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1 Construction and Working

AC servo motor has a stator and a rotor. The stator core has a hollow cylindrical shape. It is made up of sheet steel stampings. The stampings are in the shape of circular rings with slots in the inner periphery. The stampings are stacked together to the required length. The core is supported by an outer frame called yoke or stator frame. The slots carry the stator windings which are of distributed type. A distributed winding is required for ensuring sinusoidal flux distribution in the air gap. The stator is wound for two or four poles for 50 Hz supply, and for motors to be operated with 400 Hz to 1000 Hz supply, the stator may be wound for even 10 poles. The constructional details of the stator of a two-phase servo motor are shown in Fig.1 . The stator winding is done by properly connecting the coils provided in the slots. The arrangement of the armature coils depends on the number of poles (or frequency) for which the machine is designed.

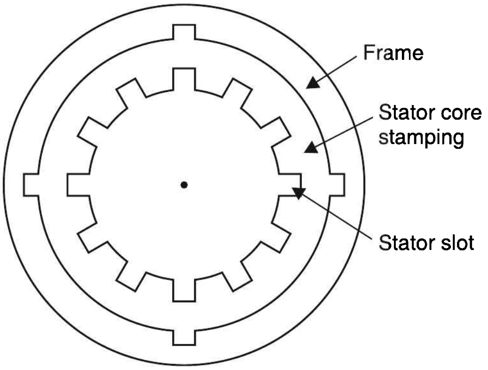


Fig. 1 **Constructional details of the stator of an AC servo motor**

For a two-pole motor, coils for a pair of poles are placed in dimetrically opposite slots. For motors with higher number of poles, the coils of each pole pair are placed in slots that are at 180° electrical apart [Electrical degree = (number of poles/2) × mechanical degree]. Servo motor has two stator windings: reference winding and control winding. These two windings form the two phases of the servo motor. The voltages in these two phases have 90° phase difference.

There is another type of stator construction in which the stator windings are provided on salient poles fixed on the stator frame. The stator consists of two pole pairs such that their axes are at 90° apart in space. Reference winding is housed on two dimetrically opposite poles and control winding on the other set of poles. The structure is shown in Fig. 2 .. The pole body is of laminated structure.

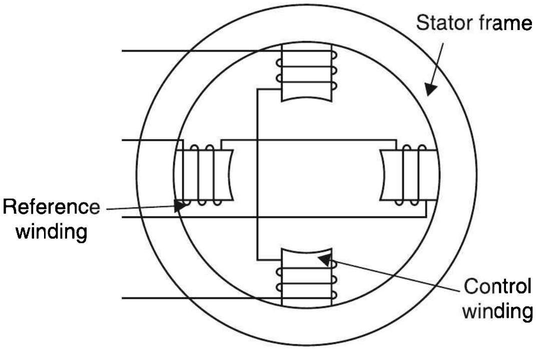


Fig. 2 **Stator with winding on projecting poles**

There are basically three different types of rotors used for two-phase AC servo motors: squirrel cage type, solid iron type and drag cup type. The squirrel cage type has a thick cylindrically shaped rotor. The rotor core is made up of sheet steel stampings. Along the periphery of the ring-shaped stampings, holes are provided as shown in Fig. 3. The stampings are stacked to the appropriate length so that the holes are along the axial direction. Thick circular copper bars are inserted in the holes. These bars are short circuited at both ends with thick rings of conducting material. Thus, the rotor bars with short-circuited end rings form a closed circuit for the rotor current to flow. All rotor bars are parallel to each other. The rotor winding is usually skewed by one slot pitch or more to avoid cogging that may occur due to magnetic force of attraction. In solid iron rotor construction, no winding is provided on the rotor. The rotor is made up of material having good conductivity and magnetic permeability. It has a shape of thin cylinder.

The torque developed in solid iron rotor type motor is less than that developed in squirrel cage rotor type motor. Cogging does not occur in such motors. The diameter of the rotor should be as small as possible to have minimum rotational inertia.

