and not in a limiting sense.

What is claimed is:

1. An electro-mechanical phase shifter providing a phase shift substantially independent of temperature comprising in combination, a synchro having a primary winding adapted to be excited by an applied alternating voltage, a pair of secondary windings in space quadrature mutually coupled to said primary winding, means coupled to one of said windings for varying the mutual coupling between said primary and secondary windings, means for combining the alternating voltages induced in said pair of secondary windings, said combining means including a resistor and a condenser coupled in series between one terminal of one secondary winding and one terminal of the other secondary winding, the opposite terminals of said pair of secondary windings being coupled to a common output terminal, means coupled between the junction of said resistor and condenser and said common output terminal for receiving a first alternating output voltage, said synchro further including an auxiliary winding arranged for substantially optimum mutual coupling with said primary winding and providing a second induced output voltage, and means coupled to said auxiliary winding for receiving said second alternating output voltage, the phase difference between said first alternating output voltage and said second alternating output voltage varying according to the mutual coupling between said primary and spaced secondary windings.

2. In combination, a phase shifter comprising a synchro having a bifilar winding consisting of first and second mutually coupled coils insulated from each other, one of said coils being adapted to be excited by an applied alternating voltage, the other of said coils providing an induced alternating output voltage, a pair of secondary windings in space quadrature mutually coupled to said bifilar winding, shaft means coupled to one of said windings for varying the mutual coupling between said bifilar and said pair of secondary windings, means for combining the alternating voltages induced in said pair of secondary windings including a condenser and a resistor coupled in series between one terminal of one of said secondary windings and one terminal of the other secondary winding, the opposite terminals of said pair of secondary windings being coupled to the common output terminal, and means coupled between the junction of said resistor and condenser and said common output terminal for receiving the combined alternating output voltage, said means being further coupled to said other coil of said bifilar winding for receiving said induced alternating output voltage, the phase difference between said combined alternating output voltage and the induced alternating output voltage from said other coil varying linearly according to the angular position of said shaft means, said phase difference being substantially independent of changes in temperature.

3. In combination, a phase shifter comprising a synchro having a bifilar winding consisting of first and second mutually coupled coils insulated from each other, one of said coils being adapted to be excited by an applied alternating voltage, the other of said coils providing an

5

induced alternating output voltage, a plurality of secondary windings mutually coupled to said bifilar winding, means coupled to one of said windings for varying the mutual coupling between said bifilar winding and said plurality of secondary windings, means for combining the alternating voltages induced in said plurality of secondary windings including a reactive phase-shift network coupled to said plurality of secondary windings, said phase-shift network producing a single alternating output voltage, means coupled to the output of said phase-shift network for receiving said single alternating output voltage, said means being further coupled to said other coil of said bifilar winding for receiving said induced alternating output voltage, the phase difference between said single alternating output voltage from said phase-shift network and the induced alternating output voltage from said other coil varying according to the angular position of said means coupled to one of said windings, said phase difference being substantially independent of changes in temperature.

4. A phase shift system for producing a first alternating output voltage and a second alternating output voltage, said second alternating output voltage having a controllable phase difference relative to said first alternating output voltage substantially independent of changes in temperature, comprising in combination, a synchro having a primary winding adapted to be excited by an applied alternating voltage, an auxiliary winding having fixed mutual coupling with said primary winding, said auxiliary winding producing said first alternating output voltage, a plurality of secondary windings mutually coupled to said primary winding, the magnitude of the voltages induced in said secondary windings being determined by the amount of mutual coupling between said primary and secondary windings, means coupled to one of said windings for varying the mutual coupling between said primary and said plurality of secondary windings, the mutual coupling between said plurality of secondary windings remaining substantially constant, means for combining the alternating voltages induced in said plurality of secondary windings including a reactive phase-shift network coupled to said plurality of secondary windings, said phase-shift network producing said second output voltage, and means coupled to said auxiliary winding and to said phase-shift network for indicating the phase difference between said first and second alternating output voltages.

