The Synchro Generator and Motor

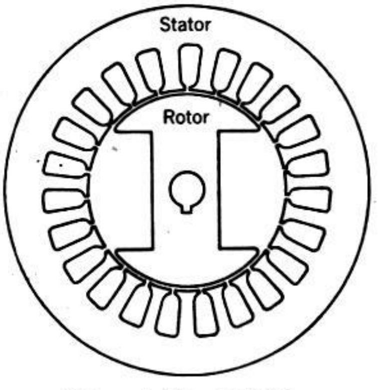
INTRODUCTORY INFORMATION

Transmitting Angular Motion of a Shaft

In remote-control applications it is sometimes necessary to have the angular motion of a shaft follow the motion of another shaft located some distance away. Though it is possible to devise a system which will transmit this motion through mechanical linkages, this is usually not the most efficient or economical method. Electromechanical systems are more flexible and are therefore used. In the electromechanical system mechanical rotations are converted into electrical currents. These currents are then transmitted to the required location and are there converted back into the desired rotation.

The angular motion of a shaft may be used to transmit information to remote indicators. For example a meter dial may be controlled to indicate the position of a rotatable antenna. Here "positioning" information must be transmitted from the antenna, as it is rotated, to an operator who may be miles away. In this application little torque is required to turn the meter dial. Hence little power is involved. A device called a "synchro" is used in this application.

The angular motion of a shaft may be used in another application, where the controlled shaft delivers more power than the controlling shaft. The electromechanical system used here is called a servo system and employs the synchro in combination with other elements. An example of a servo system is the mechanism used for turning the rudder of a large ship. A small handwheel in the control room is used for turning the large rudder. The handwheel is part of a servo system. Relatively little human effort is required to turn the small handwheel. The work is done by the servo system, which also assures the operator that the angular motion of his wheel will be followed exactly by the motion of the rudder.



Rotor and stator punchings

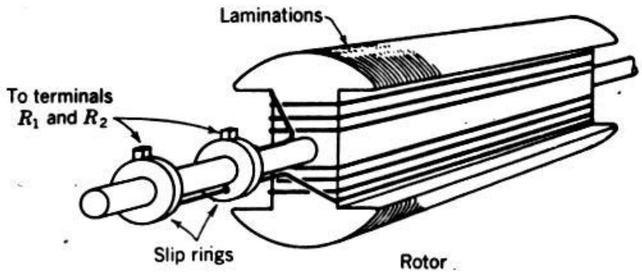


Fig. 37-1. Construction of a synchro generator.

Synchros Used for Remote Indicator System

In this job we will be concerned with remote indicator systems. The two components involved in this system are known as the synchro generator and synchro motor. The synchro is known by other names, such as selsyn, autosyn, and syncrotie. A synchro is a device used for the electrical transmission of an angular position.

The synchro generator or transmitter is constructed like a two-pole alternator (see Fig. 37-1). The rotor coil is wound on a laminated iron core. The ends of the coil are connected to slip rings. The slip rings are connected to terminals R_1 and R_2 on the frame. A shaft, mounted on ball bearings, is used for turning the rotor. Three separate stator coils are wound in uniformly spaced slots punched in the frame. The coils are spaced 120° apart around the stator. A corresponding end of each coil is connected to a common point, and the other ends are connected respectively to terminals S_1, S_2, and S_3 on the frame.

The synchro motor or receiver is identical to the synchro generator, except that the rotor of the motor has a metal flywheel mounted on one end of the shaft. The purpose of this flywheel is to damp the tendency of the motor shaft to oscillate when power is first turned on, or when the shaft is turned suddenly. Therefore it is called the damper.

Figure 37-2 is the schematic diagram of a synchro generator or motor whose stator windings are connected in wye. Synchros with delta-connected stators are also employed. Any of the three different representations (symbols) shown may be used for wye-connected synchros. Figures 37-2*a* and 37-2*b* show the axis of the rotor in line with the axis of coil S_2. When the rotor is so positioned the synchro is said to be zeroed.

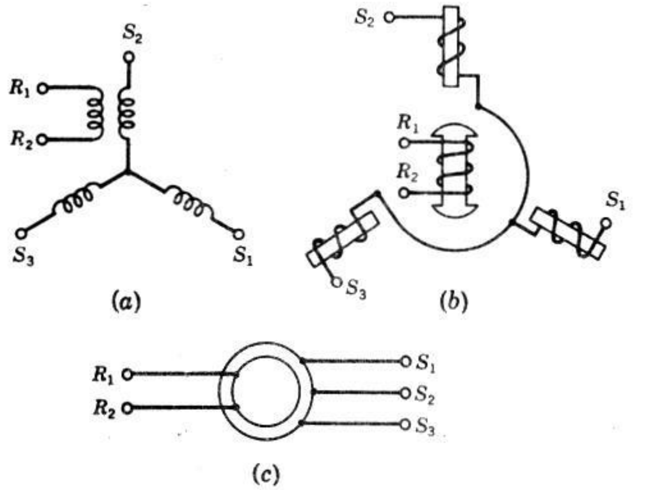


Fig. 37-2. Schematic diagrams of a synchro.

Operation of a Synchro System

Figure 37-3 is the circuit diagram of a synchro indicator system. A single-phase a-c line voltage is applied to the rotor windings of the generator G and motor M, connected in parallel. The stator windings are connected as shown, S_1 to S_1, S_2 to S_2, and S_3 to S_3. The rotor of M will follow the rotor of G to whatever position the G rotor is turned for this connection. For example, if the rotor of G is turned, say, 90° in a clockwise position, the rotor of M will also turn 90° clockwise, etc. If calibrated dials and pointers are properly positioned on the rotors of G and M, the pointer on M will follow the pointer on G and will indicate the angular displacement of the G rotor shaft.

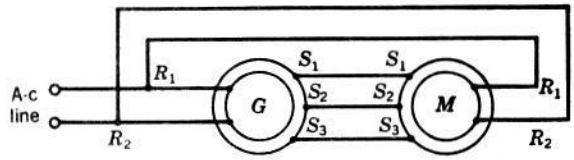


Fig. 37-3. A synchro generator connected to a synchro motor. The shaft of the synchro motor follows that of the generator and is used to indicate the position of the generator shaft.

