THREE PHASE STATOR WINDINGS

The stator windings for alternating-current motors and generators are alike. It should be noted that direct-current and alternating-current windings differ essentially by the former being of the closed-circuit type (through commutator) ,while alternating-current windings are of the open-circuit type.

Types of A-C Windings:

With reference to the arrangements of coils used in three phase stator, windings may be divided into two general classes as follows:

I. Distributed Windings:

1. Spiral or chain.
2. Lap.
3. Wave.

II. Concentrated Windings:

1. Lap.
2. Wave.

Distributed Windings:

An armature winding which has its conductors of any one phase under a single pole placed in several slots, is said to be **distributed**. When these conductors are bunched together in one slot per pole per phase, the winding is called **concentrated**. It is usual in a distributed winding to distribute the series conductors in any phase of the winding among two or more slots under each pole. A distributed winding has two principal advantages, first, a distributed winding generates a voltage wave that is nearly a sine curve, secondly, copper is evenly distributed on the armature surface, therefore, heating is more uniform and this type of winding is more easily cooled.

Concentrated Windings:

The concentrated winding gives the largest possible emf from a given number of conductors in the winding. That is for a definite fixed speed and field strength in an alternator, the concentrated winding requires a less number of conductors than a distributed winding, but increases the number of turns per coil.

Lap and Wave Windings:

Both distributed and concentrated windings make use of lap and wave connections. These arrangements are in principle the same as used in direct-current windings. The diagrams of Figs. 1 and 2 show distributed lap and wave windings .

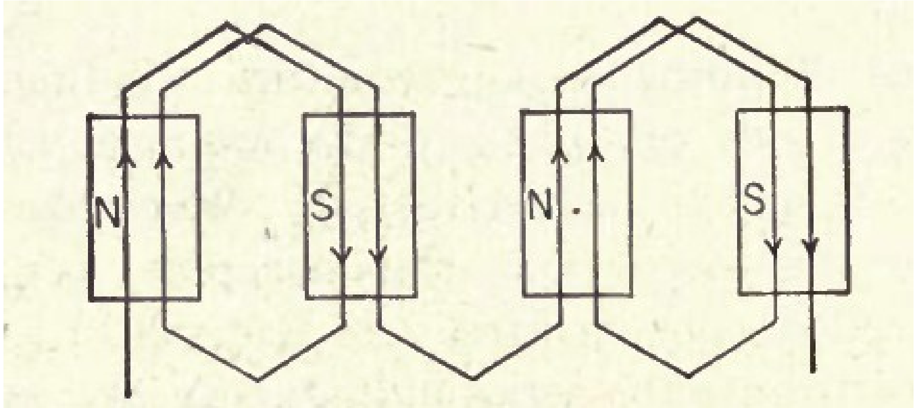


Fig. 1 Single-phase lap winding

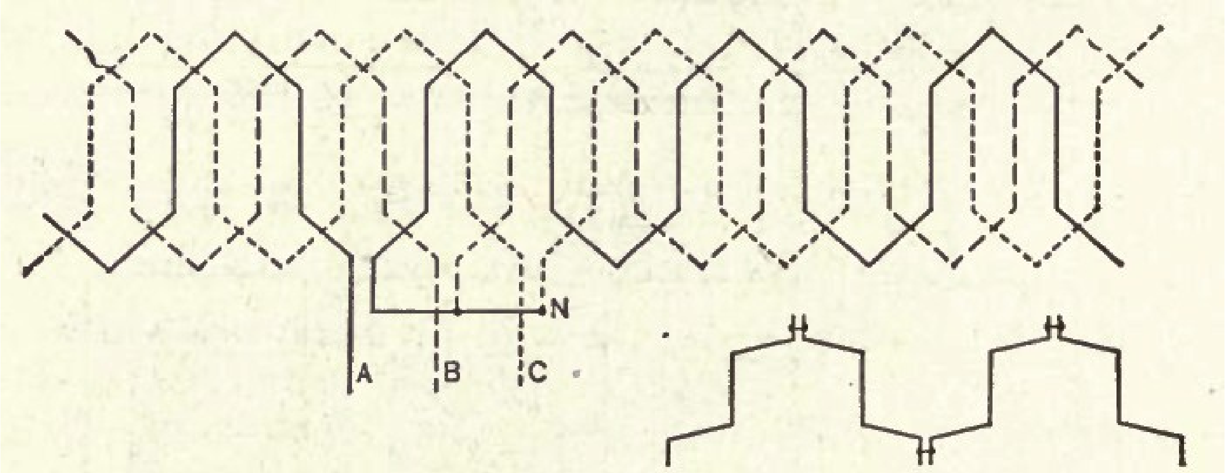


Fig 2. Three-phase wave winding , using one slot per pole per phase, star-connected.

