Single-Phase Series Motor (Universal)

The single-phase series motor is a commutator-type motor. If the polarity of the line terminals of a dc series motor is reversed, the motor will continue to run in the same direction. Thus, it might be expected that a dc series motor would operate on alternating current also.

The direction of the torque developed in a dc series motor is determined by both filed polarity and the direction of current through the armature($T \propto \Phi i_a$). Let a dc series motor be connected across a single-phase ac supply. Since the same current flows through the field winding and the armature, it follows that ac reversals from positive to negative, or from negative to positive, will simultaneously affect both the field flux polarity and the current direction through the armature. This means that the direction of the developed torque will remain positive, and rotation will continue in the same direction. Thus, a series motor can run both on dc and ac.

Motor that can be used with a single-phase ac source as well as a dc source of supply voltages are called **universal motor**. However, a series motor which is specifically designed for dc operation suffers from the following drawbacks when it is used on single-phase ac supply:

1. Its efficiency is low due to hysteresis and eddy-current losses.

2. The power factor is low due to the large reactance of the field and the armature winding.
3. The sparking at the brushes is excessive.

In order to overcome these difficulties, the following modifications are made in a d.c. series motor that is to operate satisfactorily on alternating current:

- The field core is constructed of a material having low hysteresis loss. It is laminated to reduce eddy-current loss.
- The field winding is provided with small number of turns. The field-pole areas is increased so that the flux density is reduced. This reduces the iron loss and the reactive voltage drop.
- The number of armature conductors is increased in order to get the required torque with the low flux.
- In order to reduce the effect of armature reaction, thereby improving commutation and reducing armature reactance, a compensating winding is used.

  The compensating winding is put in the stator slots. The axis of the compensating winding is 90° (electrical) with the main field axis. It may be connected in series with both the armature and field as shown in fig.1 In such a case the motor is conductively compensated.

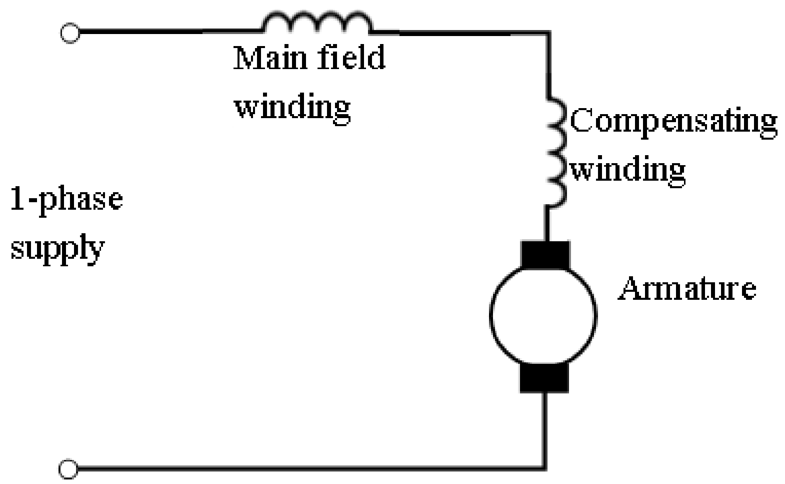

Figure. 2

The compensating winding may be short circuited on itself, in which case the motor is said to be inductively compensated (fig.2)

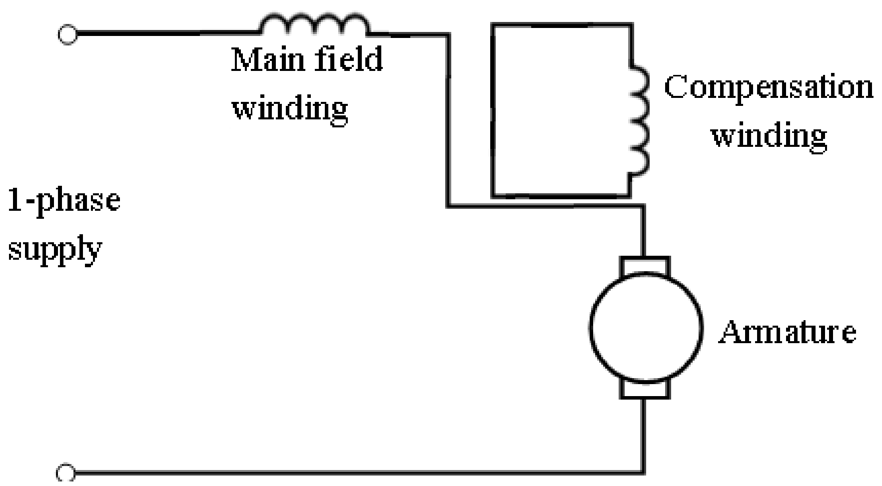

Fig. 2. Series motor with inductively compensated winding

- The armature of universal motor is of the same construction as ordinary series motor. In order to minimize commutation problems, high resistance brushes with increased brush area are used.