Why does the motor shaft follow the generator? The answer to this question lies in the voltages induced in the stator windings and in the orientation of the magnetic fields in both motor and generator.

Consider first the operation of a synchro generator. The a-c line voltage applied to the G rotor winding sets up an alternating magnetic field about the rotor. This field cuts the stator windings and by transformer action induces a voltage in each of these windings. The rotor winding acts as the primary of a transformer. The stator windings act as three secondaries of this transformer. The voltages induced in the secondaries are either in phase or 180° out of phase with each other and with the voltage in the primary, depending on the position of the rotor. Hence the stator voltages do not constitute a three-phase system.

The amplitude of voltage induced in each secondary depends on the position of the rotor and is a function of the cosine of the angle between the axis of the rotor and the axis of the stator winding. The variation of voltage induced in each secondary, as the rotor is turned slowly, is therefore sinusoidal. Maximum voltage is induced in a secondary when its axis is parallel to the axis of the rotor. Minimum voltage is induced in a secondary when its axis is perpendicular to the axis of the rotor.

If there is no load connected to the secondary windings of the generator there is no magnetic field associated with any of the stator windings because there is no current through them. However, when the stator windings of the motor are connected to the stator windings of the generator, as in Figs. 37-3 and 37-4, there is current in each of the stator windings and there is a magnetic field associated with these windings. The arrows in Fig. 37-4 represent the direction of the magnetic field associated with each secondary winding for a rotor

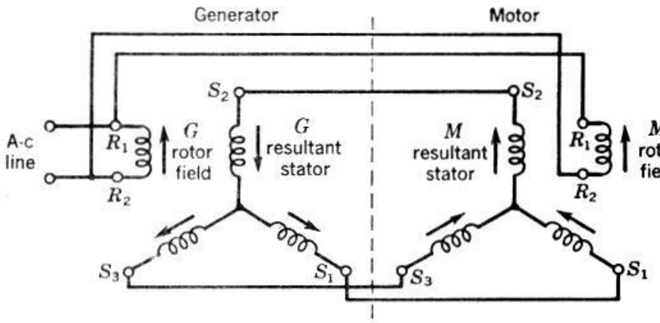


Fig. 37-4. Magnetic fields in a synchro system.

field which is parallel to the axis of S_2. The three secondary fields of the generator add vectorially, and their resultant field G is, according to Lenz's law, opposite (180° out of phase) in direction to the inducing magnetic field about the rotor.

Now consider the magnetic fields associated with the stator windings of the motor. Current through these windings will be opposite in direction to current through the synchro-generator stator windings. Since the windings of both generator and motor are in the same direction, the magnetic field associated with each stator winding on the motor is opposite in direction to the magnetic field associated with each corresponding stator field in the generator. Accordingly, the resultant magnetic field of the motor stators is opposite in direction to the resultant field of the generator stator, but is in the same direction as the magnetic field of the generator rotor.

To summarize our conclusions to this point:

A. In the synchro generator the three magnetic fields induced in the stator windings act as a single field, the resultant field, whose direction is opposite to that of the inducing field in the rotor.

B. In the synchro motor the resultant magnetic field associated with the stator windings takes the same direction as the field of the rotor of the generator.

Now let us see what happens to the rotor of the motor. For the connections shown in Figs. 37-3 and 37-4, the magnetic field about each rotor has the same direction. Now we know that a bar magnet which is free to turn takes the direction of a nearby magnetic field of a fixed magnet, as in Fig. 37-5. This fact is equally true of electromagnets. Hence the rotor field of the motor lines up with the stator field of the motor. Therefore, both rotor fields take the same direction, and the rotor of the motor lines up with the rotor of the generator.

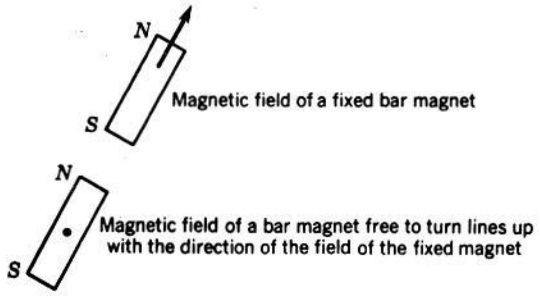


Fig. 37-5. How the poles of a magnet free to turn line up with the poles of a fixed magnet.

Figure 37-6 shows the effect of turning the generator rotor 60° clockwise. The resultant magnetic field about the stator windings of the generator also rotates 60° and is in direction opposite to the field about the rotor. The resultant magnetic field about the stator windings of the motor also rotates 60° clockwise but is in the same direction as the rotor field of the generator.

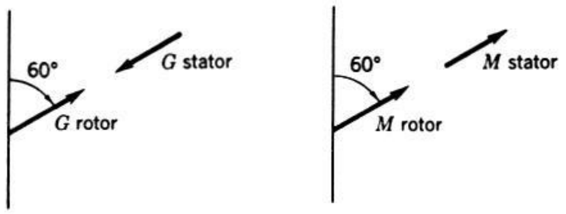


Fig. 37-6. Effect of moving the rotor of the generator 60° in a clockwise direction. The rotor of the motor also follows the 60° clockwise rotation of the generator and lines up with the G rotor.

Now the field about the motor rotor lines up with the resultant field about the stator windings of the motor, and the rotor of the motor also turns 60° clockwise, lining up with the rotor of the generator.

Similarly, it can be shown that for the connections in Fig. 37-3, the rotor of the motor follows in step with the rotor of the generator, as the generator rotor is turned from one position to another.

