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Switched Reluctance Motor (SRM)

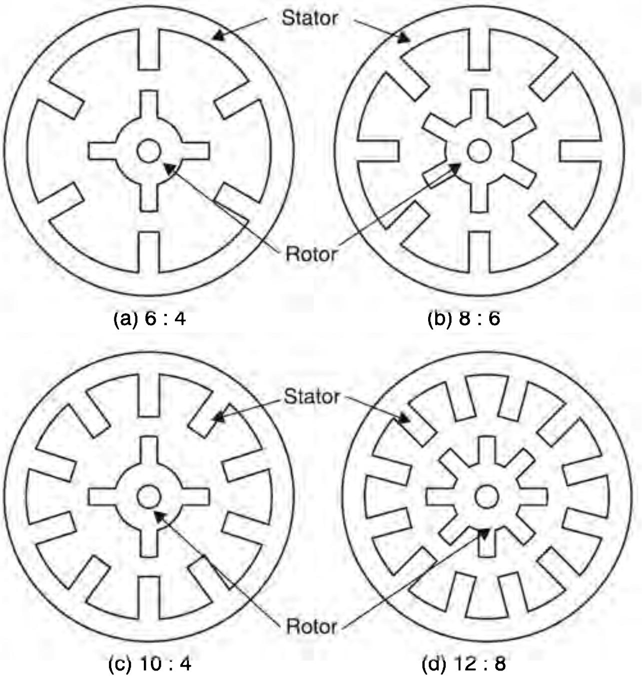
Switched reluctance motor is similar to a variable reluctance stepper motor in closed-loop operation. It requires rotor position feedback. The SRM has several advantages like high efficiency, good performance in terms of torque to inertia ratio, maximum operating speed and simple construction. Its availability in various sizes, power and speed ranges together with its ability in four-quadrant operation makes SRM an attractive solution for variable speed-applications. SRM drive is a better alternative to conventional DC series motor and variable speed induction motor drives. The performance of SRM drives depends on the control system used. Rapid developments in power electronics and digital controllers have made the implementation of semiconductor switching circuits and controllers easy and economical. At present, many industries are using SRM with its full potential.

1 Construction

Constructionally SRM is similar to variable reluctance stepper motor. The stator of the SRM is built by stacking suitably punched silicon laminations to the appropriate length. It has salient poles. The poles carry concentric windings. The coils on opposite poles are connected in series to form stator phases. The overlapping of coils is avoided to minimise the mutual inductance between the phases. End connections should be made very short.

The rotor contains no winding or permanent magnet. It is built up of steel laminations. The laminations are stacked to the shaft. It is due to this mechanical simplicity that the cost of SRM is promisingly low, which attracts many industries to use it. By selecting the number of phases, the number of stator poles and the number of rotor teeth, many configurations of SRM can be obtained. A few of such commonly used configurations are shown in Fig. 1.

The control of input is very essential for getting desired performances. Parts of an SRM drive are shown in Fig. 2. The detailed discussion on SRM control will be given later.