Chain Winding :

In this winding as shown in Fig. 3 there is only one coil side in a slot. An odd or even number of conductors per slot may be used but several shapes of coils are required since the coils enclose each other. The number of coils required in this winding is also small compared with other windings. This type of winding is mainly used in alternating current generators.

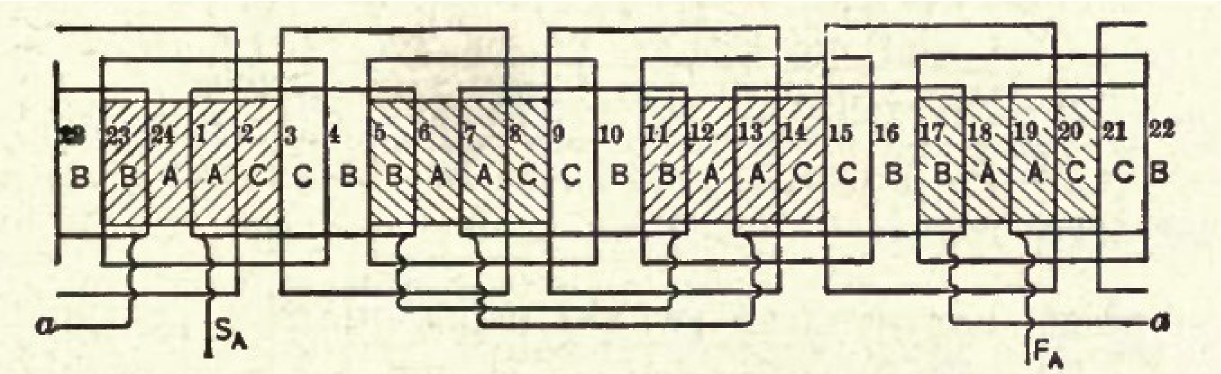


Fig. 3 Three-phase chain winding

Single layer **and** ***double layer*** **winding :**

In double layer winding two coil sides are located in each armature slot [Fig. 4]. If there is only one coil side located in each armature slot, the winding is called single layer.

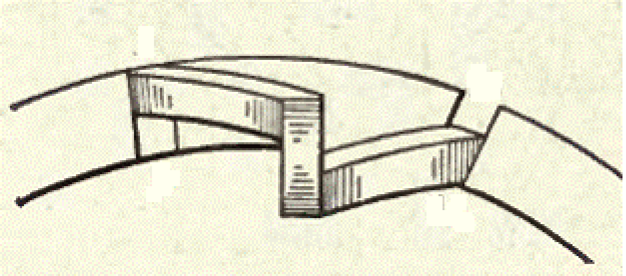


Fig. 4 A double layer winding. One side of the coil lies in the top of the slot and the other side in the bottom of the of the slot.