Reversing Rotor Connections

What is the effect on synchro action of reversing the connections R_1 and R_2 to the rotor winding of the motor, as in Fig. 37-7? Assume the connections are reversed as shown, before line voltage is applied to the rotors. Assume further that both rotors are lined up in the zero position (Fig. 37-8*a*) before voltage is applied. At the instant power is applied, the magnetic fields about the rotors would appear as shown by the arrows (Fig. 37-8*a*). The fields of the rotors are obviously 180° out of phase. Now, from our preceding discussion we know that the rotor fields of a synchro motor and generator line up in the same direction. The rotor of the motor must therefore rotate 180°, so that the magnetic fields of both rotors are in the same direction, as in Fig. 37-8*b*. When the motor rotor turns through 180°, the synchro system is again in equilibrium. Now as the rotor of the generator is turned, the rotor of the motor follows in the same direction, but always lags by 180°.

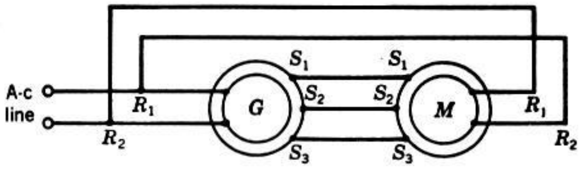
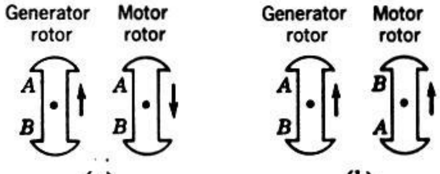


Fig. 37-7. Reversing rotor connections to synchro motor.



(*a*) (*b*)

Fig. 37-8. Reversing rotor connections to synchro motor causes motor rotor to lag generator rotor by 180°.

We may therefore conclude that reversing the rotor connections of the synchro motor introduces a 180° phase lag in the motor, but the rotor of the motor follows the rotation of the rotor of the generator.

Reversing Stator Connections S_1 and S_3

From our previous discussion it is apparent that the manner in which the rotor and stator of a synchro motor and generator are connected will affect the operation of the system. Let us analyze the effects of reversing stator connections S_1 and S_3, as in Fig. 37-9. We note that S_1 of the generator is connected to S_3 of the motor. S_3 of the generator is connected to S_1 of the motor. All other connections are as in Fig. 37-3. The resultant magnetic field of the generator has not been affected by the reversal of connections S_1 and S_3 on the motor. However, winding S_1 of the generator is now in series with winding S_3 of the motor. Hence winding S_3 of the motor will act as though it were winding S_1. Moreover, winding S_3 of the generator is in series with winding S_1 of the motor. Therefore, winding S_1 of the motor will act as though it were winding S_3. Now, if we turn the generator rotor from zero position (in zero position the axis of the rotor field is parallel to the axis of S_2 field), say 60° clockwise, the resultant magnetic field of the generator will take the position between S_2 and S_1 shown in Fig. 37-10. The resultant magnetic field of the motor will follow this rotation just as before, except that it will move counterclockwise from S_2 in the direction of S_3, since S_3 of the motor now acts like S_1. Similarly, any counterclockwise rotation of the generator rotor will cause a clockwise rotation of the motor rotor. We can conclude, therefore, that the effect of reversing stator connections S_1 and S_3 is to reverse the direction of rotation of the motor rotor, as compared with the direction of rotation of the generator rotor.

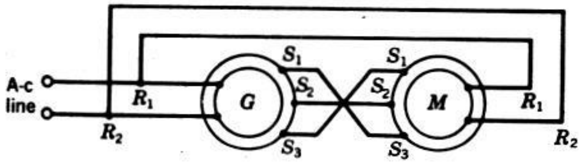


Fig. 37-9. Circuit for reversing stator connections S_1 and S_3.

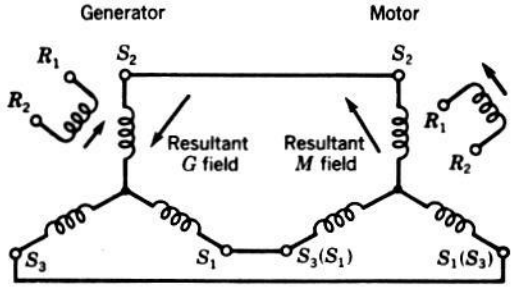


Fig. 37-10. Reversing stator connections S_1S_3 causes rotor of motor to turn in the opposite direction to rotor of the generator.

Shifting all stator connections in cyclic order, as in Fig. 37-11, will cause the motor rotor to rotate 240° clockwise, so that it always lags the generator rotor by 120°. However, rotation of both rotors will be in the same direction.

Electrical Zero

The term "electrical zero" is a standard position with relation to which the angular displacement of the rotor is measured. Electrical zero is defined as the position of the rotor for which the voltage between S_1 and S_3 is zero, and the voltage at S_2, with respect to S_1 or S_3, is in phase with that of R_1 with respect to R_2. The degrees through which the rotor angle turns is measured from electrical zero.

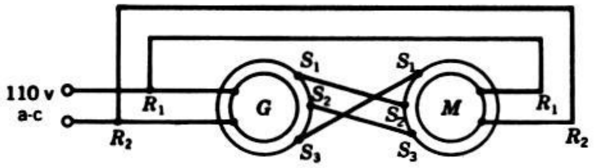


Fig. 37-11. Cyclic shift of stator connections.

The procedure for determining electrical zero takes this definition into account. To zero a selsyn system, first the synchro generator is zeroed. Then the synchro motor may be zeroed, using the generator as a standard of reference.

Differential Synchro

INTRODUCTORY INFORMATION

The Differential Synchro

In the preceding job we studied the characteristics of a synchro generator and synchro motor. We learned how these two components could be connected in a remote indicating system. There is another component in the synchro family, the differential synchro, which is also used as part of a remote indicating system. The differential synchro, like the synchro, comes in the form of a differential generator *DG* (transmitter) and a differential motor *DM* (receiver). The differential generator and differential motor are similar in construction except that the motor has a damper to eliminate its tendency to oscillate.

The differential synchro is constructed like the basic synchro, with some differences. Thus the stator of the differential synchro, like the stator of the synchro, is laminated and uniformly slotted to accommodate a three-coil winding. The coils are spaced 120° apart. Unlike the single-coil rotor of the basic synchro, the rotor of the differential synchro has a three-coil winding similar to the stator. The rotor core is slotted as in Fig. 38-1 to hold the three windings which are also spaced 120° apart. The schematic representations of a differential synchro are shown in Fig. 38-2. The differential synchro is a six-terminal device.