(a) 6 : 4
(b) 8 : 6
(c) 10 : 4
(d) 12 : 8

Fig. 1 Different configurations of SRM with stator to rotor pole ratios

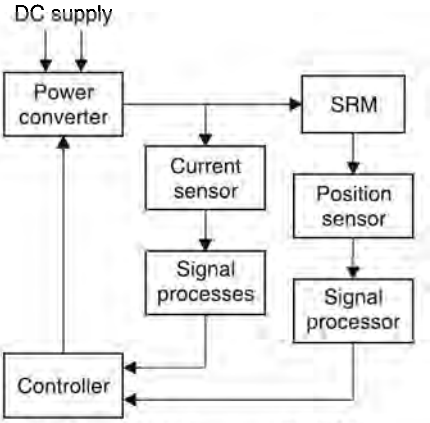


Fig. 2 Block diagram of SRM drive

2 Principle Working

Consider an SRM with eight stator poles and six rotor teeth. It has four-phases. A–A′, B–B′, C–C′, D–D′. These phases can be excited by DC supply through switches S_1, S_2, S_3 and S_4 (Fig. 3). Let phase A–A′ be energised for a significant time so that the rotor rests in the equilibrium position shown in Fig. 4. This position corresponds to the maximum inductance of phase A–A′. Also, this position repersents a stable equilibrium position because any disturbance to move the rotor from this position is opposed by the production of an electromagnetic torque to bring the rotor back to this position. Next, phase A–A′ is de-energised by turning switch S_1 OFF and excite B–B′ by turning switch S_2 ON. The rotor moves by 15° in CCW direction and occupies the position shown in Fig. 5. Phase B–B′ is switched off by turning switch S_2 OFF and closing S_3. Phase C–C′ gets excited and rotor moves in the same direction by 15° and attains the stable position indicated in Fig. 6. By operating the switches in sequence S_1, S_2, S_3, S_4, S_1,…, we can make the rotor to rotate in the CCW direction with a step angle 15°. To reverse the direction of rotation, follow the switching sequence S_1, S_4, S_3, S_2, S_1, S_4,… .

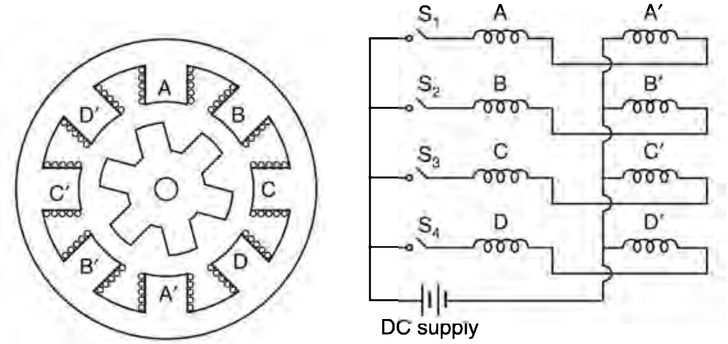


Fig. 3 Four-phase, eight-pole SRM

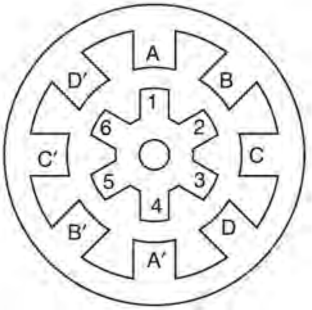


Fig. 4 Phase A excited

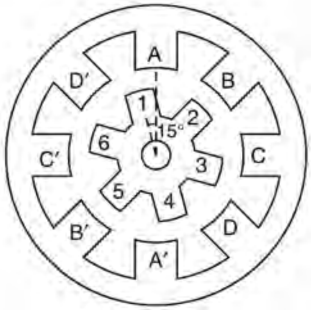


Fig. 5 Phase B excited

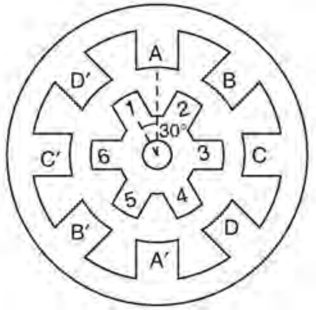


Fig. 6 Phase C excited

The operation of SRM depends on the variation of phase inductance. Inductance of the stator phase depends on the relative positions of rotor teeth with stator poles. The phase inductance increases, remains constant, decreases, remains constant and rises cyclically. This variation depends on the amount of overlap of rotor teeth with stator poles of the concerned phase. The current in the phase should be forced in the winding when the rotor tooth is just entering the stator pole of that phase. It is therefore essential to know the rotor position for switching. The energised phase should be switched OFF when the inductance of that phase is decreasing. The conditions for successful operation of SRM are summarised below:

(i) Number of rotor teeth and stator poles must be even and not equal.
(ii) Stator phase is energised when the inductance of that phase is low or increasing.
(iii) Sensor for rotor position is required. The rotor position sensing is essential for switching operations at correct instants.