Full pitch **and** ***fractional pitch*** **windings:**

For a three-phase winding the total number of coil sides or the total number of slots should be just divisible by three (the number of phases) and sometimes by the number of poles. This will result in a **full pitch** winding, that is, a winding in which a coil spans exactly the distance between the centers of adjacent poles. If the coil spans less than this distance, so that its two sides are not exactly under the centers of adjacent poles at the same time, it is said to have a **fractional-pitch**. When a fractional pitch is used, the total number of slots per phase must be a whole number. The fractional-pitch coils are frequently used in a.c. machines for two main reasons. First, less copper is required per coil and secondly the waveform of the generated voltage is improved .The number of stator slots, divided by the number of poles gives a value of the **pole pitch** expressed in terms of the slots. **Coil pitch** is expressed as a fraction of the pole pitch, in slots, or in electrical degrees. In the case of a 6 pole machine having 72 stator slots, and a double-layer winding, the pole pitch would be 12 slots(72 / 6). If the coil pitch were given as 2/3, this would be 120° (2/3 * 180°) or 8 slots (2/3 * 12). A full coil pitch for this winding would be 180 degrees, or 12 slots. A full pitch winding is one in which the coil pitch is equal to the pole pitch, and a fractional pitch winding is one in which the coil pitch is not equal to the pole pitch. For the coils used in **small machines** *round insulated wire* is most employed. These coils are either wound in the slots by hand or assembled by use of specially formed coils wound in forms and insulated before being placed in the slots. Such formed coils are usually used except in cases where the slots are closed or nearly closed. For **large machines** where the amperes to be carried in each armature circuit is a large value, *copper straps* are frequently employed for making up the armature coils. In **very large machines** a *copper bar* is used instead of the copper straps. In such a case one bar serves as a conductor of a coil having one turn per slot. The copper bars are connected to the end connections of the coils by brazing, welding or bolting. In all cases, whatever the construction of the coil used, the slots must be properly insulated with mica, polyester film or other suitable insulating material according to the adequate class of insulation. The **coil throw** refers to the start of coil from one stator slot to the finish of this coil at another stator slot . Figures 5 (a) , (b) , (c), and (d) show four different coils, in each of them the pole pitch is of 12 slots while the coil pitch in (a) is 11 slots , in (b) is 13 slots, in (c) is 9 slots, and in (d) is 15 slots .

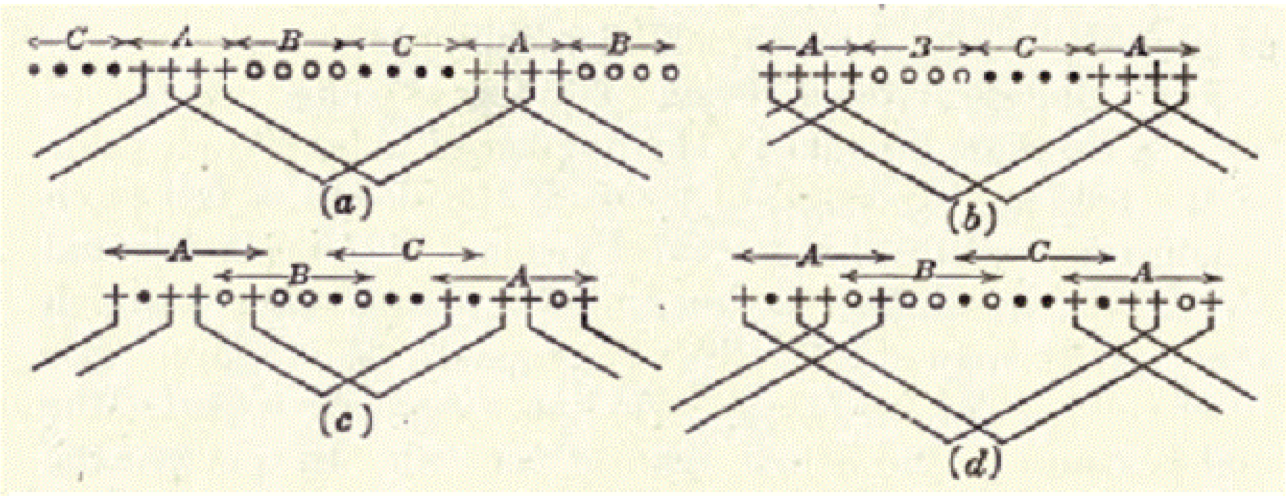


Fig. 5. Possible pitch for one coil per slot windings(pole pitch=24 slots/2poles=12) **(a)** coil throw 1 to 12, coil pitch=12-1=11 **(b)** coil throw 1 to 14, coil pitch=14-1=13 **(c)** coil throw 1 to 10, coil pitch=10-1=9 , **(d)** coil throw 1 to 16, coil pitch=16-1=15 **.**

Phase belt **and** ***phase spread*** **:**

A group of adjacent slots belonging to one phase under one pole pair is known as **phase belt**. The angle subtended by a phase belt is known as **phase spread**. The 3-phase windings are always designed for 60° phase spread . Fig. (6) shows a 2-pole, 3-phase double-layer, full pitch, distributed winding for the stator of an alternator. There are 12 slots and each slot contains two coil sides. The coil sides that are placed in adjacent slots belong to the same phase such as(a1, a3) or (a2, a4)constitute a phase belt. Since the winding has double-layer arrangement, one side of a coil, such as (a1), is placed at the bottom of a slot and the other side (- a1) is placed at the top of another slot spaced one pole pitch apart. Note that each coil has a span of a full pole pitch or 180 electrical degrees. Therefore. the winding is a full-pitch winding. Note that there are 12 total coils and each phase has four coils. The four coils in each phase are connected in series so that their voltages aid. The three phases then may be connected to form Y or Δ-connection. Fig. (7) shows how the coils are connected to form a Y-connection. Any star diagram can be readily changed into a corresponding delta diagram by opening the star points and connecting the inner end of phase A to the outer end of phase B, the inner end of phase B to the outer end of phase C , and the inner end of phase C to the outer end of phase A .

