

1 Rotating Magnetic Field

1.1 Overview

Simplest way to develop a rotating magnetic field is to physically rotate a permanent bar magnet about its axis. In this unit, some elegant methods of producing a rotating magnetic field is discussed which do not require any thing to be physically rotated.

1.2 Summary

A rotating magnetic field can be created by a balanced polyphase distributed winding carrying balanced polyphase current. The unit emphasises how to decide on the magnitude, speed and direction of such rotating field created by the distributed winding. The term synchronous speed which is nothing but the speed of the rotating field is introduced.

1.3 Objectives

After going through the unit, the students will be able to:

1. appreciate that a rotating magnetic field can also be created by stationary coils carrying currents.
2. calculate speed and direction of rotation of such field.
3. identify factors on which speed of rotation of the field depends.

1.4 Suggested material to meet the objectives

Rotating magnetic field

A permanent bar magnet if rotated by some external agency will produce a rotating magnetic field. Obviously the speed of this rotating field is decided by the speed at which it is driven as shown in figure 1(a).

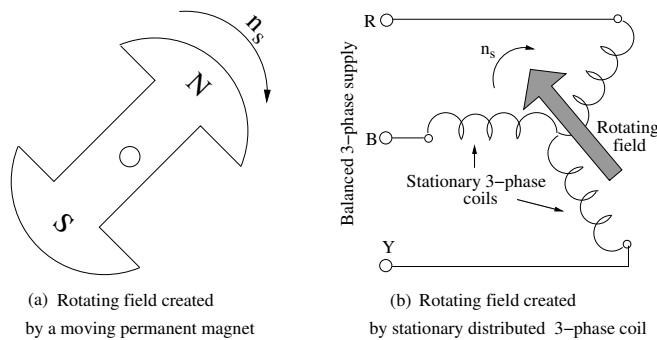


Figure 1: Production of rotating field.

It was Nicolus Tesla who for the first time invented that the above kind of rotating field can also be created without using any kind of mechanical rotation. He explained that a *3-phase distributed stationary coil* as shown in the figure 2, energised from a three phase balanced power supply, produces a *rotating magnetic field* the speed of which is given by $n_s = \frac{2f}{p}$ rps with respect to the structure which houses 3-phase distributed coil, f being the supply frequency and p being the number of poles of the machine. This speed, n_s , is called the *synchronous speed*. Figure 1(b) depicts the suggested alternative way of producing a rotating magnetic field by using stationary coils.

Elementary 3-phase distributed winding

The term *distributed* means, the coils comprising the winding are distributed in space along the air gap of the machine. The direction of the magnetic field produced by the coils will therefore be naturally different. If the axes of the coils are mutually displaced in space 120° , the field directions of the coils too will be displaced mutually by 120° . In contrast, the coils on the limb of the transformer can not be said to be distributed in space as the fields created by different turns are all along the same direction. An elementary 3-phase winding distributed in space is shown as sectional view in the figure 2(a). Each coil is rectangular shaped and the coil sides are put in the diametrically opposite slots. The coil sides are joined at the back and in the front two free terminals are available. The start of A phase coil is marked with a and its finish is marked with a' . The start of B phase begins after 120° from the start of A phase and start of C phase begins after 120° from the start of B phase. It may be noted that the angle between any two consecutive slots is 60° . If at any time current enters through the start point of phase A, i.e., a , the field produced will be directed along vertically. Similarly when current enters through the starts of B and C phase coils the field produced will be mutually displaced in space by 120° . This three phase winding has one coil per phase and produces two poles. It is possible to have winding producing more than two poles which is discussed in detail in the latter stage.