The universal motor is simply, and cheap. It is used usually for rating not greater than 750 W.

The characteristics of universal motor are very much similar to those of d.c. series motors, but the series motor develops less torque when operating from an a.c. supply than when working from an equivalent d.c. supply. The direction of rotation can be changed by interchanging connections to the field with respect to the armature as in d.c. series motor.

Speed control of universal motors is best obtained by solid-state devices. Since the speed of these is not limited by the supply frequency and may be as high as 20,000 r.p.m. (greater than the maximum synchronous speed of 3000 r.p.m. at 50 Hz), they are most suitable for applications requiring high speeds.

Applications

There are numerous applications where universal motors are used, such as portable drills, hair dryers, grinders, table-fans, blowers, polishers, kitchen appliances ets. They are also used for many other purposes where speed control and high values of speed are necessary. Universal motors of a given horse power rating are significantly smaller than other kinds of a.c. motors operating at the same frequency.

Phasor Diagram of a.c. Series Motor

The schematic diagram and phasor diagram for the conductively coupled single-phase ac series motor are shown in fig. 3

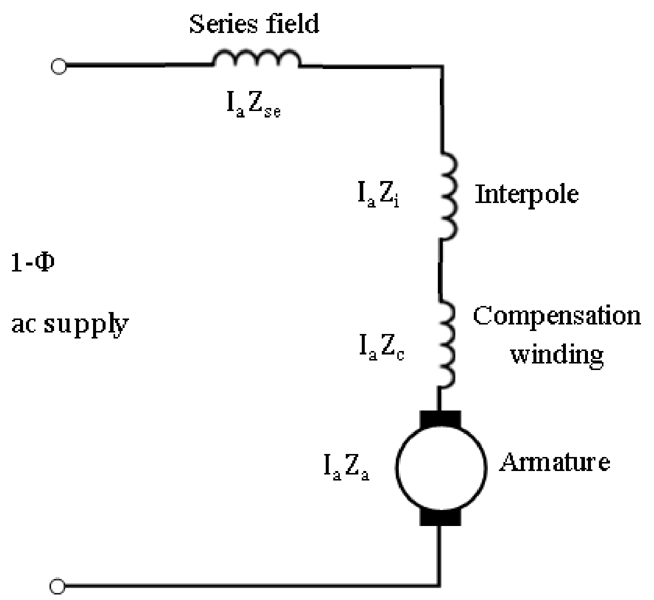

Fig. (3-a). Schematic diagram of conductively coupled ac series motor.

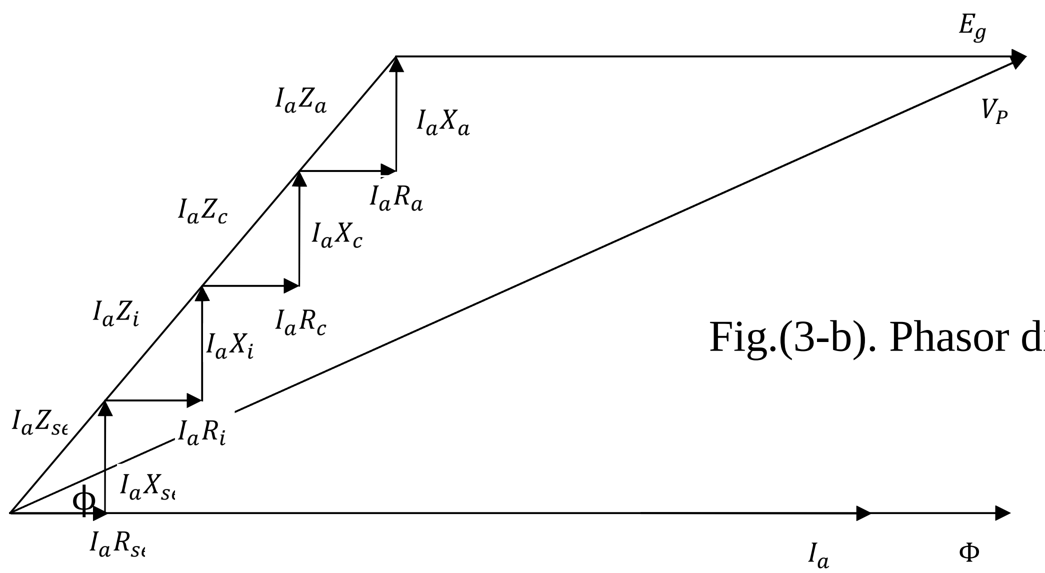

Fig.(3-b). Phasor diagram

The resistance drops $I_aR_{se},, I_aR_i, I_aR_c$ and I_aR_a due to resistances of series field, interpole winding, compensating winding and of armature respectively are in phase with armature current I_a. The reactance drops $I_aX_{se}, I_aX_i, I_aX_c$ and I_aX_a due to reactance of series field, interpole winding compensating winding and of armature respectively lead current I_a by 90°. The generated armature counter emf is E_g. the terminal phase voltage V_p is equal to the phasor sum of E_g and all the impedance drops in series.