5. An electro-mechanical phase shifter providing an output voltage whose phase is adjustable with respect to a reference voltage, the phase difference between said reference and output voltages being substantially independent of changes in temperature, comprising in combination, a synchro having crossed-field windings and first and second single windings mutually coupled to said crossed-field windings, means for intercoupling said crossed-field windings, said means including a reactive phase-shift network, a first pair of terminals coupled to said first single winding, a second pair of terminals coupled to said phase-shift network, one of said first or second pairs of terminals being adapted for receiving an applied alternating voltage, the other of said first or second pairs of terminals being adapted for supplying said output voltage, a third pair of terminals coupled to said second single winding, said second single winding providing said reference voltage across said third pair of terminals, the first or second pair of terminals supplying said output voltage and said third pair of terminals being coupled to phase indicating means, means coupled to one of the windings of said synchro for varying the mutual coupling between said crossed-field windings and said first single winding, said mutual coupling varying means varying the phase difference between said output voltage and said reference voltage.

6. A phase shift system for measuring the difference in phase between a first voltage wave and a second volt-

6

age wave delayed in phase with respect to said first voltage wave, the phase difference measurement being substantially independent of changes in temperature, comprising in combination, a synchro having a first winding adapted to be excited by an applied alternating voltage, a second winding having fixed mutual coupling with said first winding, said second winding providing an induced reference alternating output voltage, a plurality of windings mutually coupled to said first and second windings, means for combining the alternating voltages induced in said plurality of windings, said combining means including a reactive phase-shift network coupled to said plurality of windings, said phase-shift network producing a single alternating output voltage, phase indicating means coupled to said second winding and to said phase-shift network for indicating the phase difference between said single output voltage and said reference output voltage, means adapted for coupling said first voltage wave and said delayed second voltage wave to said phase indicating means, said phase indicating means indicating the phase difference between said first and second voltage waves, means including a shaft means coupled to one of the windings of said synchro for varying the phase difference between said single output voltage and said reference output voltage, and means for adjusting the angular position of said shaft means for providing the same phase difference between said single output voltage and said reference output voltage as exists between said first and second voltage waves, the angular position of said shaft means denoting the phase difference between said first and second voltage waves.

7. A phase shift system for measuring the difference in phase between a first voltage wave and a second voltage wave delayed in phase with respect to said first voltage wave, the phase difference measurement being substantially independent of changes in temperature, comprising in combination, a synchro having a primary winding, means including an oscillator means coupled to said primary winding for supplying an alternating voltage thereto, an auxiliary winding having fixed mutual coupling with the primary winding of said synchro, said auxiliary winding providing an induced reference output voltage, a plurality of secondary windings mutually coupled to said primary and auxiliary windings, means for combining the alternating voltages induced in said plurality of secondary windings, said combining means including a reactive phase-shift network coupled to said plurality of secondary windings, said phase-shift network providing a single alternating output voltage, phase indicating means coupled to said auxiliary winding and to said phase-shift network for indicating the phase difference between said single output voltage and said reference output voltage, means adapted for coupling said first voltage wave and said delayed second voltage wave whose phase difference is to be measured to said phase indicating means, said phase indicating means indicating the phase difference between said first and second voltage waves, means coupled to said oscillator means for maintaining the frequency of said single output voltage and said reference output voltage substantially equal to the frequency of said first and second voltage waves, means including a shaft means coupled to one of the windings of said synchro for varying the phase difference between said single output voltage and said reference output voltage, the phase difference between said single output voltage and said reference output voltage varying according to the angular position of said shaft means, and means for adjusting the angular position of said shaft means for providing the same phase difference between said single output voltage and said reference output voltage as exists between said first and second voltage waves, the angular position of said shaft means denoting the phase difference between said first and second voltage waves.

8. The phase-shift system as defined in claim 7 where-
in said phase indicating means coupled to said auxiliary

7

winding and to said phase-shift network is a cathode-ray oscilloscope.