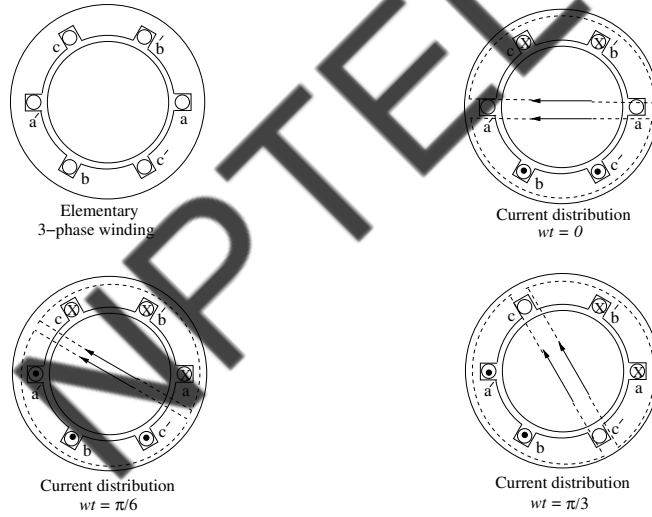


Figure 2: Rotating field by distributed coil.

We have seen earlier, that a single rectangular coil carrying direct current shown in figure 3, produces an *rectangular* mmf distribution in space as shown in the figure 4. The height of the rectangular mmf is proportional to the magnitude of the current and the number of turns of the coil. This mmf distribution along the air gap of the machine is equivalent to a strong fundamental and a number odd harmonics with progressively reduced magnitudes. To begin with we shall only consider the fundamental component of the mmf and *neglect the other harmonics*.

Obviously so long the current through the coil is fixed, M_{max} is constant. However, if the current through the coil is a harmonically varying function of time, M_{max} will be modulated by the time varying term and it can be expressed as $M_{max} = B_{peak} \cos \omega t$ when the current through the coil is assumed to be $i_{aa'} = I_{max} \cos \omega t$. Therefore mmf distribution for a single coil carrying alternating current, considering fundamental component alone, is given by:

$$b_a = B_{peak} \cos \omega t \cos \theta$$

This distribution will be pictured in the figure 5, where each sinusoid corresponds to a particular time. At times when instantaneous current is zero, mmf distribution will be the flat along θ axis.

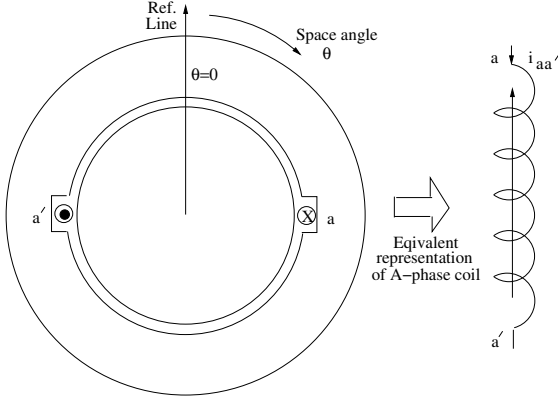


Figure 3: A coil carrying constant current.

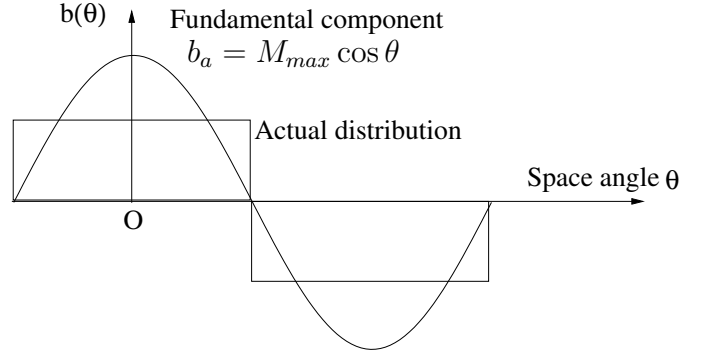


Figure 4: MMF distribution in space.