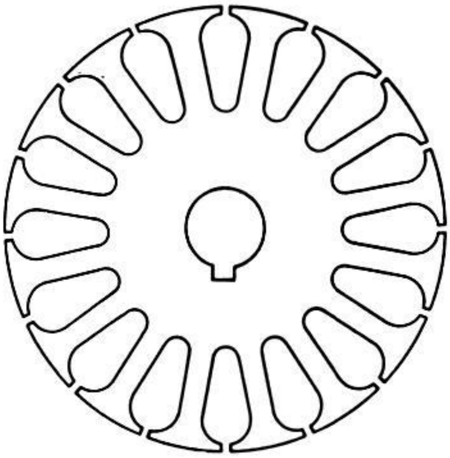


Fig. 38-1. Rotor-core differential synchro.

The stator *S* and rotor *R* windings act like the primary and secondary windings, respectively, of a transformer. Alternating current flowing in the primary (stator) induces a voltage in the secondary (rotor). When the rotor windings are terminated in a load, the voltages induced cause current to flow in the load and in the rotor windings, and there is a magnetic field associated with each of the rotor windings. The vectorial sum of the three magnetic fields is the resultant field associated with the rotor. The position of the resultant magnetic field of the rotor relative to the stator is determined by two factors, namely, the mechanical orientation of the rotor shaft relative to the stator and the electrical position of the field within the rotor windings.

Figure 38-3 shows the zero position of the differential synchro. We see that the axis of the R_2 winding is in line with the axis of the S_2 winding.

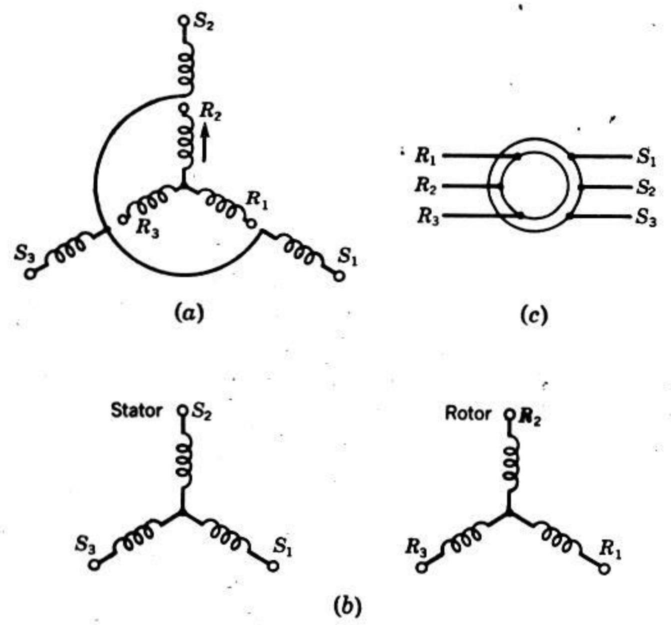


Fig. 38-2. Symbols used to represent the differential synchro.

Differential Synchro Generator Connected for Subtraction

The differential synchro generator is used when it is necessary to control a synchro motor *M* from two sources, namely a *DG* and a synchro generator *G*. Figure 38-4 shows a differential generator *DG* connected in an indicating system which employs also a synchro generator *G* and a synchro motor *M*.

A dial and pointer are attached to the motor. The dial on the motor acts as the *indicator*. The *M* indicator shows the effects of rotation of the *G* and *DG*. We should note that in this system, the *M* shaft is free to turn in response to positional information transmitted by the *G* and *DG*. The *G* and *DG* are each geared to a separate device whose angular rotation we wish the *M* to follow. The *G* will rotate only when the specific device to which it is geared rotates. The *DG* will rotate only when the specific device to which it is geared rotates.

The rotor winding of the *G* and *M* are connected as usual to a-c line voltage. The stator windings of the *DG* are connected respectively to the stator windings of the *G*. The rotor windings of the *DG* are connected to the stator windings of the *M*. It is evident therefore that the *DG* stator windings receive their excitation from the stator windings of the *G*.

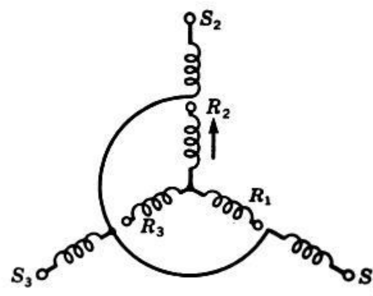


Fig. 38-3. Zero position of the differential synchro.

The rotor windings of the *DG* transmit excitation fields to the stator windings of the *M*. The position of the *M* shaft will then be determined by the position of both the *G* shaft and the *DG* shaft.

In this system, then, two inputs affect the position of the *M* shaft. One is the *G* shaft. As the *G* shaft is turned, the *G* generator transmits an electrical signal to the stator windings of the *DG*, which corresponds to the new angular position of the *G* shaft. The other input is the *DG* rotor. As this is turned, it affects the position of the *DG* stator field relative to the axis of the *DG* rotor. This relative shift between the axis of the rotor and the direction of the stator field of the *DG* is then transmitted to the synchro *M* and the rotor of the synchro *M* turns to align itself with this shift.

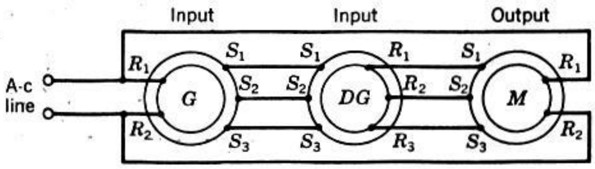


Fig. 38-4. Indicator system using a differential synchro generator connected for subtraction.

To understand the operation of the system let us analyze the effect of the *G* and *DG* on the *M* shaft. Suppose the system is at zero position, that is, the *G*, *DG*, and *M* are each set at electrical zero. The system is then at rest. Now assume that the *G* shaft is turned 60° clockwise, while the *DG* shaft is held fixed. We will show that the *M* shaft will also turn 60° clockwise.