$$V_p = E_g + I_aZ_{se} + I_aZ_i + I_aZ_c + I_aZ_a$$

The power factor angle between V_p and I_a is φ.

Example.

A universal series motor has a resistance of 30Ω and an inductance of 0.5 H. when connected to a 250 V dc supply and loaded to take 0.8 A it runs at 2000 rpm. Determine the speed, torque and power factor, when connected to a 250 V, 50 Hz ac supply and loaded to take the same current.

Solution Operation of motor on dc

$$\mathrm{E_{bdc}} = \mathrm{V} - \mathrm{I_aR_a} = 250 - 0.8 \times 30 = 226\,\mathrm{V}$$

$$\mathrm{N_{dc}} = 2000\ \mathrm{r.p.m}$$

Operation motor on ac

$$\mathrm{X_L} = 2\pi \mathrm{fL} = 2\pi \times 50 \times 0.5 = 157\ \Omega$$

From the phasor diagram shown in fig. 4,

$$\mathrm{AF^2} = \mathrm{AG^2} + \mathrm{GF^2}$$

$$\mathrm{V^2} = (\mathrm{AB} + \mathrm{BG})^2 + \mathrm{GF^2} = (\mathrm{AB} + \mathrm{DF})^2 + \mathrm{GF^2}$$

$$= (\mathrm{I_aR_a} + \mathrm{E_{bac}})^2 + (\mathrm{I_aX_L})^2$$

$$\mathrm{E_{bac}} + \mathrm{I_aR} = \sqrt{\mathrm{V^2} - (\mathrm{I_aX_L})^2}$$

$$\mathrm{E_{bac}} = -0.8 \times 30 + \sqrt{(250)^2 - (0.8 \times 157)^2}$$

$$= -24 + 216.12 = 192.12\,V$$

Since the currents in dc and ac operation are equal, the flux will also be equal ($\Phi_{ac} = \Phi_{dc}$)

$$\frac{E_{bdc}}{E_{bac}} = \frac{KN_{dc}\Phi_{dc}}{KN_{ac}\Phi_{ac}} = \frac{N_{dc}}{N_{ac}}$$

$$\mathrm{N_{ac}} = \mathrm{N_{dc}}\frac{\mathrm{E_{bac}}}{\mathrm{E_{bdc}}} = 2000 \times \frac{192.12}{226} = 1700 \text{ rpm}$$

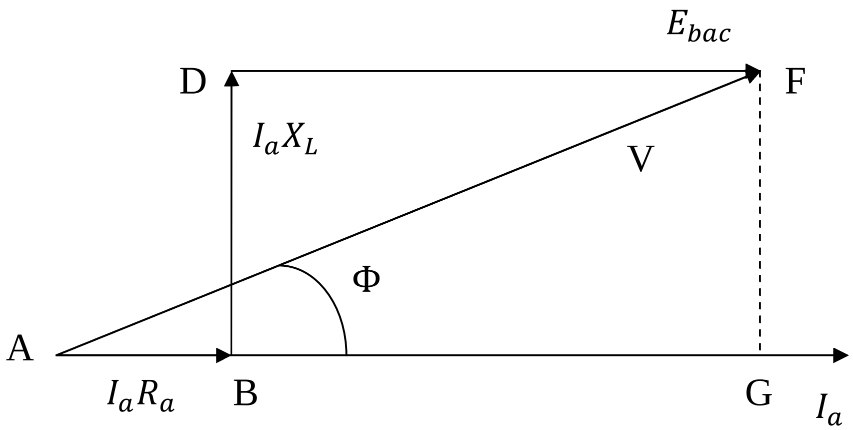

Fig.4

Power factor, $\cos\phi = \frac{AG}{AF} = \frac{E_{bac+}I_aR_a}{V}$

$$= \frac{192.12 + 0.8 \times 30}{250} = 0.8645\ (lagging)$$

Mechanical power developed

$$\mathrm{P_{mech}} = \mathrm{E_{bac}I_a} = 192.12 \times 0.8 = 153.7 \text{ W}$$

Torque developed

$$\tau = \frac{P_{mech}}{\omega_m} = \frac{P_{mech}}{2\pi n_{ac}}$$

$$= \frac{153.7}{2\pi \times (1700/60)} = 0.8633\ Nm$$

Stepper (Or Stepping) Motors

The stepper or stepping motor has a rotor movement in discrete steps. The angular rotation is determined by the number of pulses fed into the control circuit. Each input pulse initiates the drive circuit which produces one step of angular movement. Hence, the device may be considered as a digital-to-analogue converter.