(iv) The flux density is changing in magnitude and direction in the magnetic circuit when rotor moves. This results in iron loss. To reduce iron loss, laminated rotor and stator structures should be used.

3 Basics of SRM Analysis

SRM has no windings on its rotor. Its only source of excitation consists of stator windings. This is an important feature as it requires that all the resistive winding losses occur on the stator. This makes the cooling easy and more effective. This results in smaller motor for a given rating and frame size.

To produce torque, SRM should be designed in such a way that the stator winding inductance vary with the position of rotor teeth. Double saliency of the motor satisfies this requirement. The inductance of the stator winding varies with rotor position such that the inductance is maximum when the rotor axis is aligned with the magnetic axis of that phase and minimum when the two axes are perpendicular. For analysis, consider an SRM with:

α_s = stator slot angle in degrees
α_r = rotor slot angle in degrees
β_s = stator pole arc in degrees
β_r = rotor tooth arc in degrees
N_s = number of stator poles
N_r = number of rotor teeth
T_c = turns per coil
R = radius of rotor at the air gap
g = air gap length
L = inductance per phase
q = overlap angle
μ_0 = permeability of air
θ = rotor displacement in degrees

Assuming no fringing of flux and flux to be confined entirely in the overlap of the rotor teeth and stator pole, the inductance per phase is given by

$$L = \frac{T_c^2 \mu_0 lRq}{2g} \qquad (.\ 1)$$

where lRq represents the area of the airgap.

The variations of inductance can be studied with the help of the diagram shown in Fig. 7. It represents a portion of rotor and stator of an eight-pole SRM with six rotor teeth. The developed diagrams for various positions of rotor teeth are shown in Fig. 8.

In Fig. 8(a), the positions of the stator pole A and rotor tooth B when the overlap begins are shown. The inductance starts increasing at this instant. This position is taken as the reference for displacement, $\theta = 0$. Figure 8(b) shows the condition where inductance reaches its maximum value. The positions of rotor tooth and stator pole are shown in Fig. 8(c). This figure indicates the instant at which the overlap starts decreasing and inductance begins falling. The instant at which the overlap ends and inductance reaches its minimum value is shown in Fig. 8(d). The variations of inductance with rotor movement are shown in Fig. .9.

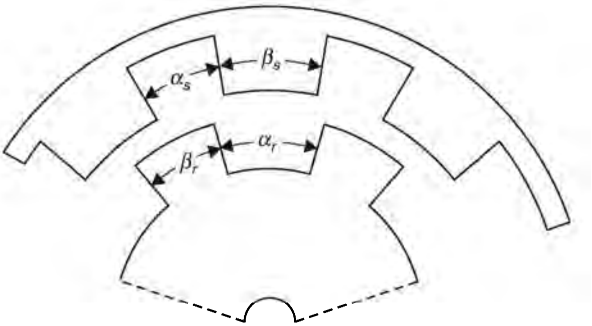
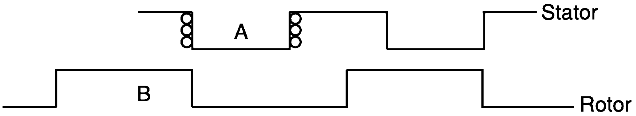
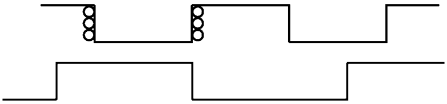


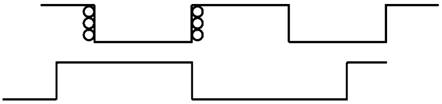
Fig. 7 Portions of rotor and stator of eight-pole SRM