When the *G* rotor is turned 60° clockwise from zero position, the direction of the magnetic field of the *G* rotor is also rotated 60° clockwise as in Fig. 38-5. The voltage induced

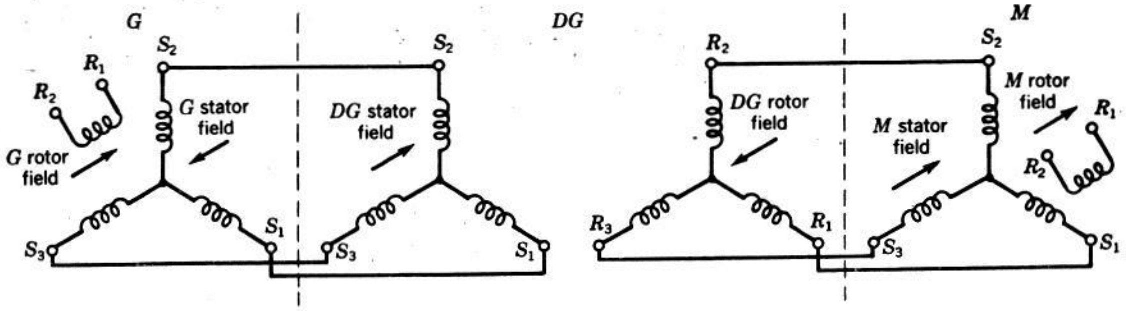


Fig. 38-5. Effect on motor of turning G shaft 60° clockwise, while holding DG shaft fixed at zero. The motor shaft will also turn 60° clockwise.

in the *G* stator causes current to flow through the *G* stator and its load. Hence by Lenz's law the magnetic field induced in the *G* stator opposes the inducing field in the rotor and the stator field of the generator is 180° out of phase with the rotor field of the generator, as shown. Similarly, since the stator winding of the generator is in series with the stator winding of the *DG*, the magnetic field associated with the *DG* stator is 180° out of phase with the stator field of the generator, and is as shown in Fig. 38-5. Now the stator field of the *DG* induces a field in the rotor windings of the *DG*. The *DG* rotor field is 180° out of phase with the *DG* stator field. Note the direction of the *DG* rotor field. Since the *DG* rotor field is in series with the stator field of the motor, the magnetic field of the *M* stator winding is 180° out of phase with the *DG* rotor field. We note that the field of the *M* stator is now in phase with the *G* rotor field, that is, it has rotated 60° clockwise. The *M* rotor field now aligns itself with the magnetic field of the *M* stator windings, and the *M* rotor turns 60° clockwise. Thus a 60° clockwise rotation of the *G* shaft is transmitted by the *DG* to the motor, and the motor shaft turns 60° clockwise also.

Figures 38-6 and 38-7 offer another view of the magnetic-field conditions in the synchro system which we are discussing. Thus Fig. 38-6 shows the direction of the rotor axis of the *G*, *DG*, and *R* and the direction of the stator field of the *DG*, while the system is at zero. In Fig. 38-7 we see the effect of rotating the *G* rotor 60° clockwise. In the *DG* the stator field is rotated 60° clockwise relative to the *DG* rotor axis. That is, the *DG* stator field is 60° to the right (clockwise) of the *DG* rotor axis. The stator field of the motor is also rotated 60° clockwise, and the *M* rotor takes the position of the *M* stator field.

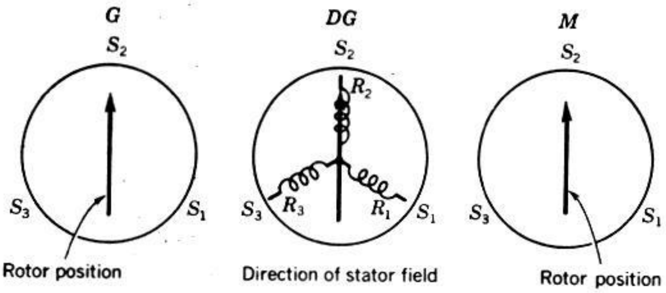


Fig. 38-6. Field and rotor positions in a synchro system at zero.

Similarly, we can show that a counterclockwise rotation of the *G* shaft while the *DG* shaft is held fixed will cause an equal counterclockwise angular rotation of the motor shaft. We can therefore conclude that for the connections of the system as shown in Fig. 38-5, the *M* shaft follows the rotation of the *G* shaft both in angular displacement and in direction.

Now, what is the effect, in the system of Fig. 38-5, of turning the *DG* shaft in a clockwise direction, while holding the *G* shaft fixed? We will see that the *M* shaft will turn in a counterclockwise direction. The angular displacement of the *M* shaft will be equal to the angular displacement of the *DG* shaft, but in the opposite direction. Refer to Fig. 38-8. We can see that when the *DG* shaft is turned 60° clockwise, the *DG* stator field is 60° to the left (counterclockwise) of the *DG* rotor axis. This is clearly shown in the equivalent diagram (Fig. 38-9). The *DG* generator will therefore transmit to the stator windings of the motor a magnetic field which will be 60° to the left of the *M* rotor axis. The *M* rotor will now align itself with the *M* stator axis by turning 60° to the left, that is, 60° counterclockwise.

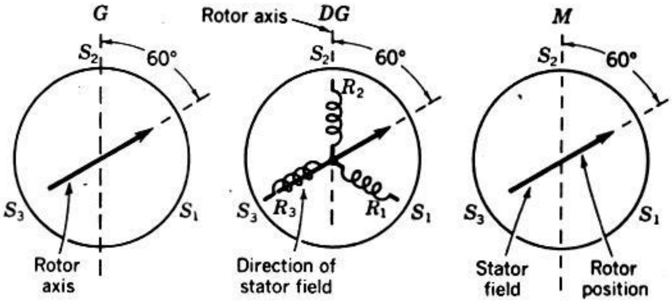


Fig. 38-7. Field and rotor position in a synchro system in which G rotor is turned 60° clockwise while DG rotor is held fixed.