There are three most popular types of rotor arrangements:

1. Variable reluctance (VR) type
2. Permanent magnet (PM) type
3. Hybrid type, a combination of VR and PM.

Step Angle

The angle by which the rotor of a stepper motor moves when one pulse is applied to the stator (input) is called **step angle.** This is expressed in degrees. The resolution of positioning of stepper motor is decided by the step angle. Smaller the step angle the higher is the resolution of positioning of the motor. The **step number or resolution** of a motor is the number of steps it makes in one revolution of the rotor.

$$Resolution = \frac{number\ of\ steps}{number\ of\ revloutions\ of\ the\ rotor}\ .$$

Higher the resolution, grater is the accuracy of positioning of objects by the motor. Stepper motor are realizable for very small step angles. Some precision motors can make 1000 steps in one revolution with a step angle of 0.36°. A standard motor will have a step angle of 1.8° with 200 steps per revolution.

Variable Reluctance (VR) Stepper Motor

A variable reluctance (VR) stepper motor can be of single-stack type or the multi-stack type.

i- Single-Stack Variable Reluctance Motor

A Variable reluctance stepper motor has salient-pole (or tooth) stator. The stator has concentrated winding places over the stator poles (teeth). The number of phases of the stator depends upon the connection of stator poles. Usually three or four phases winding are used. The rotor is slotted structure made from ferromagnetic material and carries no winding. Both the stator and rotor are made up of high quality magnetic materials having very high permeability so that the exciting current required is very small. When the stator phases are excited in a proper sequence from dc source with the help of semiconductor switch, a magnetic field is produced. The ferromagnetic rotor occupies the position which presents minimum reluctance to the stator field. That is, the rotor axis aligns itself to the stator field axis.

Elementary operation of variable reluctance motor can be explained through the diagram of fig. 1.

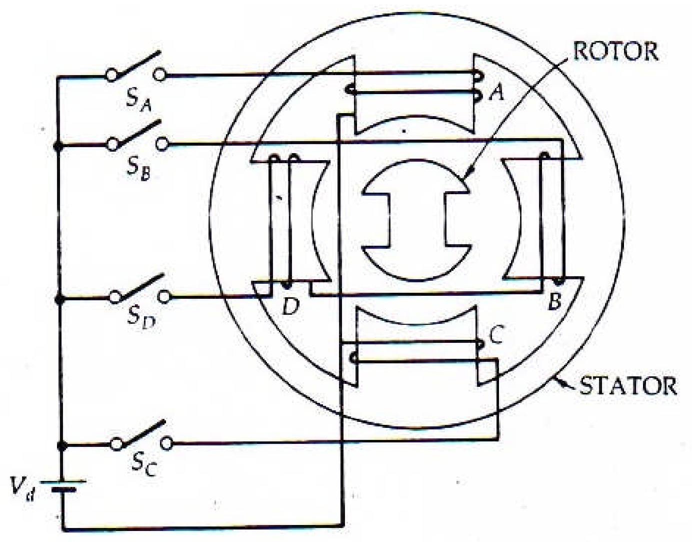

Fig.(1)four phase 4/2 VR stepper motor

It is a four-phase, 4/2-pole (4 poles in the stator and 2 in the rotor), single-stack, variable reluctance stepper motor. Four phases are A, B, C and D are connected to dc source with the help of semiconductor switches S_A, S_B, S_C and S_D respectively. The phase winding of the stator are energised in the sequence A, B, C, D, A. When winding A is excited, the rotor aligns with the axis of phase A. The rotor is stable in this position and cannot move until phase A is de-energised. Next, phase B is excited and A is disconnected. The rotor moves through 90°in clockwise direction to align with the resultant air gap field which now lies along the axis of phase B. Further, phase C is excited and B is disconnected, the rotor moves through a further step of 90° in the clockwise direction. In this position, the rotor aligns with the resultant air gap field which now lies along the axis of phase C. Thus, as the phases are excited in the sequence A, B, C, D, A the rotor moves through a step of 90 at each transition in clockwise direction. The rotor completes one revolution through four steps. The direction of rotation can be reversed by reversing the sequence of switching the winding, that is A, D, C, B, A. it is seen that the direction of rotation depends only on the sequence of switching the phases and is independent of the direction of currents through the phases.