With reversal of current, the mmf distribution will suffer a reversal. Such an mmf distribution in the air gap of the machine is called a *standing pulsating wave*. In conclusion we can say, a single coil carrying alternating current, produces a *pulsating* but *standing* mmf distribution in the air gap. This result can be applied to obtain the resultant field distribution when a 3-phase winding carry balanced 3-phase alternating current. Let the currents through the coils be:

$$\begin{aligned} i_a = i_{aa'} &= I_{max} \cos \omega t \\ i_b = i_{bb'} &= I_{max} \cos(\omega t - \frac{2\pi}{3}) \\ i_c = i_{cc'} &= I_{max} \cos(\omega t + \frac{2\pi}{3}) \end{aligned}$$

Now noting that the space angle θ is measured from the point where maximum mmf of A-phase occurs or from the axis of the A-phase coil, the θ coordinate of the same point will be $(\theta - \frac{2\pi}{3})$ and $(\theta + \frac{2\pi}{3})$ with respect to B and C-phase respectively as shown in the figure 6.

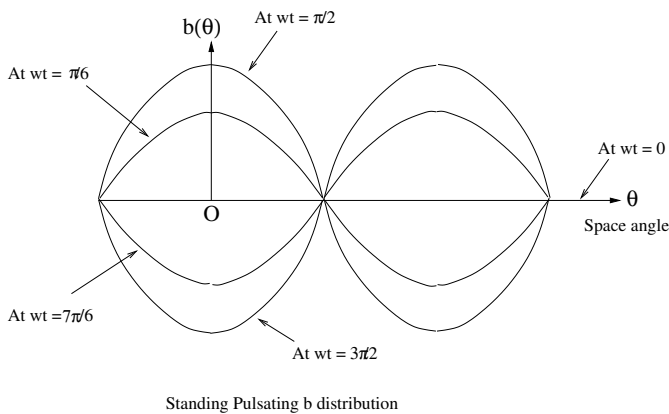


Figure 5: Pulsating field.

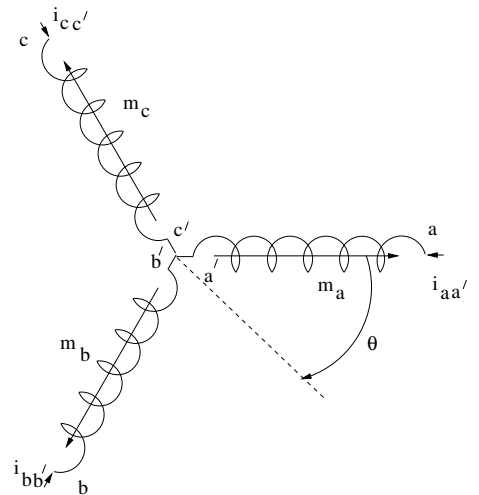


Figure 6: Simplified representation of 3-phase winding.

The sum of the fields of the 3-phases at a given arbitrary position will give the resultant field i.e., $b_{res} = b_a + b_b + b_c$. Fields contributed by the individual phases are given by:

$$b_a = B_{peak} \cos \omega t \cos \theta$$

$$b_b = B_{peak} \cos\left(\omega t - \frac{2\pi}{3}\right) \cos\left(\theta - \frac{2\pi}{3}\right)$$

$$b_c = B_{peak} \cos\left(\omega t + \frac{2\pi}{3}\right) \cos\left(\theta + \frac{2\pi}{3}\right)$$

The resultant field, $b_{res} = b_a + b_b + b_c$

$$\begin{aligned} &= B_{peak} \cos \omega t \cos \theta + B_{peak} \cos\left(\omega t - \frac{2\pi}{3}\right) \cos\left(\theta - \frac{2\pi}{3}\right) \\ &\quad + B_{peak} \cos\left(\omega t + \frac{2\pi}{3}\right) \cos\left(\theta + \frac{2\pi}{3}\right) \end{aligned}$$