9. A system for measuring the time difference interval between an applied first voltage wave and an applied second voltage wave delayed in time with respect to said first voltage wave, the time difference measurement being substantially independent of changes in temperature, comprising in combination, a synchro having crossed-field windings and first and second single windings mutually coupled to said crossed-field windings, means for intercoupling said crossed-field windings, said means including a reactive phase-shift network, a first pair of terminals coupled to said first single winding, a second pair of terminals coupled to said phase-shift network, one of said first or second pairs of terminals being adapted for receiving an applied alternating voltage, the other of said first or second pairs of terminals being adapted for supplying a variable phase output voltage, a third pair of terminals coupled to said second single winding, said second single winding providing a reference output voltage, time difference indicating means coupled to said third pair of terminals for receiving said reference output voltage, said time difference indicating means being further coupled to the other of said first or second pairs of terminals for receiving said variable phase output voltage, said time difference indicating means indicating the time difference between said variable phase output voltage and said reference output voltage, means adapted for coupling said first voltage wave and said delayed second voltage wave whose time difference interval is to be measured to said time difference indicating means, said time difference indicating means indicating the time difference between said first and second voltage waves, shaft means coupled to one of the windings of said synchro for varying the mutual coupling between said crossed-field windings and said first single winding, said mutual coupling varying means varying the time difference between said variable phase output voltage and said reference voltage, and means for adjusting the angular position of said shaft means for providing the same time difference interval between said variable phase output voltage and said reference output voltage as exists between said first and second voltage waves, the angular position of said shaft means denoting the time difference between said first and second voltage waves.

10. A phase shift system for producing a first alternating output voltage and a second alternating output voltage, said second alternating output voltage having a controllable phase difference relative to said first alternating output voltage substantially independent of changes in temperature, comprising in combination, a synchro having a primary winding adapted to be excited by an applied alternating voltage, an auxiliary winding having fixed mutual coupling with said primary winding, said auxiliary winding producing said first alternating output voltage, a plurality of secondary windings mutually coupled to said primary winding, the magnitude of the voltages induced in said secondary windings being determined by the amount of mutual coupling between said primary and secondary windings, said mutual coupling being controllable, means for combining the alternating voltages induced in said plurality of secondary windings including a reactive phase-shift network coupled to said plurality of secondary windings, said phase-shift network producing a second output voltage, an electrical network coupled to said reactive phase-shift network and responsive to said second output voltage for producing a third output voltage, and means coupled to said auxiliary winding and to said network for indicating the phase difference between said third output voltage and said first alternating voltage.

8

said phase-shift network producing said second output voltage, and means coupled to said auxiliary winding and to said phase-shift network for indicating the phase difference between said first and second alternating output voltages.

11. An electro-mechanical phase shifter providing an output voltage whose phase is adjustable with respect to a reference voltage, the phase difference between said reference and output voltages being substantially independent of changes in temperature, comprising in combination, a synchro having a single winding and a plurality of windings mutually coupled to said single winding, said mutual coupling being controllable, a reactive phase-shift network connected to said plurality of windings, an auxiliary winding fixed with respect to one of said windings, a first pair of terminals connected to said reactive phase-shift network, a second pair of terminals connected to said single winding, and phase difference indicating means coupled to said auxiliary winding and to one of said first and second pair of terminals.

12. A phase shifting system substantially independent of changes in temperature, comprising in combination, a synchro having a primary winding adapted to be excited by an applied alternating voltage, an auxiliary winding having fixed mutual coupling with said primary winding, said auxiliary winding producing a first alternating output voltage, a plurality of secondary windings mutually coupled to said primary winding, the magnitude of the voltages induced in said secondary windings being determined by the amount of mutual coupling between said primary and secondary windings, said mutual coupling being controllable, means for combining the alternating voltages induced in said plurality of secondary windings including a reactive phase-shift network coupled to said plurality of secondary windings, said phase-shift network producing a second output voltage, an electrical network coupled to said reactive phase-shift network and responsive to said second output voltage for producing a third output voltage, and means coupled to said auxiliary winding and to said network for indicating the phase difference between said third output voltage and said first alternating voltage.

13. Electro-mechanical phase shifting apparatus substantially independent of changes in temperature comprising a synchro having a single winding and a plurality of windings mutually coupled to said single winding, said mutual coupling being controllable, a reactive phase-shift network connected to said plurality of windings, an auxiliary winding fixed with respect to one of said windings, a first pair of terminals connected to said reactive phase-shift network, a second pair of terminals connected to said single winding, an electrical network coupled to one of said first and second pairs of terminals, and phase difference indicating means coupled to said auxiliary winding and to said network.

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