The magnitude of step angle for any VR and PM stepper motor is given by

$$\alpha = \frac{360}{m_s N_r}$$

Where $\alpha = step\ angle$

$$m_s = number\ of\ stator\ phases\ or\ stacks$$

$$N_r = number\ of\ rotor\ teeth\ (or\ rotor\ poles)$$

The step angle is also expressed as

$$\alpha = \frac{N_s - N_r}{N_s N_r} \times 360°$$

Where $N_s = stator\ poles\ (teeth)$

The step angle can be reduced from 90 to 45 by exciting phases in the sequence A, A+B , B , B+ C , C, C+ D , D, D + A, A. Here (A+B) means that phase winding A and B are excited together and the resultant stator field will be midway between the poles carrying phase winding A and B. That is, the resultant field axis makes an angle of 45 with the axis of pole A in the clockwise direction. Therefore when phase A is excited, the rotor aligns with the axis of phase A. when phases A and B are excited together, the rotor moves by 45 in the clockwise direction. Thus, It is seen if the windings are excited in the sequence A, A+ B, B, B+ C, C, C+ D, D, D+A, A the rotor rotates in steps of 45 in the clockwise direction. The rotor can be rotated in steps of 45 in the anticlockwise direction by exciting the phase in the sequence A, A + D, D, D + C, C, C + B, B, B + A, A. this method of gradually shifting excitation from one phase to another (for example, from A to B with an intermediate step of A+ B) is known as micro stepping. It is used to realize smaller steps. Lower values of step angle can be obtained by using a stepping motor with more number of poles on stator and teeth on rotor. Consider a four-phase, 8/6 pole, single stack variable reluctance motor shown in fig 2.

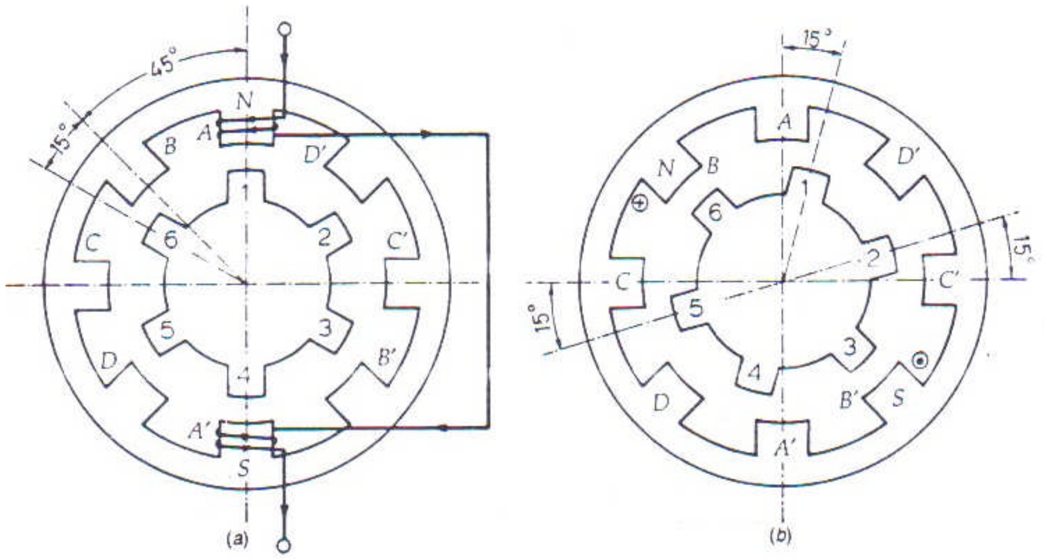

Fig. (2): four – phase, 8/6 VR stepper motor.

The coils wound around diametrically opposite poles are connected in series and four circuits (phase) are found. These phases are energised from a dc source through electronic switching device. The rotor has six poles (teeth). For the sake of simplicity, only phase A winding is shown in fig (2-a). when phase A (coil A-A`) is excited, rotor teeth numbered 1 and 4 aligned along the axis of phase A winding. Next phase winding A is de-energised and phase winding B is excited. Rotor teeth numbered 3 and 6 get aligned along the axis of phase B and the rotor moves through a step angle of 15 in the clockwise direction. Further clockwise rotation of 15 is obtained by de-energising phase winding B and exciting phase winding C. with the sequence A, B, C, D, A, four steps of rotation are completed and the rotor moves through 60 in clockwise direction. For one complete revolution of the rotor, 24 steps are required. For anticlockwise rotation of rotor through each step of 15, the phase windings are excited in reverse sequence of A, D, C, B, A.