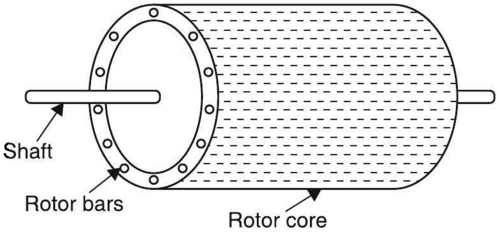


Fig. 3 **Squirrel cage rotor**

Another popular type of AC servo motor is one with drag cup rotor. The constructional details of drag cup AC servo motor are shown in Fig. 4.

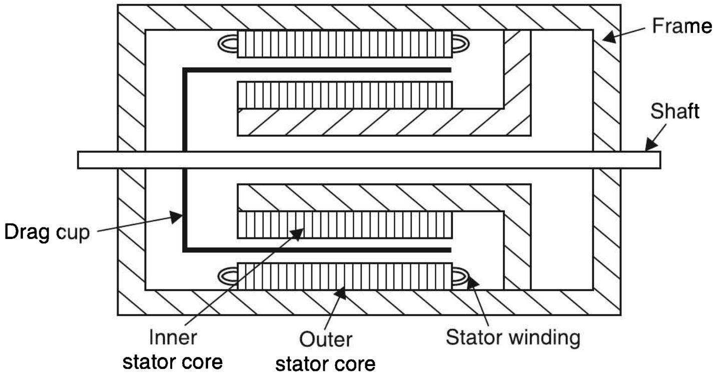


Fig. 4 **Constructional details of drag cup AC servo motor**

The drag cup motor has an outer stator core carrying the winding and an inner stator core. The outer stator core is supported by the motor frame. Both inner and outer stator cores are cylindrical in shape and made up of laminated steel sheets. The inner stator core is also supported by the motor frame. The drag cup is mounted on the shaft. The drag cup is able to rotate freely in the air gap between the inner and the outer stator cores. The drag cup is made up of conducting material. It is called drag cup as it has the shape of a cup. It is in the form of a hollow cylinder with one side open. It is very thin and light, so the inertia is very small and considerable torque can be obtained. The air gap between the inner stator core and the outer stator core should be minimum. Compared with solid iron and squirrel cage rotors, drag cup rotor has higher effective air gap. AC servo motor is represented as shown in Fig.5

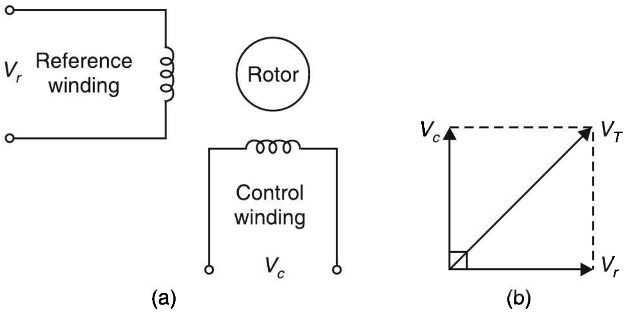


Fig. 5 **(a) Representation of servo motor, and (b) phasor diagram of voltages**

The voltage ratings of reference and control windings need not be equal. Usually the reference voltage is kept constant and control voltage is varied according to the error signal.

For speed or position control applications, speed or position error is first amplified by a servo amplifier. The amplified voltage is then applied to the control winding. The speed is directly proportional to control voltage and the polarity of the control voltage decides the direction of rotation of the rotor. The major power is supplied by the reference winding and power supplied by the control winding is very less. This results in smaller size and lesser weight for the servo amplifier. For obtaining 90° phase difference between control voltage and reference voltage, a capacitor is connected in series with the reference winding. This phase shift can also be achieved by using a phase shift circuit in the servo amplifier circuit. As the input impedance of the servo motor is highly inductive, the power factor is very low. To improve the power factor, a resonating capacitor is connected across the output terminals of the servo amplifier. The servo motor with servo amplifier is shown in Fig. 6

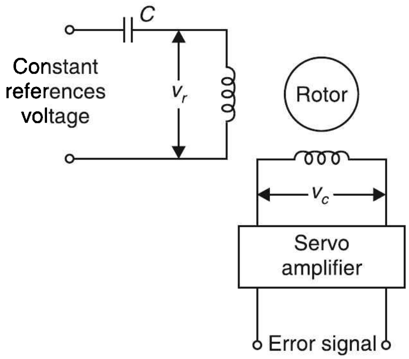


Fig. 6 **Servo motor with servo amplifier**

When the windings are energised, currents flow through them. As the voltages have 90° phase shift, the currents also have 90° phase difference. These currents establish fluxes in the air gap with 90° phase difference as shown in Fig. 7 . Let the flux produced by the control and reference windings have the same maximum value Φ_m and vary sinusoidally.