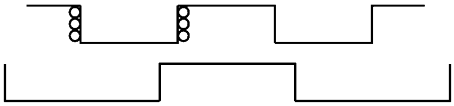
(a) Overlap begins



(b) Position of max inductance



(c) Overlap starts decreasing



(d) Overlap ends

Fig. .8 Relative positions of rotor teeth and stator poles

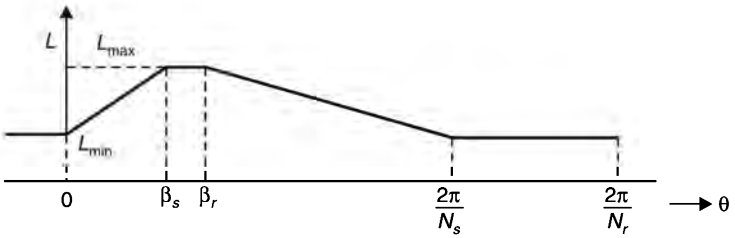


Fig. 9 L–θ profile

L–θ profile as shown in Fig. 9 is obtained as follows:

For $0 < \theta < \beta_s$, the inductance rises from $L_{\min}$ to $L_{\max}$.

For $\beta_s < \theta < \beta_r$, the inductance remains constant. This angle $\beta_r – \beta_s$ is called dwell angle.

For $\beta_r < \theta < \dfrac{2\pi}{N_s}$, the inductance starts decreasing and reaches $L_{\min}$ at $\theta = \dfrac{2\pi}{N_s}$.

For $\dfrac{2\pi}{N_s} < \theta < \dfrac{2\pi}{N_r}$, the inductance remains constant at $L_{\min}$. $\dfrac{2\pi}{N_r} - \dfrac{2\pi}{N_s}$ is the dwell angle.

.4 Constraints on Pole Arc and Tooth Arc

For choosing the slot and tooth dimensions of the stator and the rotor, the following constraints are considered. These constraints are to be satisfied for obtaining optimum and feasible values for $L_{\max}$ and $L_{\min}$.

- For fast building up of current from the voltage source, the stator phase should be switched on while the inductance is minimum and constant. This can be achieved by providing a dwell time during which inductance is minimum. For this

$$\beta_s < \alpha_r$$

i.e.

$$\beta_s < \frac{2\pi}{N_r} - \beta_r$$

i.e.

$$\beta_s + \beta_r < \frac{2\pi}{N_r}$$

- Stator slot angle must be less than stator pole pitch

i.e.

$$\beta_s < \frac{2\pi}{N_s}$$

- To avoid negative torque production, there must be a dwell period during which inductance is maximum. To meet this requirement

$$\beta_r > \beta_s$$

- The period during which the slope of L–θ curve is positive should be more than the step angle, θ_s. To satisfy this

$$\beta_s > \frac{2\pi}{N_r} - \frac{2\pi}{N_s}$$

These constraints are graphically represented in Fig. . 10. The feasible region is shaded.