Simplifying, we get, $b_{res} = \frac{3}{2} B_{peak} \cos(\theta - \omega t)$

The final expression of the b_{res} is the familiar equation of a *rotating field* moving with an angular velocity of ω radian per second and in the direction of θ . If we could take snap shots of the resultant field at various time, the field distribution would look like as shown in figure 7. A sinusoidal mmf wave with constant amplitude of $\frac{3}{2} B_{peak}$ is moving from left to right where B_{peak} is the maximum value of mmf produced per phase. In the above we have assumed that supply A-phase, B-Phase and

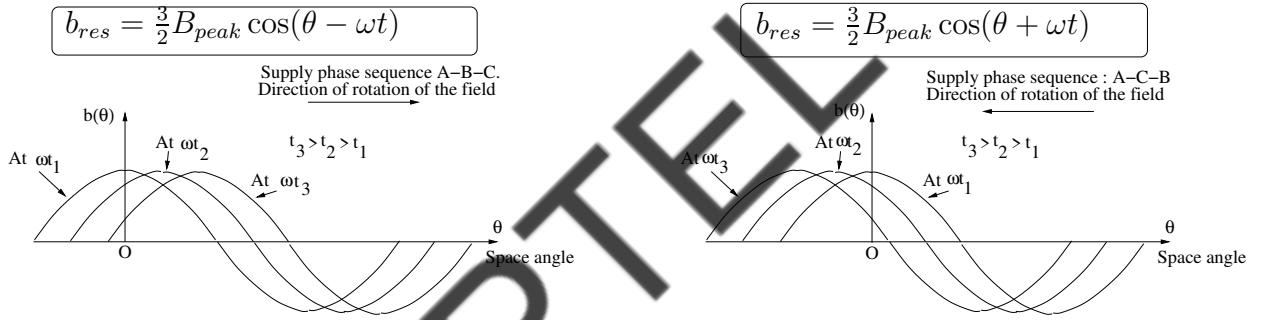


Figure 7: Rotating field - phase sequence A-B-C. Figure 8: Rotating field - phase sequence A-C-B.

C-phase are connected respectively to winding terminals terminal a , b and c . In other words supply phase sequence has been A-B-C. The rotating field physically rotates from the axis of a-phase coil, to axis of b-phase coil and to c-phase axis. The direction of rotation of this field can be easily changed by changing the supply phase sequence. Suppose supply B-phase is connected to winding terminal c and supply C-phase is connected to winding terminal b and the supply A-phase is connected to winding terminal a . In this case, the winding currents can be written as,

$$\begin{aligned} i_a = i_{aa'} &= I_{max} \cos \omega t \\ i_b = i_{bb'} &= I_{max} \cos\left(\omega t + \frac{2\pi}{3}\right) \\ i_c = i_{cc'} &= I_{max} \cos\left(\omega t - \frac{2\pi}{3}\right) \end{aligned}$$

The individual and resultant mmf distribution will be:

$$b_a = B_{peak} \cos \omega t \cos \theta$$

$$b_b = B_{peak} \cos\left(\omega t + \frac{2\pi}{3}\right) \cos\left(\theta - \frac{2\pi}{3}\right)$$

$$b_c = B_{peak} \cos\left(\omega t - \frac{2\pi}{3}\right) \cos\left(\theta + \frac{2\pi}{3}\right)$$

The resultant field, $b_{res} = b_a + b_b + b_c$

$$\begin{aligned} &= B_{peak} \cos \omega t \cos \theta + B_{peak} \cos\left(\omega t - \frac{2\pi}{3}\right) \cos\left(\theta - \frac{2\pi}{3}\right) \\ &\quad + B_{peak} \cos\left(\omega t + \frac{2\pi}{3}\right) \cos\left(\theta + \frac{2\pi}{3}\right) \end{aligned}$$

$$+B_{peak} \cos(\omega t + \frac{2\pi}{3}) \cos(\theta + \frac{2\pi}{3})$$

Simplifying, we get, $b_{res} = \frac{3}{2}B_{peak} \cos(\theta + \omega t)$

From the final expression it can be concluded that the rotating field now moves in the opposite direction as shown in figure 8.