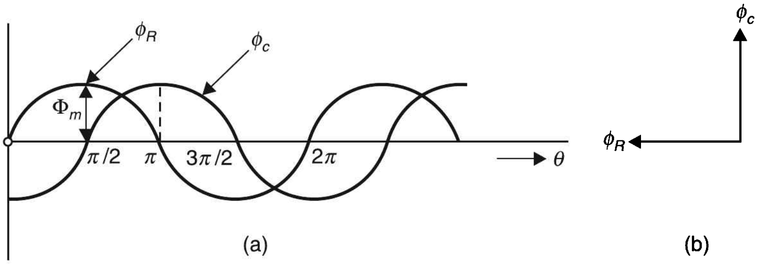


Fig. 7 (a) Flux waveforms, and (b) positive directions of fluxes

$$\phi_R = \Phi_m \sin\theta$$

$$\phi_c = \Phi_m \sin\left(\theta - \frac{\pi}{2}\right)$$

At $\theta = 0$

$$\phi_R = 0$$

$$\phi_c = -\Phi_m$$

The resultant flux, $\phi_R = \Phi_m$

The resultant flux is Φ_m and it is directed downwards as shown in Fig.8.a

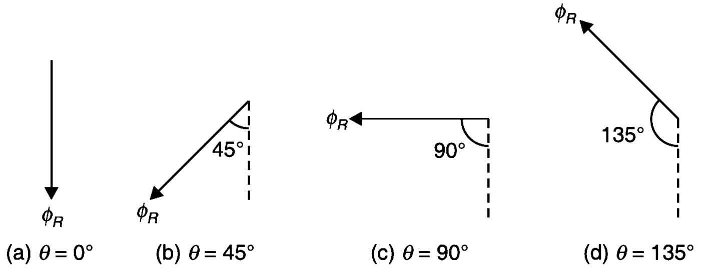


Fig. 8 Resultant flux and its relative locations at different values of θ

At $\theta = 45°$

$$\phi_R = \frac{\Phi_m}{\sqrt{2}}$$

$$\phi_c = -\frac{\Phi_m}{\sqrt{2}}$$

$\therefore$ $\phi_R = \Phi_m$

The resultant flux is shown in Fig.8.b

At $\theta = 90°$

$$\phi_R = \Phi_m$$

$$\phi_c = 0$$

$$\phi_R = \Phi_m$$

and is shown in Fig. 8. c.

For $\theta = 135°$

$$\phi_r = \frac{\Phi_m}{\sqrt{2}}$$

$$\phi_c = -\frac{\Phi_m}{\sqrt{2}}$$

$$\therefore \qquad \phi_R = \Phi_m$$

and has the direction shown in Fig.8.d

Proceeding in this way, we can see that the resultant flux has a constant magnitude and completes one rotation when one cycle of the input voltage is completed. For unbalanced voltage in magnitude, the magnitude of the resultant flux will only change, but its speed of rotation remains same. The speed of the rotating magnetic field is given by

$$N_S = \frac{2f}{P} \text{ rps}$$

where

f = frequency of the supply
P = number of poles

This rotating magnetic field induces voltage in the rotor conductors and current flows through the rotor circuit as it is a closed circuit. The interaction of the rotating flux with the rotor current makes the rotor to move. The production of torque is possible only if there exists a relative velocity between the rotating magnetic field and the rotor. So the rotor speed (N) is less than N_S. Thus, for the operation of the AC servo motor, there should be a slip defined as:

$$S = \frac{N_S - N}{N_S}$$

.2 Analysis of Two-Phase AC Servo Motor

In the previous section, the working of the servo motor was explained with the assumption that the motor is operated with balanced two-phase voltages. But in actual practice, the voltages need not be exactly balanced. The reference voltage is fixed and the control voltage is variable in servo applications. The analysis of servo motor supplied with unbalanced two-phase voltage is presented in this section. The concept of symmetrical components is used for the analysis.