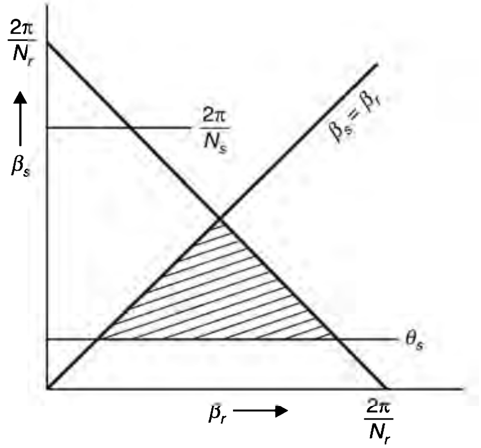


Fig. .10 Graphical representation of constraints on B_r and B_s

5 Torque Equation and Characteristics

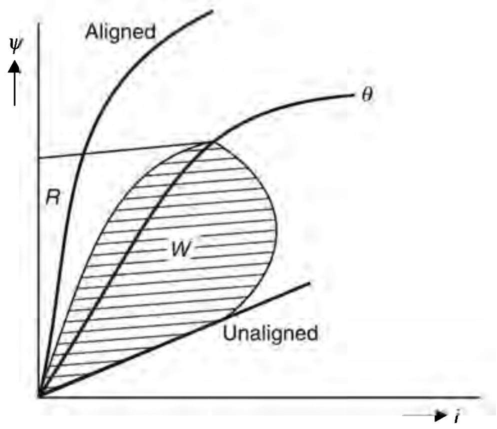


Fig. 11 ψ–i **curve**

For explaining the torque generation principle, the mechanism of electromechanical energy conversion is investigated. The stator phase is excited at the unaligned position (the position where the stator pole and the rotor tooth have the maximum air gap length). The magnetisation of the excited pole will magnetically polarise the closest rotor tooth and produce a force of attraction. The tangential component of this force produces an electromagnetic torque in the direction which reduces the air gap length between the stator pole and the rotor tooth. As the rotor tooth approaches aligned position (the position where the stator pole and the rotor tooth have the minimum air gap length), the tangential component of the attractive force decreases and becomes zero. The phase current may be switched off before the rotor tooth occupies the aligned position. Flux linkage (ψ) versus phase current characteristics are shown in Fig. 11. The shaded portion represents the electromechanical energy developed. Region R corresponds to the energy returned to supply. This area is less than the stored energy as a part of it is used by the motor during free wheeling period. The shape of the conversion loop (the shaded portion in Fig. 11) and its area W depend on variation of current with rotor angle, control parameters, speed and motor design.

In one revolution, the number of changes for a phase = N_r
Energy converted into mechanical revolution/phase = $N_r W$ joules
Energy converted/revolution = $nN_r W$
Where n = number of phases.

Mechanical energy developed/sec = $nN_r W \dfrac{\omega}{2\pi}$

where ω = angular velocity, in radians/sec.
Mechanical power developed,

$$P_m = \frac{nN_r W \omega}{2\pi} \qquad (2)$$

∴ Torque developed,

$$T = \frac{nN_r W}{2\pi} \text{ N-m} \qquad (3)$$

The developed torque per ampere ore can be increased by the following means:

- Aligned inductance should be as large as possible. This can be achieved by reducing the aligned air gap length.
- The unaligned inductance should be as small as possible. For this, keep the air gap length at the unaligned position maximum.
- Operate the magnetic circuit at highly saturated condition.

Advantages of SRM

The advantages of SRM are summarised as follows:

1. The rotor construction is simple. Rotor has low inertia.
2. Rotor has no winding and permanent magnet and hence higher permissible temperature.
3. Major losses occur in stator and hence it is easy to cool the motor.
4. The stator is easy to wind, end turns are short and no phase-to-phase crossover.
5. The torque is independent of the polarity of phase current and hence less number of switching devices can be used for certain applications.
6. Under fault, the short-circuit current and open-circuit voltage are zero or small.
7. Starting torque is high.
8. Suitable for high-speed applications.
9. SRM can be used in generating and motoring modes.
10. SRM is self-starting.
11. No shoot-through fault occurs in power circuits.

Disadvantages of SRM

1. Presence of ripples in torque.
2. Developes acoustic noice.
3. Undesirable harmonics in current waveforms for high speed.
4. An accurate position-sensing mechanism is eesential.

Applications of SRM

SRMs are used in washing machines, vacuum cleaners, fans, robotic control applications and traction.

Worked Examples

1. A four-phase eight-pole switched reluctance motor has six rotor teeth. Find the step angle and commutation frequency for a speed of 6000 rpm.

Solution

Given:

Number of phases, $n = 4$

Number of stator poles, $N_s = 8$

Number of rotor poles, $N_r = 6$

Speed, $N = 6000$ rpm

Step angle, $$\varepsilon = \frac{2\pi}{nN_r} = \frac{360}{4\times 6} = 15^\circ$$

Also, step angle, $$\varepsilon = \frac{N_s - N_r}{N_s \times N_r}\times 360 = \frac{8-6}{8\times 6}\times 360 = 15^\circ$$

Commutation frequency, $f_c = N_r \times \text{speed in rps}$

$$= 6 \times \frac{6000}{60} = 600 \text{ Hz}$$

2. A three-phase SRM has six stator poles and four rotor teeth. Draw the feasible zone for stator and rotor pole arcs. Design the pole arc and rotor tooth arc. Sketch the L–θ profile.