We can also show that a rotating field will result by vectorially adding the individual fields produced by the phases at different instants of time. Consider the instant $\omega t = 0$, assuming phase sequence to be A-B-C, $i_{aa'} = +I_{max}$, $i_{bb'} = -\frac{1}{2}I_{max}$ and $i_{cc'} = +\frac{1}{2}I_{max}$. Therefore, field produced by A-phase will be B_{peak} and will be directed along the axis of the phase in the radially outward direction. Field strength of B-phase will be $\frac{1}{2}B_{peak}$ and will be directed inward since the current is negative. Similarly C-phase field will be $\frac{1}{2}B_{peak}$ but directed outward as the current is positive. The situation is explained in the figure 9. After vector addition, the resultant field strength is found to be $\frac{3}{2}B_{peak}$ and directed horizontally.

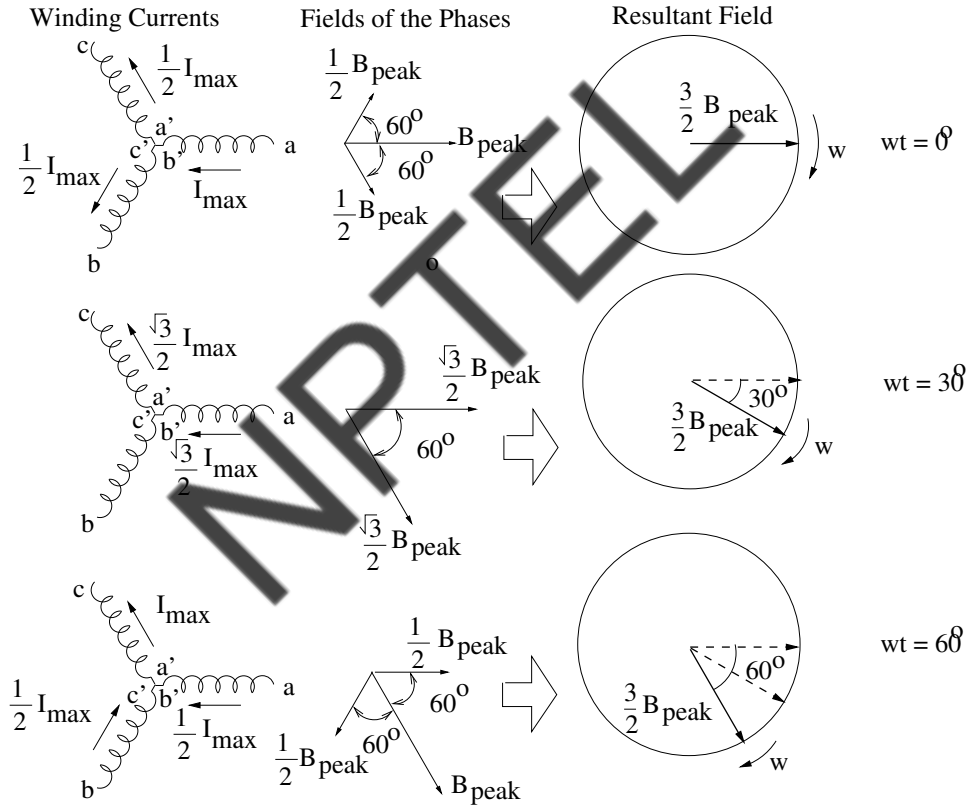


Figure 9: Winding currents and resultant fields at different instants.

The same thing is repeated for $\omega t = 30^\circ$ and the resultant field strength is found to remain same as that of $\omega t = 0$ however its direction is shifted by 30° in the clockwise direction. In this way at different times if this exercise is carried out we find that a constant strength field rotates with a velocity of ω .