Theory of operation based on symmetrical components

Consider a two-phase servo motor supplied with unbalanced voltages as shown in Fig.9). The fixed reference voltage, V_r and variable control voltage, V_c are not equal in magnitude and their phase difference is $\theta°$.

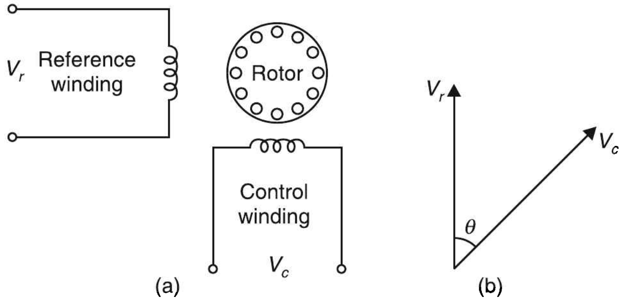
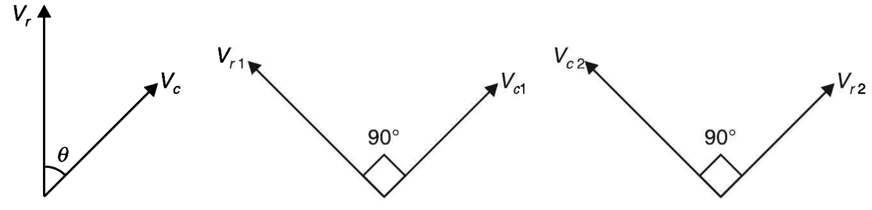


Fig. 9 (a) Two-phase AC servo motor, and (b) phasor diagram

Any unbalanced system of voltages can be represented by three symmetrical components: positive sequence, negative sequence and zero sequence components. The positive sequence voltages have three voltages equal in magnitude and displaced by 120° in forward direction, producing torque in the same direction. The negative sequence voltages are also of equal magnitudes and phase shift of 120° from each other, but producing torque in reverse direction. The zero sequence components are equal in magnitude and have same direction. In two-phase unbalanced system, only positive sequence and negative sequence components are present. The reference voltage and control voltage can be resolved into positive sequence components V_{r_1} and V_{c_1} and negative sequence components V_{r_2} and V_{c_2}. They are shown in Fig.10. For two-phase system, the phase difference is 90° instead of 120° as shown in Fig.10 .



(a) Terminal voltages (b) Positive sequence (c) Negative sequence

Fig. 10 **Symmetrical components of V_r and V_c**

The positive sequence components have equal magnitudes and 90° phase difference, and rotates in CCW direction. The negative sequence components with equal magnitudes and phase difference 90° rotate in clockwise direction. The sequence components of reference voltage are given by

$$V_{r_1} = \frac{1}{2}\,(V_r + JV_c)$$

$$V_{r_1} = \frac{1}{2}\,(V_r + JV_c)$$

In terms of symmetrical components, the reference winding and control winding voltages are given by

$$V_r = V_{r_1} + V_{r_2}$$

$$V_c = V_{c_1} + V_{c_2} = aV_{r_1} + a^3V_{r_2} \qquad (a = 1\ \angle{-90} = -J,\ a^3 = 1\ \angle 90 = J)$$

$$\therefore \quad V_c = -JV_{r_1} + JV_{r_2}$$

Thus, both reference and control voltages may be considered to have two components with 90° phase shift. The positive sequence components V_{r_1} and V_{c_1} produce a revolving magnetic field of constant magnitude in the forward direction. This rotating field interacts with the rotor current and produces a torque, T_f, in forward direction. The negative sequence components V_{r_2} and V_{c_2} establish a rotating magnetic field of constant magnitude in the backward direction. This magnetic field interacts with the rotor current to develop torque T_b in the backward direction. The net torque on the rotor is the difference between T_f and T_b, and the rotor moves in the direction of higher torque among T_f and T_b. A schematic diagram for representing the servo motor based on the above analysis is shown in Fig.11 . The reference and control windings are split into two pairs as shown in the figure. The rotor is assumed to be consisting of two fictitious rotors which are mechanically coupled. By using this technique, we can treat the AC servo motor operated with unbalanced voltages as equivalent to two motors operated with balanced voltages.