ii- Multi-Stack Variable Reluctance Stepper Motor

A multi-stack (or m-stack) variable reluctance stepper motor can be considered to be made up of m identical single-stack variable reluctance motors with their rotors mounted on a single shaft. The stators and rotors have the same number of poles (or teeth) and, therefore, same poles pitch. For m-stack motor, the stator poles in all m stacks are aligned, but the rotor poles are displaced by 1/m of the pole pitch angle from one another. All the stator pole windings in given stack are excited simultaneously and, therefore, the stator winding of each stack forms one phase. Thus, the motor has the same number of phases as the number of stacks.

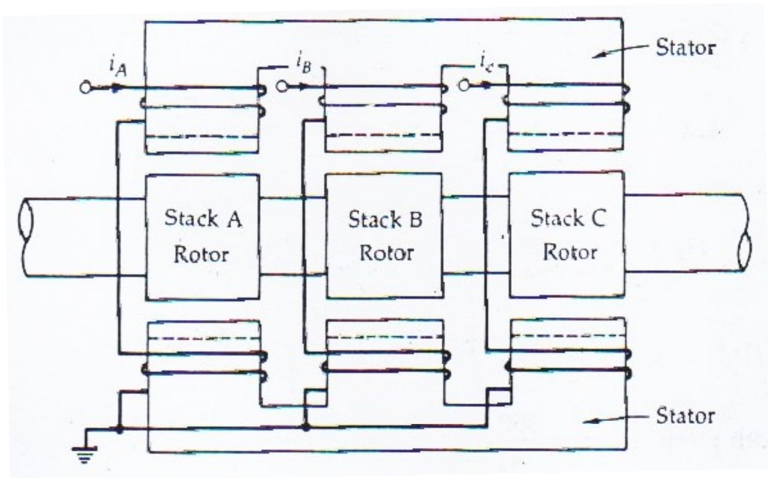

Fig.3 shows the cross-section of a three-stack (three-phase) motor parallel to the shift. In each stack, stators and rotors have 12 poles. For a 12-pole rotor, the pole pitch is 30, and therefore the rotor poles are displaced from each other by one-third of the pole pitch or 10°. The stator teeth in each stack are aligned. When the phase winding A is excited rotor teeth of stack A are aligned with the stator teeth as shown in fig. (4-a).