Solution

Given:

Number of poles, $N_s = 6$

Number of teeth, $N_r = 4$

Let

$$\text{stator pole arc} = \beta_s$$

$$\text{rotor tooth arc} = \beta_r$$

$$\text{stator slot width} = \alpha_s$$

$$\text{rotor slot width} = \alpha_r$$

$$\text{stator pole pitch} = \frac{2\pi}{N_s} = 60^\circ$$

$$\text{rotor tooth pitch} = \frac{2\pi}{N_r} = 90^\circ$$

The constraints on pole arc and tooth arc are:

$$\beta_s + \beta_r < 90^\circ$$

$$\beta_s < 60^\circ$$

$$\beta_s < \beta_r$$

$$\beta_s > \text{step angle}$$

Step angle, $\varepsilon = \dfrac{2\pi}{n \times N_r} = \dfrac{360}{3 \times 4} = 30^\circ$

$\therefore$ $\beta_s > 30^\circ$

These constrains give the feasible zone having the corners (30°, 30°), (45°, 45°) and (60°, 30°).

The feasible zone is the shaded region in Fig. 12

To maximise the difference ($L_{\max} - L_{\min}$) the rotor tooth arc can be selected as about 40% of the rotor slot pitch.

$$\text{rotor slot pitch} = \frac{2\pi}{N_r} = 90^\circ$$

$\therefore$ $\beta_r = 0.4 \times 90 = 36^\circ$

$\alpha_r = 90^\circ - 36^\circ = 54^\circ$

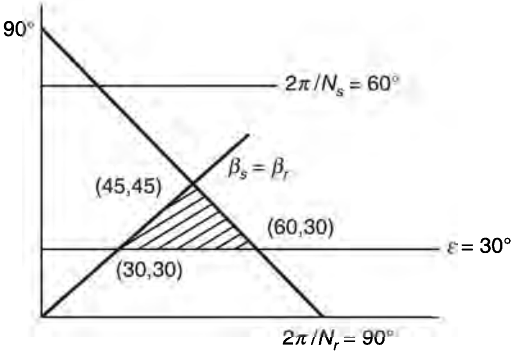


Fig. 12 . **Feasible zone.**

Allowing a dwell of 3°

$$\beta_s = 36 - 3 = 33°$$
$$\alpha_s = 60 - 33 = 27°$$

The *L*–*θ* profile is shown in Fig. 13.

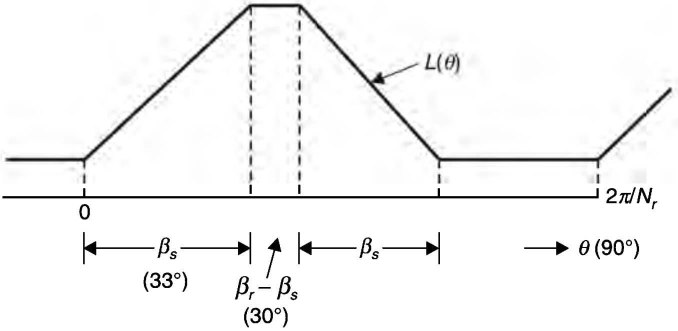


Fig. 13 ***L*–*θ* profile**

3. A three-phase six-pole SRM with four rotor teeth has an aligned inductance of 10 mH and unaligned inductance of 1 mH. Saturation can be neglected.

(a) Find the instantaneous torque when the rotor is 30° before the aligned position if the phase current is 5A.

(b) Calculate the maximum energy conversion in one stroke if the current is limited to 5A. Also determine the average torque corresponding to this energy conversion.

(c) What is the flux linkage in the aligned position when the phase current is 5A? If this flux is maintained constant and rotor moves from unaligned position to aligned position at low speed, find the energy conversion per stroke and average torque.

Stator pole arc is 30° and rotor tooth arc is 32°.