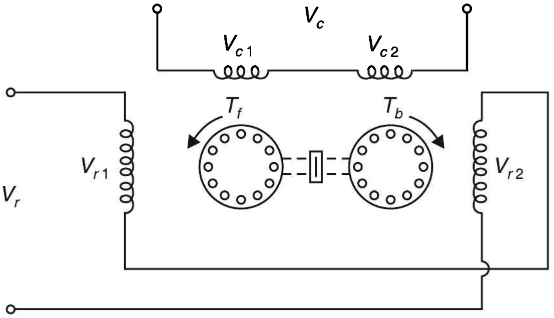
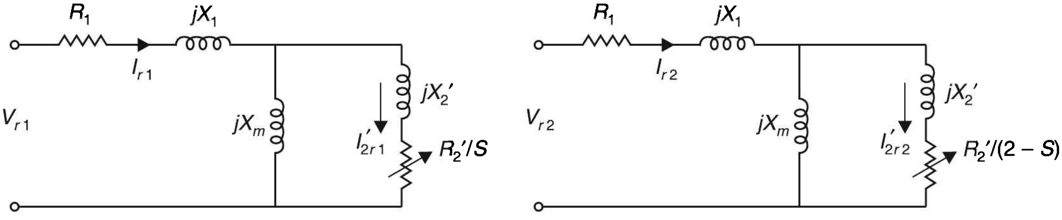


Fig. 11 Two-phase AC servo motor

Equivalent circuit of AC servo motor

For the analysis of the servo motor based on the symmetrical components, two equivalent circuits are needed. One circuit represents the motor for positive sequence voltages and other for negative sequence voltages. The equivalent circuits are shown in Fig.12 .. It is assumed that the core loss is zero.



(a) Positive sequence equivalent circuit (b) Negative sequence equivalent circuit

Fig. 12 **Equivalent circuit of two-phase AC servo motor**

In the above circuit;

R_1 = stator winding resistance/phase

X_1 = stator leakage reactance/phase

X_m = magnetising reactance/phase

X_2' = leakage reactance of rotor referred to stator

R_2' = resistance of rotor referred to stator

I_{r_1} = positive sequence input current

I'_{2r1} = positive sequence rotor current referred to stator

I_{r2} = negative sequence input current

I'_{2r2} = negative sequence rotor current referred to stator

S = slip

Torque equation

The torque equation can be derived by using the equivalent circuit of AC servo motor shown in Fig.12 . Consider Fig. 12.a

The positive sequence impedance of the servo motor is,

$$z_p = R_1 + jX_1 + \frac{jX_m\left(\frac{R_2'}{S} + jX_2'\right)}{\frac{R_2'}{S} + j(X_m + X_2')}$$

The input current,

$$I_{r1} = \frac{V_{r1}}{z_p}$$

Rotor current,

$$I'_{2r1} = I_{r1}\frac{jX_m}{\frac{R_2'}{S} + j(X_m + X_2')}$$

Power developed by the positive sequence current,

$$P_1 = 2(I'_{2r1})^2\frac{R_2'}{S}$$

∴ Torque developed,

$$T_f = \frac{P_1}{\omega_s} \text{ N-m}$$

where ω_s is synchronous speed in rad/sec.