Instead of considering different times and obtaining resultant field in the above way, one can arrive at the same result by considering any arbitrary time ωt . The instantaneous fields of the three phases are shown in the figure 10 for any arbitrary time. The sum of these three space vectors b_a, b_b and b_c will give us the resultant field. For simplification in addition, we find out the X-components and the Y-components of the vectors. The X-component of the resultant will be the sum of the X-components of the constituent vectors and the Y-component of the resultant will be the sum of the Y-components of the constituent vectors. Now at any time ωt ,

$$\text{X-component of } b_a = B_{peak} \cos \omega t$$

$$\text{X-component of } b_b = -B_{peak} \cos(\omega t - 120^\circ) \cos 60^\circ$$

$$\text{X-component of } b_c = -B_{peak} \cos(\omega t + 120^\circ) \cos 60^\circ$$

$$B_{res}(x) = B_{peak} \cos \omega t - B_{peak} \cos(\omega t - 120^\circ) \cos 60^\circ - B_{peak} \cos(\omega t + 120^\circ) \cos 60^\circ$$

$$\text{Y-component of } b_a = 0$$

$$\text{Y-component of } b_b = -B_{peak} \cos(\omega t - 120^\circ) \sin 60^\circ$$

$$\text{Y-component of } b_c = B_{peak} \cos(\omega t + 120^\circ) \sin 60^\circ$$

$$B_{res}(y) = -B_{peak} \cos(\omega t - 120^\circ) \sin 60^\circ + B_{peak} \cos(\omega t + 120^\circ) \sin 60^\circ$$

It is left as an exercise to the reader to verify that the

$$\text{Resultant field, } B_{res} = \sqrt{B_{res}^2(x) + B_{res}^2(y)} = \frac{3}{2} B_{peak}$$

$$\text{The angle by which it is displaced from X-axis is } \tan^{-1} \frac{B_{res}(y)}{B_{res}(x)} = -\omega t$$

The above treatment confirm that at all times the resultant field strength is $\frac{3}{2} B_{peak}$ and as time elapses by ωt the field too rotates by an angle of ωt . Naturally the mechanical speed of the rotating field will be 3000rpm for 50Hz supply frequency. Recall that in a 2-pole machine mechanical and electrical speeds are equal.

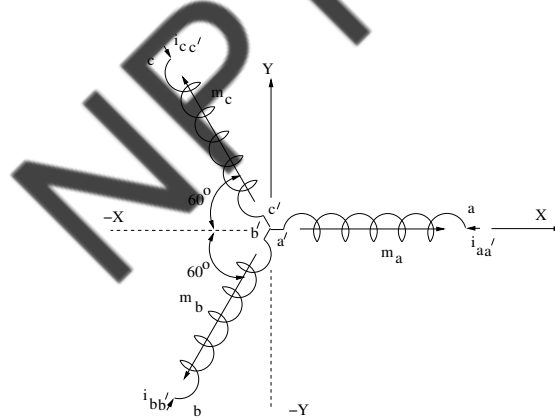


Figure 10: individual fields at any arbitrary time.

3-phase windings with more than two pole

The elementary 3-phase winding considered above can produce 2-pole rotating magnetic field. It is possible to have distributed windings which can produce 4, 6, 8 $\dots$ number of poles also. Here we shall discuss in brief how 4-pole winding can be carried out. Consider only A-phase of the winding. Unlike two pole winding, here the A-phase must have two coils, each producing a pair of pole. The terminals of the coils are marked as $A_1 - A'_1$ and $A_2 - A'_2$ respectively for the two coils belonging to A-phase as shown in figure 11. The angle between any two consecutive slots is 30° mechanical. The coil span in this case should be 90° mechanical (or 180° electrical) as the number of pole is 4. For this reason, the return coil side of the first coil is placed after 3 slots from the start coil side. The start of the second coil is 180° mechanical (or 360°) electrical away from the start of the first coil.