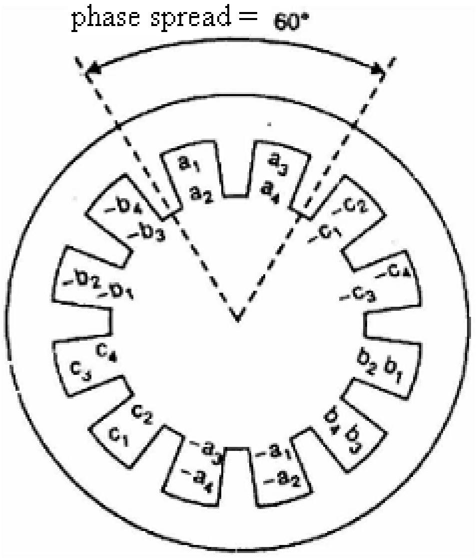


Fig. 6

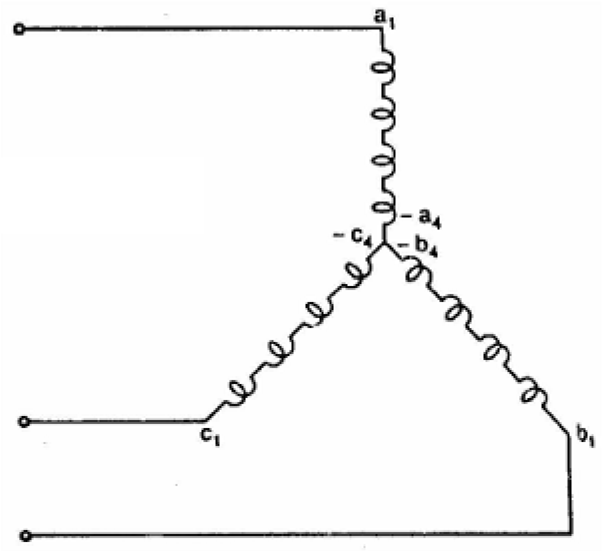


Fig. 7

<u>Simple rule for checking proper phase relationship in a three-phase winding</u>:

A fundamental consideration when checking the instantaneous flow of current in a three phase circuit, is to imagine that when the current flows in the same direction in two legs of the circuit, it flows in the opposite direction in the third leg. This principle can be applied to both motors and generators. In Figure 8, it must be supposed that current flows in all three leads of the star connection toward the point of the star connection. And that in the case of a delta connection the current flows around the three sides of the delta in the same direction. Then in either case for a three-phase winding, the polarity of each of the pole-phase groups will alternate regularly around the winding and can be indicated by arrows as in Fig. 8. By the use of this scheme there is no chance for a reversal of a phase to be passed by not noticed when checking the winding.

① P= 18 acc. to curr. direction

② curr. direction in Phase start oppose that in phase end.