Similarly, we can show for Fig. 38-5 that when the *G* rotor is held fixed and the *DG* rotor is turned, say, *B* degrees counterclockwise, the *M* rotor will turn *B* degrees clockwise.

For the connections of Fig. 38-4 the exact position of the *M* shaft for any rotation of the *G* and *DG* shafts can be determined exactly from these facts:

A. An *A*° clockwise or counterclockwise rotation of the *G* shaft will cause an *A*° clockwise or counterclockwise rotation, respectively, of the *M* shaft.

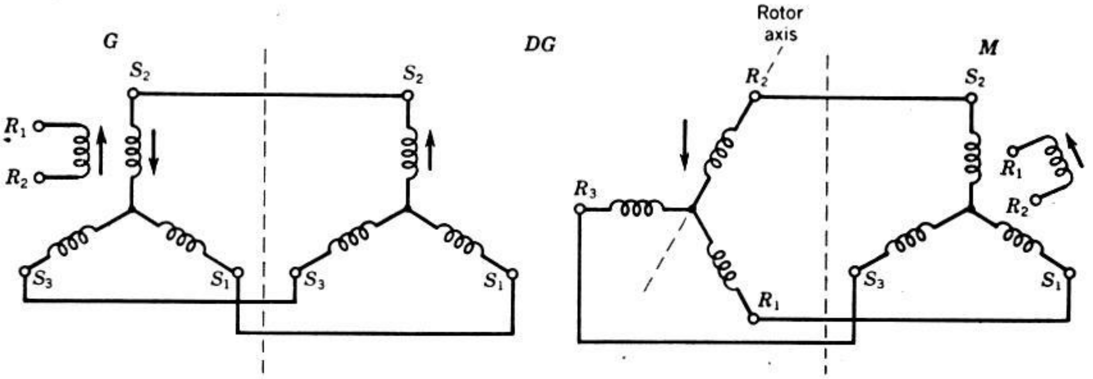


Fig. 38-8. Effect on motor of turning DG shaft 60° clockwise while holding the G shaft fixed at zero. The motor shaft will turn 60° counterclockwise.

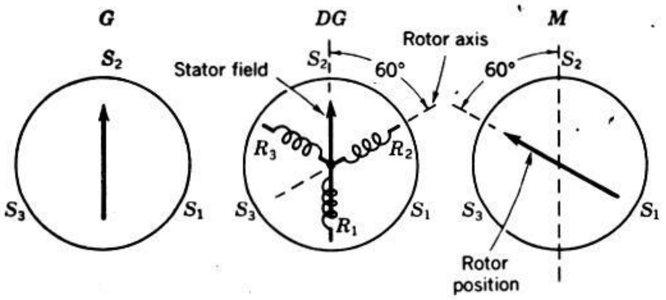


Fig. 38-9. Effect on motor of turning DG shaft 60° clockwise while holding the G shaft fixed at zero. The motor shaft will turn 60° counterclockwise.

B. A $B°$ clockwise or counterclockwise rotation of the *DG* shaft will cause a $B°$ counterclockwise or clockwise rotation, respectively, of the *M* shaft.

C. Let us designate as plus a clockwise rotation of any of the rotor shafts; as minus a counterclockwise rotation of any of the rotor shafts. Then the final position of the *M* shaft will be equal to the algebraic difference of *A* and *B*, that is, $M = (A - B)°$. Of course it will be necessary to choose the correct sign for *A* and *B* depending on the direction of rotation respectively of the *G* shaft and *DG* shaft. Finally, whether the direction of rotation of the *M* shaft is clockwise or counterclockwise will depend on whether the sign of $A - B$ is plus or minus, respectively.

For example, if the *G* shaft is turned 30° clockwise, $A = +30$. If the *DG* shaft is turned 60° clockwise, then $B = +60$. The position of the *M* shaft is $(A - B°) = (30 - 60)° = -30°$. Hence the *M* shaft will turn 30° counterclockwise.

Differential Synchro System for Addition

A three-component synchro team consisting of a *G*, *DG*, and *M*, connected as shown in Fig. 38-10, constitutes a system for addition. In this system, if the *G* shaft is rotated $A°$, and the *DG* shaft is rotated $B°$, then the *M* shaft takes the position $(A + B)°$, where $A + B$ is the algebraic sum of *A* and *B*. As in the preceding discussion, the plus sign represents a clockwise rotation, the minus sign a counterclockwise rotation. As in the preceding system, indicator *M* responds to positional information broadcast by the *G* and *DG*.

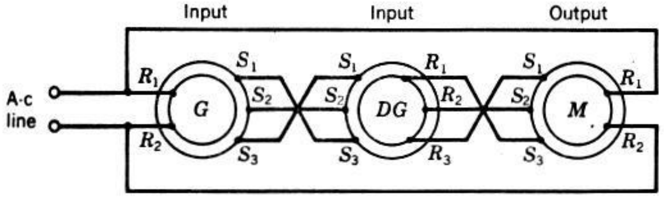


Fig. 38-10. Differential synchro generator connected for addition.

An analysis of this system would show that:

A. An $A°$ clockwise or counterclockwise rotation of the *G* shaft will cause an $A°$ clockwise or counterclockwise rotation respectively of the *M* shaft.

B. A $B°$ clockwise or counterclockwise rotation of the *DG* shaft will cause a $B°$ clockwise or counterclockwise rotation respectively of the *M* shaft.

C. The final angular position of the *M* shaft will be equal to $(A + B)°$. For example, if *A* is turned 60° counterclockwise, and *B* 75° clockwise, then $(A + B)° = (-60 + 75)° = +15°$, and the *M* shaft will turn 15° clockwise.

Differential Synchro Motor (*DM*) Connected to Show Difference of Two G Inputs

The differential motor is used as an indicator to show the sum or difference of two synchro generator *G* inputs. In this case the indicator dial and pointer are on the shaft of the *DM*. The position of the pointer on the *DM* shaft is then controlled by the positions of the shafts of G_1 and G_2.