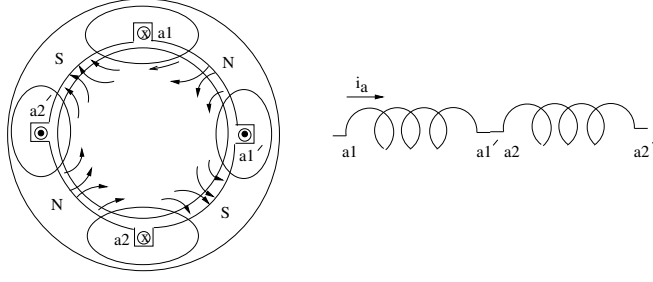


Figure 11: Two coils producing 4-pole.

If the coils are connected in series and current enters through terminal A_1 and leaves from terminal A'_2 , then 4-pole will be produced in the air gap as depicted in figure 11.

In order to produce a 4-pole rotating magnetic field, a 3-phase distributed winding is necessary. Naturally a minimum of 4 number of slots will be required for each phase i.e., 12 slots in all. Mechanical angle between two consecutive slot is 30° (or 60° electrical). We already know how A-phase has been wound. if you look at the winding shown in figure 12 carefully, it will be noticed that B-phase and C-phase coils are in no way different from the A-phase coils, except for the fact that they are displaced in space by 120° electrical angle. The simplified connection is shown beside with the phases connected in star.

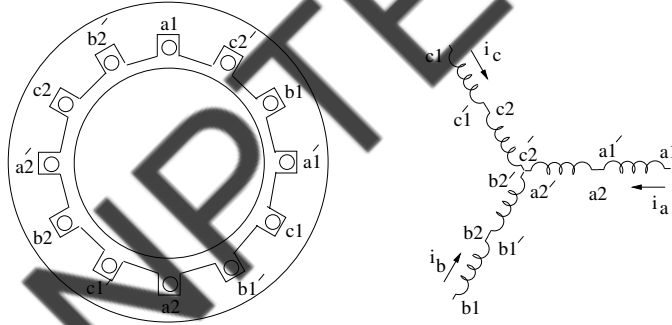


Figure 12: 3-phase winding for 4-pole.

As we did earlier for 2-pole connection, direction of current distributions in the coils at different instants are shown in figure 13 assuming the phase currents to be $i_a = I_{max} \cos \omega t$, $i_b = I_{max} \cos(\omega t + \frac{2\pi}{3})$ and $i_c = I_{max} \cos(\omega t - \frac{2\pi}{3})$. From the pattern of the flux lines, it is easily seen that indeed 4-poles are produced and that moves in the clockwise direction. However the mechanical speed of the rotating field in this case is 1500 rpm, half that of the 2-pole case. When angular time changes from $\omega t = 0$ to $\omega t = 60^\circ$, the resultant field rotates by 30 mechanical degrees. Electrical speed of the field is of course always 3000 rpm and independent of the number poles.

In general following comments can be made about the production of rotating magnetic field:

- A single phase winding, excited from a single phase source, produces a *standing pulsating field*. No rotating field is possible.
- A balanced *polyphase* distributed winding wound for p number of poles, and excited by a polyphase supply system ,produces a rotating magnetic field. As our supply system is 3-phase, 3-phase winding is most popular and widely used.
- The *mechanical speed* of such a field is given by $n_s = \frac{2f}{p}$ rps = $\frac{120f}{p}$ rpm where p is the number of poles.