Solution

Given:

Number of phases, $n = 3$

Number of stator poles, $N_s = 6$

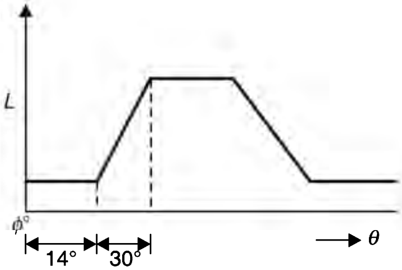


Fig. 14 L-θ **profile.**

Number of rotor teeth, $N_r = 4$

Stator pole arc, $\beta_s = 30°$

rotor tooth arc, $\beta_r = 32°$

Inductance in aligned positon, $L_a = 10$ mH

Inductance in unaligned position,

$L_4 = 1$ mH

(a) Rotor slot angle,
$$\alpha_r = \frac{2\pi}{N_r} - \beta_r$$
$$= 90 - 38 = 58$$

L–θ profile is shown in Fig. 14

$$\frac{\alpha_r - \beta_s}{2} = \frac{58 - 30}{2}$$
$$= 14°$$

Inductance varies from 1 mH to 10 mH for θ varying from 14° to 44°.

$$\therefore \qquad \frac{dL}{d\theta} = \frac{10 \times 10^{-3} - 1 \times 10^{-3}}{44 - 14} = \frac{9 \times 10^{-3}}{30}$$
$$= \frac{9 \times 10^{-3}}{\pi/6}$$
$$i = 5A$$

$$\therefore \qquad \text{Instantaneous torque} = \frac{1}{2} i^2 \frac{dL}{d\theta} = \frac{1}{2} \times 5^2 \times \frac{9 \times 10^{-3}}{\pi/6}$$
$$= 0.215 \text{ N-m}$$

(b) The flux linkage is given by

$$\psi = Li$$

The ψ–i curves for aligned and unaligned positions are shown in Fig. 15

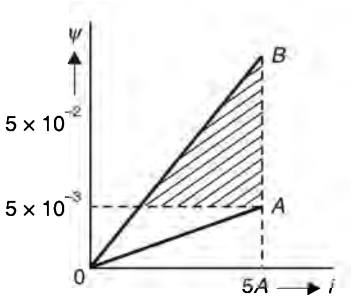


Fig. 15 $\psi - i$ **curve.**

Energy transferred, $W_m = \text{Area OAB}$

$$= \frac{1}{2} \times 5 \times (5 \times 10^{-2} - 5 \times 10^{-3})$$
$$= \frac{1}{2} \times 5 \times 5 \times (0.01 - 0.001)$$
$$= 0.1125 \text{ J}$$

Energy transferred/revolution = $W_m \times N_r \times n$

Power transferred, $P_m = W_m N_r n\omega/2\pi$

where ω = Angular velocity, rad./sec.

Average torque = P_m/ω

$= 0.21497$ N-m

(c) Flux linkage corresponding to aligned position = $5 \times 10 \times 10^{-3}$

Flux linkage corresponding to unaligned position = $j \times 1 \times 10^{-3}$

For constant flux linkage

$$i \times 10^{-3} = 5 \times 10 \times 10^{-3}$$

$$\therefore \quad i = 50 \text{ A}$$

The $\psi - i$ characteristics are shown in Fig. 16

Energy transferred/stroke,

$$W_m = \frac{1}{2}(50 - 5)(5 \times 10 \times 10^{-3})$$

$$= 2.125 \text{ J}$$

$$\text{Average torque} = \frac{W_m \times N_r \times n}{2\pi}$$

$$= 4.06 \text{ N-m}$$

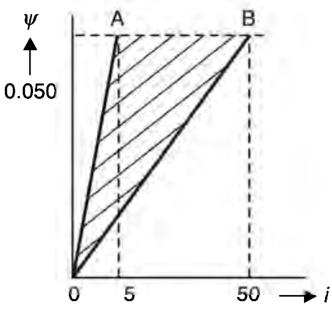


Fig. 16 $\psi - i$ curve.