A differential motor connected for subtraction is shown in Fig. 38-11. An analysis of this system would show the following:

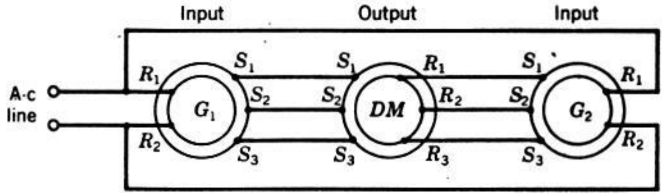


Fig. 38-11. A differential motor connected for subtraction.

A. An $A°$ clockwise or counterclockwise rotation of the G_1 shaft will cause an $A°$ clockwise or counterclockwise rotation respectively of the *DM* shaft.

B. A $B°$ clockwise or counterclockwise rotation of the G_2 shaft will cause a $B°$ counterclockwise or clockwise rotation respectively of the *DM* shaft.

C. The final position of the *DM* shaft is the algebraic difference of *A* and *B*, that is, $=(A - B)°$. For example, if the G_1 shaft is rotated 60° clockwise, and the G_2 shaft is rotated 60° clockwise, then $(A - B)° = (60 - 60)° = 0$, and the *DM* shaft would not move. If the G_1 shaft is rotated 60° clockwise, and the G_2 shaft is rotated 60° counterclockwise, then $(A - B)° = [60 - (-60)] = 120°$, and the *DM* shaft would rotate 120° clockwise.

Differential Synchro Motor Connected to Show the Sum of Two G Inputs

If the rotor leads R_1 and R_3 of the *DM* are reversed, so that R_1 and R_3 connect respectively to S_3 and S_1 of G_2, as in Fig. 38-12, then the *DM* is connected to show the sum of two *G* inputs. The following facts may be deduced:

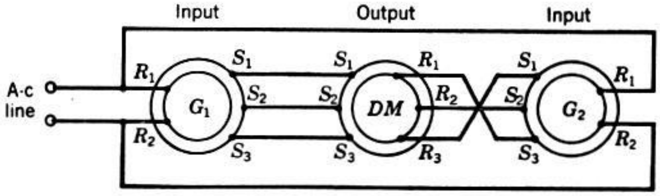


Fig. 38-12. A differential motor connected for addition.

A. An $A°$ clockwise or counterclockwise rotation of the G_1 shaft will cause an $A°$ clockwise or counterclockwise rotation respectively of the *DM* shaft.

B. A $B°$ clockwise or counterclockwise rotation of the G_2

shaft will cause a $B°$ clockwise or counterclockwise rotation respectively of the *DM* shaft.

C. The final angular position of the *DM* shaft will equal $(A + B)°$.

The Synchro Control Transformer and Its Use in Servomechanisms

INTRODUCTORY INFORMATION

Do Synchros Deliver Power to a Load?

The synchro components which we studied in the preceding jobs are intended for use in indicating systems. Very little power is required to turn the dial on the shaft of a synchro motor or on a differential motor. These components are therefore designed to produce little torque. When it is necessary to move a load, for example, position the rudder of a ship, a power device must be used.

Rotary devices (motors) are used to deliver power. Thus we can devise a system which will not only turn the rudder of a ship but hold the ship on a predetermined course, automatically correcting for any tendency of the ship to move off course. The mechanism which can accomplish this job is called a servomechanism, or simply a servo.

There are various types of servomechanisms and they are used in many applications, but all have certain characteristics in common. Thus a servo must be able to:

A. Receive an instruction for a specific job

B. Determine whether the job is being accomplished as directed

C. Correct the action if it has strayed from the desired result

A servomechanism, therefore, must exhibit a high degree of built-in intelligence. It must possess the ability to detect an error and to correct the error.

Servomechanisms utilize various control devices. Synchro control is but one of these. In this job, we will be concerned with a synchro-controlled servo system.

A synchro-controlled servo used for steering a ship is shown in block diagram in Fig. 39-1. In this system, the helmsman sets the ship's course by turning a small handwheel. The handwheel turns the shaft of a synchro generator. The signal developed in the stator windings of the generator is transmitted to a device called a control transformer. The control transformer compares the direction of the ship's course with the desired setting of the synchro *G* and develops an error

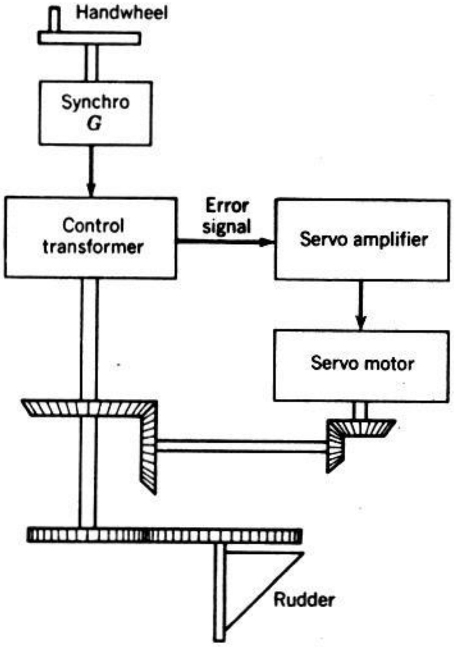


Fig. 39-1. A positioning servomechanism.

signal when the ship is not on course. This error signal is amplified by an electronic servo amplifier whose output actuates a servo motor. The motion of the servo motor is mechanically transmitted by a gearing arrangement to turn the ship's rudder. The position of the rudder is similarly transmitted to the shaft of the control transformer so that the new position of the rudder may be compared with the setting of the handwheel. As the rudder turns in the required direction, the error signal decreases and finally becomes zero when the ship is on course.

The action of wind or tide may turn the rudder, forcing the ship off course. This action is now transmitted to the shaft of the control transformer, where an error signal is again developed which reactivates the servo motor and causes it to turn in a proper direction to bring the ship back on course.

It is apparent that the servo motor must be able to turn in either direction in responding to the error signal developed by the control transformer.

The Control Transformer

The "brain" in this servomechanism is a device called a synchro control transformer. The control transformer is used to detect the difference between the relative positions of two shafts which are free to rotate. We note that this is a new addition to the synchro family. Now what is a *CT* and how does it work?