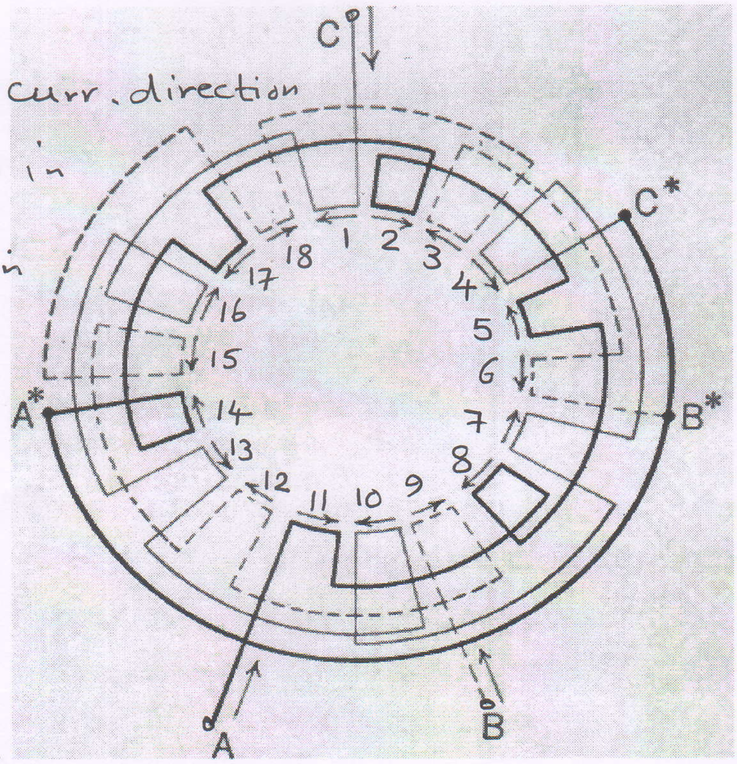


Fig. 8 Simple scheme of alternately reversing arrows of pole-phase groups to check correct phase polarity of a 3-phase winding. It is supposed in this case that current flows in the three leads toward the star points of the winding which are indicated thus (*) .

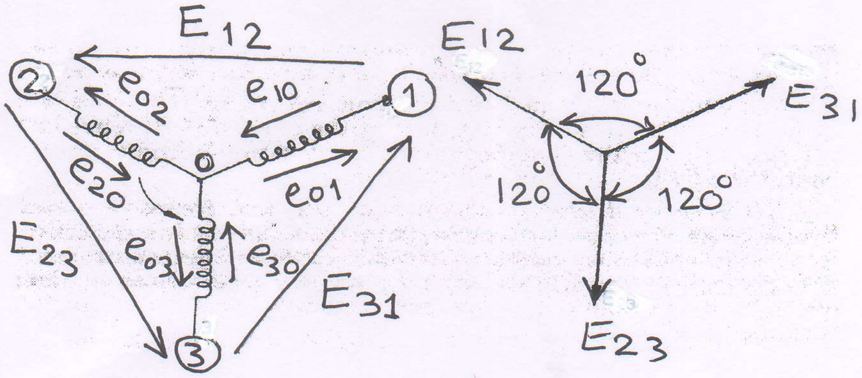
Why the alternators have their windings connected in star?

Because the star connection has the following advantages over delta connection:

(i) To obtain a desired voltage between outside terminals of a generator, the voltage built up in any one phase need be only 58 percent(1 / √3) of the terminal value. Hence only 58 percent of the turns required for a Δ-connected armature are necessary with a consequent lowering of insulation cost.

(ii) A star connected winding offers the advantage of a fourth or neutral lead making possible the advantages of a four-wire system, with or without grounded neutral.

(iii) The wave shape of a star-connected winding is improved, owing to the elimination of third harmonics and multiples of third harmonics from the terminal voltage. Fig.9 shows a star connected armature(stator), The terminal voltages E_{12}, E_{23} and,E_{31} are 120 electrical degrees apart. In the third harmonics the e.m.f.'s of three phases (e01 ,e02 ,e03) are being in phase(3 X 120° = 360°= 0°),to obtain terminal voltages, the resultant is zero. Hence no third harmonics appears between terminals.The circulating currents from the third harmonics cause unnecessary losses and dangerous heating in Δ-connected alternator, where it is not in the Y-connected alternator case. In addition the use of a(5/6)th pitch winding in three-phase Y-connected generators reduces the fifth and seventh harmonics, if pesent, to almost nil, so the lowest harmonics that can be present is eleventh.



$$\left.\begin{aligned} E_{12}&=e_{02}+e_{10}=e_{02}-e_{01}, && E_{12}\angle 0^\circ \\ E_{23}&=e_{03}+e_{20}=e_{03}-e_{02}, && E_{23}\angle 120^\circ \\ E_{31}&=e_{01}+e_{30}=e_{01}-e_{03}, && E_{31}\angle 240^\circ \end{aligned}\right\}\text{for fundamental waveform}$$

Fig. 9

for third harmonics E_{12}, E_{23}, E_{31} are being in phase

$$E_{12}\angle 0^\circ \times 3 = E_{12}\angle 0^\circ$$

$$E_{23}\angle 120^\circ \times 3 = E_{23}\angle 360^\circ = E_{23}\angle 0^\circ$$

$$E_{31}\angle 240^\circ \times 3 = E_{31}\angle 720^\circ = E_{31}\angle 0^\circ$$

so, $E_R = E_{12}+E_{23}+E_{31}$

$$=(e_{02}-e_{01})+(e_{03}-e_{02})+(e_{01}-e_{03})$$

$$\boxed{E_R = 0}$$

Windings factors:

The stator winding of synchronous machine is distributed over the entire stator. The distributed winding produces nearly a sine waveform and the heating is more uniform. Likewise, the coils of armature winding are not full-pitched i.e., the two sides of a coil are not at corresponding points under adjacent poles. The fractional pitched armature winding requires less copper per coil and at the same time waveform of output voltage is improved. The distribution and pitching of the coils affect the voltages induced in the coils. We shall discuss two winding factors:

(i) Distribution factor (Kd).
(ii) Pitch factor (Kp).

(i) Distribution factor (Kd) :

A winding with only one slot per pole per phase is called a concentrated winding. In this type of winding, the e.m.f. generated/phase is equal to the arithmetic sum of the individual coil e.m.f.s in that phase. However, if the coils/phase are distributed over several slots in space (distributed winding), the e.m.f.s in the coils are not in phase (i.e., phase difference is not zero) but are displaced from each by the **slot angle** β (The angular displacement in electrical agrees between the adjacent slots is called slot angle). The e.m.f./phase will be the phasor sum of coil e.m.f.s. The distribution factor Kd is defined as:

$$K_d = \frac{\text{e.m.f. with distributed winding}}{\text{e.m.f. with concentrated winding}}$$

$$= \frac{\text{phasor sum of coil e.m.f.s/phase}}{\text{arithmetic sum of coil e.m.f.s/phase}}$$

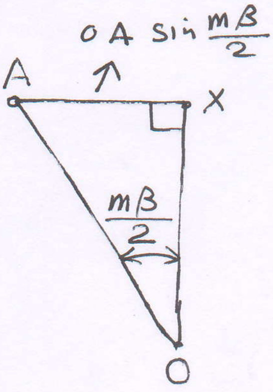
Note that numerator is less than denominator so that $K_d < 1$.

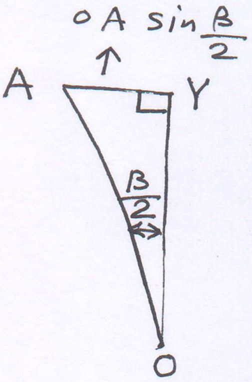
Expression for K_d

Let β = slot angle $= \frac{180^\circ \text{ electrical}}{\text{No. of slots/pole}} = \frac{180^\circ}{n}$

m = slots per pole per phase $= \frac{n}{3}$

The distribution factor can be determined by constructing a phasor diagram for the coil e.m.f.s. Let m = 3. The three coil e.m.f.s are shown as phasors AB, BC and CD [See Fig. 10 (i)] each of which is a chord of circle with centre at O and subtends an angle β at O. The phasor sum of the coil e.m.f.s subtends an angle mβ (Here m = 3) at O. Draw perpendicular bisectors of each chord such as Ox, Oy etc [See Fig. 10 (ii)].





$$K_d = \frac{AD}{m \times AB} = \frac{2 \times Ax}{m \times (2Ay)} = \frac{Ax}{m \times Ay}$$

$$= \frac{OA \times \sin(m\beta/2)}{m \times OA \times \sin(\beta/2)}$$

$$\therefore \quad K_d = \frac{\sin(m\beta/2)}{m \sin(\beta/2)}$$

Note that (m β) is the phase spread.