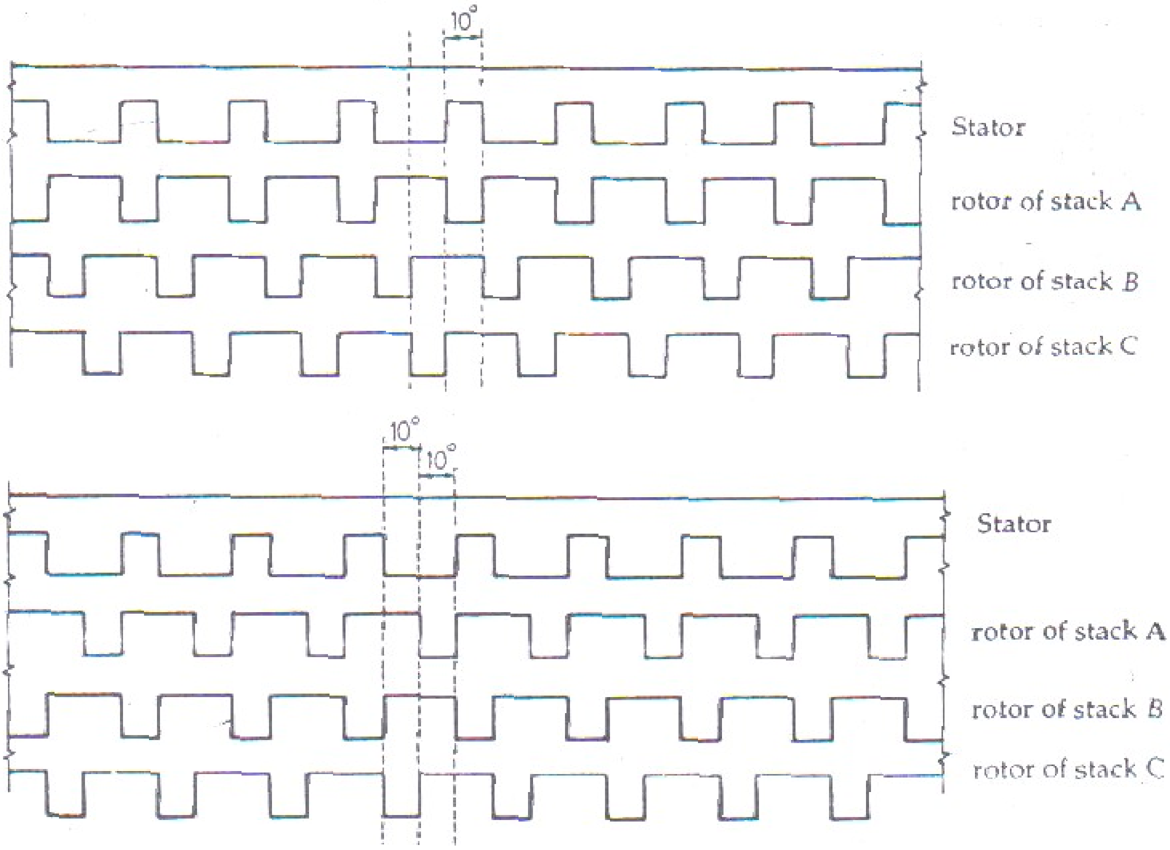

Fig.(4) position of stator and rotor teeth in 3 – stack VR motor
(a)phase A is excited (b) phase B is excited

When phase A is de-energized and phase B is excited, rotor teeth of stack B are aligned with stator teeth. This new alignment is made by the rotor movement of 10° in the anticlockwise direction. Thus the motor moves one step (equal to $\frac{1}{3}$ pole pitch) due to change of excitation from stack A to B (fig.4-b).

Next phase B is de-energized and phase C is excited. The rotor moves by another step of one-their of pole pitch in the anticlockwise direction. Another change of excitation from stack C to stack A will once more align the stator and rotor teeth in stack A. however, during this process $(A \rightarrow B \rightarrow C \rightarrow A)$ the rotor has move one rotor tooth pitch.

Let N_r be the number of rotor teeth and m the number of stacks or phases.

Then

$$Tooth\,pitch \qquad \tau_p = \frac{360°}{N_r}$$

$$Step\ angle \qquad = \frac{360°}{mN_r}$$

$$In\ our\ case, \qquad \tau_p = \frac{360°}{12} = 30°$$

$$Step\ angle \qquad = \frac{360°}{3 \times 12} = 10°$$

Multi-stack variable reluctance stepper motors are widely used to obtain smaller step size, typically in the range of 2 to 15 degrees.

The variable reluctance motors, both single and multi-stack type, have high torque to inertia ratio. The reduced inertia enables the VR motor to accelerate the load faster.

Permanent Magnet (PM) Stepper Motor

Permanent-magnet (PM) stepper motor has a stator construction similar to that of the single-stack variable reluctance motor. The rotor is cylindrical and consists of permanent-magnet poles made of high retentivity steel. Figure 5 shows a 4/2-pole PM stepper motor. The concentrated windings on diametrically opposite poles are connected in series to form 2-phase winding on the stator.

The rotor poles align with the stator teeth depending on the excitation of the winding. The two coils A-A` connected in series form phase A winding. Similarly, the two coils BB` connected in series form phase B winding.