The *CT* may be compared to a synchro motor. Thus it has a two-terminal rotor and a three-terminal stator. The stator of the *CT* is similar in construction to the stator of other synchro motors, that is, it has three slotted windings spaced 120° apart. However, unlike other synchro stators, the *S* windings of the *CT* are high-impedance windings which limit the flow of current through them.

The rotor of the *CT* is round. The rotor winding is a continuous winding laid in uniformly spaced slots. The rotor and its winding are so constructed that the magnetic field of the stator does not exert any torque on the rotor shaft. The shaft turns only as a result of coupling to the shaft of an external motor. The rotor shaft turns on ball bearings. Brushes riding on two slip rings bring out the rotor signal.

Figure 39-2 shows two symbols used to represent the *CT* in circuit diagrams.

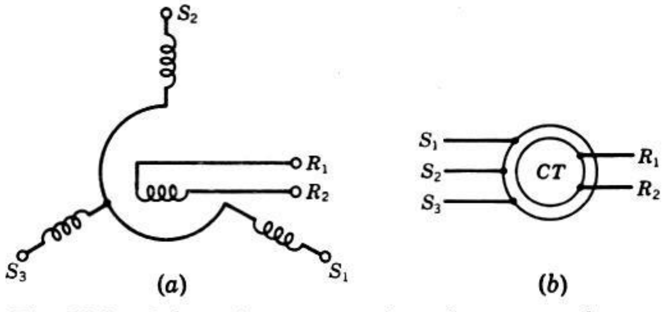


Fig. 39-2. Schematic representations for a control transformer.

Unlike the synchro motor, the rotor windings of the *CT* do not receive excitation from the a-c line. Instead the rotor windings are used to transmit a signal voltage (error signal) induced in them by the action of the *S* windings.

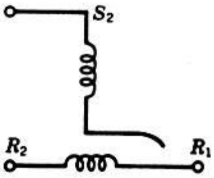


Fig. 39-3. Control transformer aligned at electrical zero.

Figure 39-3 shows the zero position of a *CT*. The rotor coil axis is at right angles to the S_2 winding axis. We know that the voltage induced in the rotor by the magnetic field associated with the *S* windings will be minimum when the *S* magnetic-field axis is at right angles to the axis of the rotor winding. In the rotor position shown in Fig. 39-3, minimum voltage is induced in the rotor since the *S* magnetic-field axis is perpendicular to the axis of the S_2 winding. Now if the direction of the magnetic field of the *S* windings changes, or if the position of the rotor changes, the amplitude of voltage induced in the rotor windings will be proportional to the cosine of the angle between the rotor axis and the *S* field axis.

We know that the polarity of the voltage induced in the rotor windings depends on the direction in which the inducing magnetic field cuts the *R* windings. Suppose that the *S* field is rotated, say 30° clockwise from its zero position, as in Fig. 39-4*a*. Now assume that the voltage induced in the rotor windings has the polarity shown in Fig. 39-4*b*. If instead of rotating the *S* field in a clockwise direction, we had rotated it 30° counterclockwise as in Fig. 39-4*c*, the voltage induced in the rotor would have had the opposite polarity (Fig. 39-4*d*). The reason is that the magnetic field is cutting the coil in a direction opposite to what it was before.

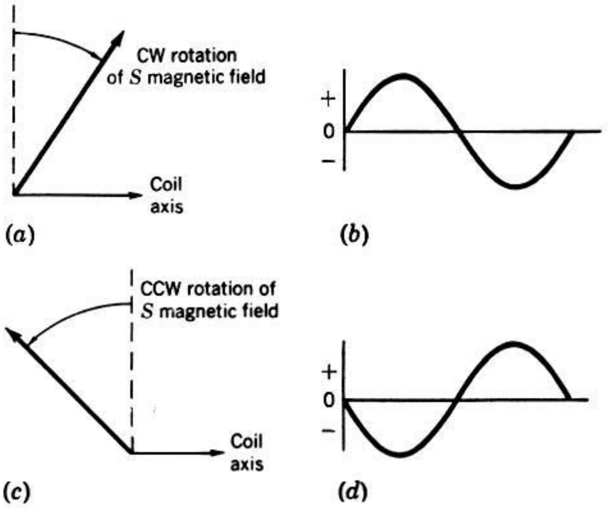


Fig. 39-4. Effect of a clockwise and a counterclockwise rotation of the magnetic field associated with the S windings on the polarity of the voltage induced in the rotor windings of a control transformer.

The same effect can be obtained by holding the *S* field fixed and turning the rotor. It should be noted that regardless of the position of the *S* field or the rotor, as long as their relative position is such that the *S* magnetic field is at right angles to the axis of the rotor, the voltage induced in the rotor windings will be minimum (zero).

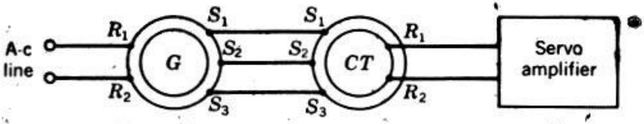


Fig. 39-5. Connecting a synchro generator to a control transformer.

Figure 39-5 shows how a synchro generator is electrically connected to a *CT*. The rotor of the generator receives its power from the a-c line. The stator windings of the *G* are connected to the stator windings of the *CT*. The rotor winding of the *CT* is coupled to the input of a servo amplifier.

Assume that the *G* and *CT* are both at electrical zero. The output across R_1R_2 of the *CT* is zero (minimum). If the shaft of the *CT* is held fixed while the *G* rotor is rotated 60° clockwise, the magnetic field of the stator windings of the *CT* will also be rotated 60° clockwise. The amplitude of voltage induced in the rotor winding of the *CT* will be proportional to the cosine of 60°, and it will be in phase with the a-c line voltage across R_1R_2. As *G* is rotated clockwise so that it is 90° away from zero, the voltage induced in the *R* winding of the *CT* will be maximum. Now by rotating the shaft of the *CT* 90° in a clockwise direction we can bring the output voltage back to zero.