Consider the equivalent circuit shown in Fig. 12.b . The negative sequence impedance of the servo motor is,

$$Z_n = R_1 + jX_1 + \frac{jX_m\left(\frac{R_2'}{2-S} + jX_2'\right)}{\frac{R_2'}{2-S} + j(X_m + X_2')}$$

The input current,

$$I_{r2} = \frac{V_{r2}}{Z_n}$$

Rotor current,

$$I'_{2r2} = I_{r2}\frac{jX_m}{\dfrac{R'_2}{2-S} + j(X_m + X'_2)}$$

∴ The power developed by the negative sequence current,

$$P_2 = 2\cdot(I'_{2r2})^2\frac{R'_2}{2-S}$$

The backward torque developed,

$$T_b = \frac{P_2}{\omega_S}$$

The resultant torque developed by the motor,

$$T = T_f - T_b$$

The currents in the windings are given by

$$I_r = I_{r1} + I_{r2}$$

$$I_c = -jI_{r1} + jI_{r2}$$

For balanced applied voltage, the equivalent circuit is shown in Fig. 13.

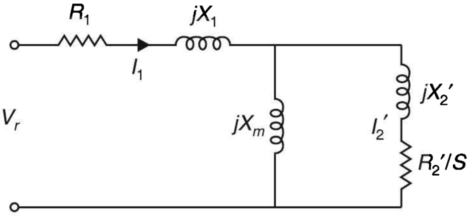


Fig. 13 Equivalent circuit of servo motor applied with balanced voltages

For balanced applied voltage

$$V_r = V_c, \quad \theta = 90°$$

$$Z_1 = R_1 + jX_1 + \frac{jX_m\left(\dfrac{R'_2}{S} + jX'_2\right)}{\dfrac{R'_2}{S} + j(X_m + X'_2)}$$

$$I_1 = \frac{V_r}{Z_1}$$

$$I'_2 = I_1\frac{jX_m}{\dfrac{R'_2}{S} + j(X'_2 + X_m)}$$

Power developed,

$$P = 2I_2'^2 \frac{R_2'}{S}$$

Torque developed,

$$T = \frac{P}{\omega_s} \text{ N-m}$$

3 Torque–Speed Characteristics of Servo Motor

In many servo applications, the reference winding is supplied with constant rated voltage and control winding is energised with a varying voltage from an amplifier. The reference voltage is 90° out of phase with control voltage. Under this condition the unbalance in the phase voltages is only in magnitude.

Let $$m = \frac{V_c}{V_r}$$

Then, $$V_c = -J_m V_r$$

$$V_{r1} = \frac{V_r}{2} (1 + m)$$

$$V_{r2} = \frac{V_c}{2} (1 - m)$$

A set of torque–speed curves for a two-phase servo motor corresponding to various values of control voltage expressed as a fraction of the control voltage and the reference voltage are shown in Fig. 14.

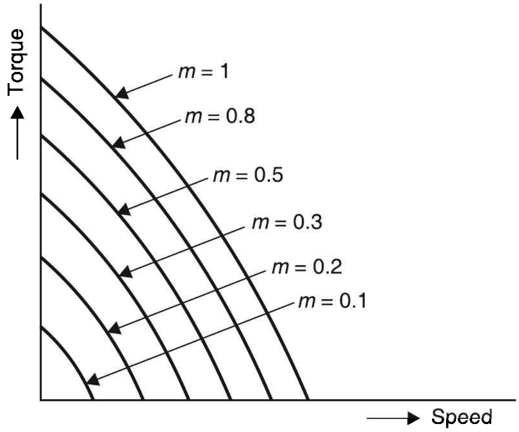


Fig. 7.14 Torque–speed characteristics of servo motor

Figure 15 depicts the torque vs *m* with slip as a parameter.

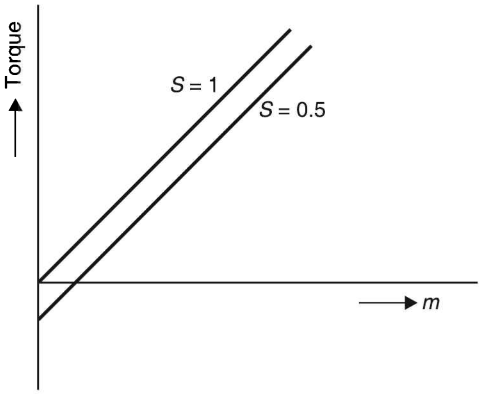


Fig. 15 Torque vs *m* characteristics