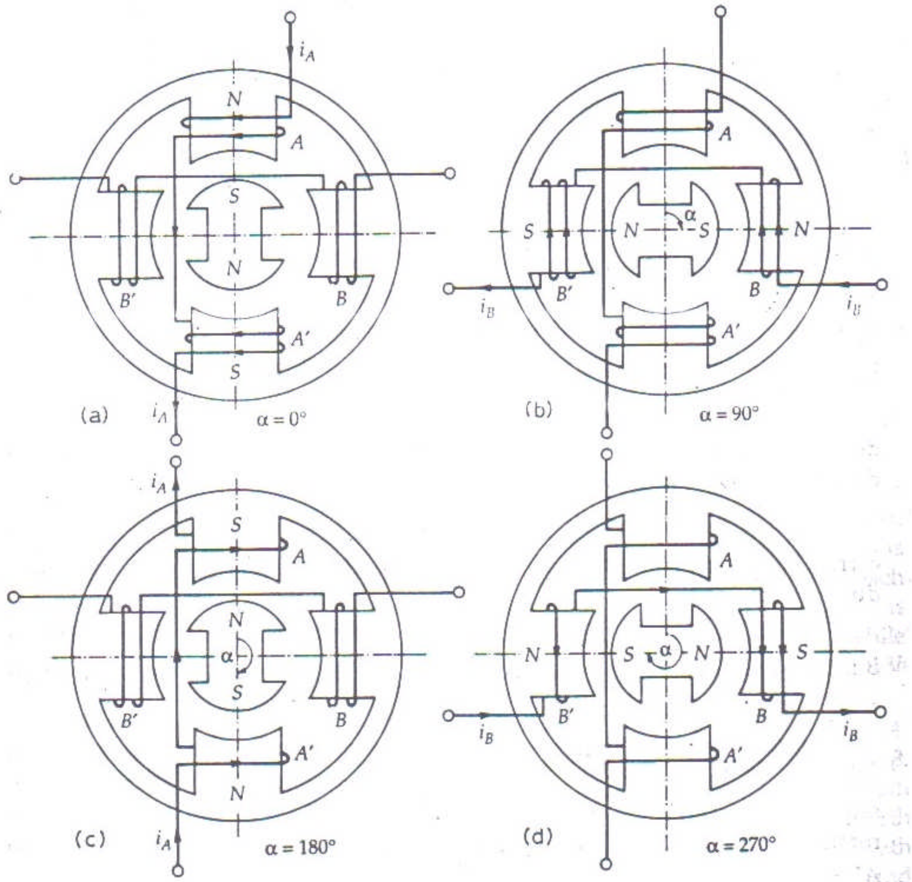

Fig .5 2-phase 4/2-pole PM stepper motor

Fig.5-a shows the condition when phase A winding is excited with current i_A^+. here south pole of rotor is attracted by the stator phase A pole so that the magnetic axes of the stator and rotor coincide and $\alpha = 0°$.

In fig.5-b, phase A winding does not carry any current and the phase B winding is excited by i_B^+. stator produced poles now attract the rotor pole and the rotor moves by a step of 90 in the clockwise direction, that is, $\alpha = 90$

In fig.5-c, phase A winding is excited by i_A^- and phase B winding is de-energized. The rotor moves through a further step of 90 in clockwise direction so that $\alpha = 180$.

In fig.5-d, phase B winding is excited by i_B^- and phase A winding carries no current. The rotor again moves further by a step of 90 in clockwise direction so that $\alpha = 270$.

For further 90 clockwise rotation of rotor so that $\alpha = 360$, phase winding B is de-energized and phase A winding is excited by current i_A^+ . Thus, four steps complete one revolution of the rotor.

It is seen that in a permanent-magnet stepper motor, the direction of rotation depends on polarity of phase current. For clockwise rotor movement the sequence of exciting the stator phase windings is A^+, B^+, A^-, B^-, A^+. for anticlockwise rotation the sequence of switching the phase windings should be reversed to A^+, B^-, A^-, B^+, A^+.

It is difficult to make small PM rotor with large numbers of poles and , therefore stepper motor of this type are restricted to larger step size in the range of 30 to 90. However disc type PM stepper motors are available to give small step size and low inertia.

Permanent magnet stepper motors have higher inertia and , therefore lower acceleration than VR stepper motors. The maximum step rate for PM stepper motors is 300 pulses per second, whereas it can be as high as 1200 pulses per second for VR stepper motors. The PM stepper motors produces more toque per ampere stator current than VR motor.

Detent Torque or Restraining Torque

The residual magnetism in the permanent magnet material produced a detent torque on the rotor when the stator coils are not energized. This torque prevent the motor from drifting when the machine supply is turned off.

In case the motor is unexcited, the permanent magnet and hybrid stepping motor are able to develop a detent torque restricting the rotor rotation. The detent torque is defined as the maximum load torque that can be applied to the shaft of unexcited motor without causing continuous rotation.

Hybrid Stepper Motor

A hybrid stepper motor combines the features reluctance and permanent magnet stepper motors.

The main advantages of hybrid stepper motors compared with variable reluctance stepper motors are as follows:

1. Small step length.
2. Greater torque per unit volume.
3. Provides detent torque with windings de-energized.
4. Less tendency to resonate.
5. High efficiency at lower speed and lower stepping rates.

Disadvantages of hybrid stepper motors

1. High inertia and weight due to presence of rotor magnet.
2. Performance affected by change in magnetic strength.
3. More costly than variable reluctance stepper motor.

Example (1)

Calculate the stepping angle for a 3- stack, 16 – teeth variable reluctance motor.

Solution : stepping angle $\propto = \frac{360}{m_s \times N_r}$

Where $m_s = number\ of\ stator\ phases\ or\ stacks$

$$N_r = number\ of\ rotor\ teeth\ (rotor\ poles)$$

$$\therefore \propto = \frac{360}{3 \times 16} = 7.5°\ per\ step.$$

Example (2)

Calculate the stepping angle for a 3- phase , 24 – pole permanent magnet stepper motor.

Solution :

stepping angle $\propto = \frac{360}{m_s \times P_r} = \frac{360}{3\times 24} = 5° \, per \; step.$