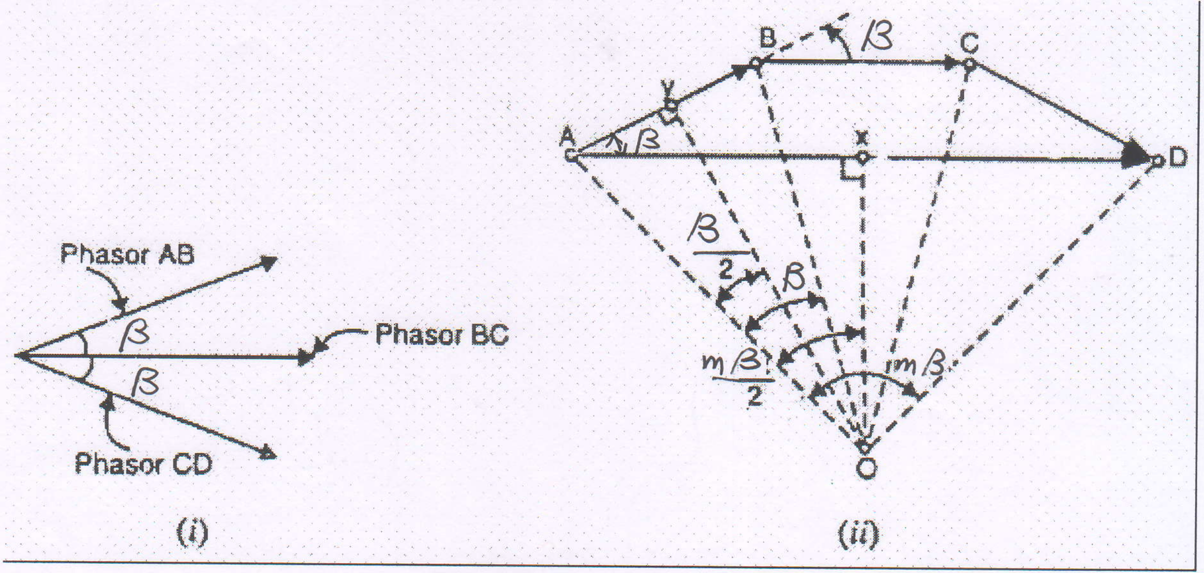


Fig. 10

(ii) Pitch factor (K_p) :

A coil whose sides are separated by one pole pitch (i.e., coil span is 180° electrical) is called a full-pitch coil. With a full-pitch coil, the e.m.f.s induced in the two coil sides a in phase with each other and the resultant e.m.f. is the arithmetic sum of individual e.m.fs. However the waveform of the resultant e.m.f. can be improved by making the coil pitch less than a pole pitch. Such a coil is called short-pitch coil. This practice is only possible with double-layer type of winding The e.m.f. induced in a short-pitch coil is less than that of a fullpitch coil. The factor by which e.m.f. per coil is reduced is called pitch factor K_p. It is defined as:

$$K_p = \frac{\text{e.m.f. induced in short - pitch coil}}{\text{e.m.f. induced in full - pitch coil}}$$

Consider a coil AB which is short-pitch by an angle Θ electrical degrees as shown in Fig. (11). The e.m.f.s generated in the coil sides A and B differ in phase by an angle Θ and can be represented by phasors E_A and E_B respectively as shown in Fig. (12). The diagonal of the parallelogram represents the resultant e.m.f. E_R of the coil.

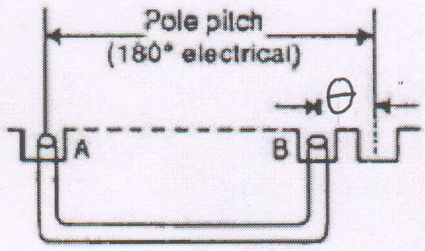
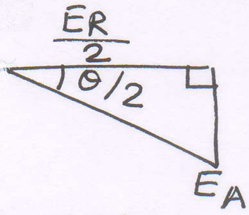


Fig. 11



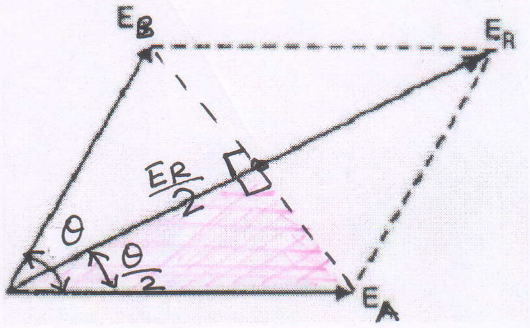


Fig. 12

Phasor sum

Since $E_A = E_B$, $E_R = 2E_A \cos\theta/2$

$$\text{Pitch factor, } K_p = \frac{\text{e.m.f. in short - pitch coil}}{\text{e.m.f. in full - pitch coil}} = \frac{2E_A \cos\theta/2}{2E_A} = \cos\theta/2$$

$\therefore \quad K_p = \cos\theta/2$

arithmetic sum
$E_A + E_A$

For a full-pitch winding, $K_p = 1$. However, for a short-pitch winding, $K_p < 1$.

Note that Θ is always an integer multiple of the slot angle β.