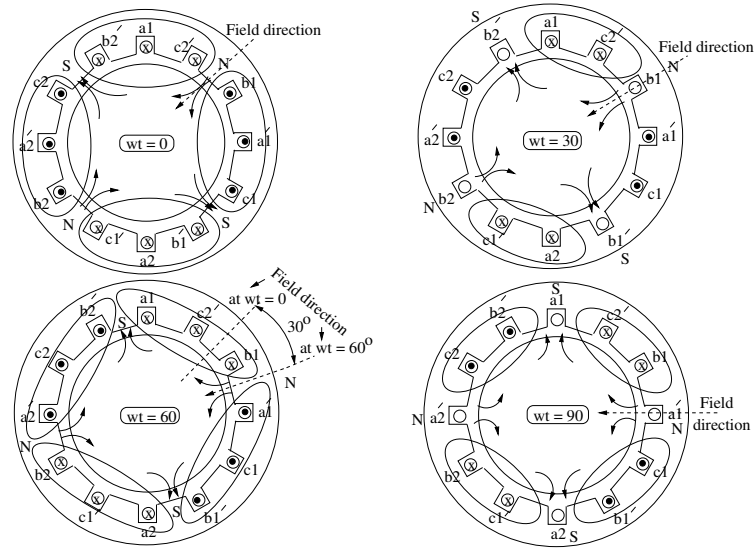


Figure 13: Current distribution at different times & resultant field.

- The direction of rotation of such a field, depends upon the supply phase sequence. in fact by changing phase sequence, one can reverse the direction of rotation of the field.

1.5 Problems

1. Suppose a balanced 3-phase, 6 pole, distributed winding is housed on a stationary structure. If it is energised from a 3-phase, 50 Hz supply, calculate the speed of the rotating field with respect to a stationary observer.
2. Suppose a 3-phase distributed winding when excited, produces a rotating field in the clock wise direction. What should be done to reverse the direction of the field?
3. Suppose a balanced 3-phase, 6 pole, distributed winding is housed on a structure which can be rotated by external means. If it is energised from a 3-phase, 50 Hz supply, calculate
 - (i) the speed of the rotating field with respect to a stationary observer if the rotor speed is zero.
 - (ii) the speed of the rotating field with respect to a stationary observer if the rotor speed is 700 rpm in the same direction of the rotating field.
 - (iii) the speed of the rotating field with respect to a stationary observer if the rotor speed is 700 rpm in the opposite direction of the rotating field.
 - (iv) the speed of the rotating field with respect to an observer sitting on rotor, if the rotor speed is zero.
 - (v) the speed of the rotating field with respect to an observer sitting on rotor, if the rotor speed is 700 rpm in the same direction of the rotating field.
 - (vi) the speed of the rotating field with respect to an observer sitting on rotor if the rotor speed is 700 rpm in the opposite direction of the rotating field.
4. A 3-phase, 8 pole, distributed winding is excited from a 3-phase, 4 pole generator which is driven at 1000 rpm by a diesel engine. Calculate the speed of the rotating field.

Three Phase Winding

Tapas Kumar Bhattacharya

Department of Electrical Engineering
I.I.T Kharagpur

January 18, 2019

NPTEL

Contents

1	Typical three phase distributed winding	2
1.1	Overview	2
1.2	Objectives	2
1.3	Example of a typical double layer, 3-phase winding	2
1.4	Numbering a coil	3
1.5	Developed diagram	3
1.6	An example	4
1.7	Problems	5

1 Typical three phase distributed winding

1.1 Overview

In this unit, practical 3 phase-windings are dealt with. In practice, a number of interconnected distributed coils constitute a phase winding and these coils may also be short chorded. Basic winding terms are first presented and then with the help of an example, a 3-phase double layer problem is solved.

1.2 Objectives

After going through this unit, students will be able to

1. get acquainted with some basic terms such as coil span, pole pitch, the meaning of double layer winding etc.
2. make a winding table for a 3-phase double layer winding.
3. draw the winding diagram from the winding table.
4. understand the phase spread of a 3-phase winding.
5. connect groups of coil belonging to a particular phase with due regard to the polarity.

1.3 Example of a typical double layer, 3-phase winding

- A **coil** has two coil sides occupying two distinct specified slots. Generally to maximize induced voltage in a coil, the spacing between them should be close to 180° electrical. This essentially means that if at a given time one coil side is under the center of the north pole, the other coil side should be under the center of the adjacent south pole and the coil is said to be a full pitched coil.
- **Coil span** is nothing but the spacing between the two coil sides of a coil. The spacing is expressed in terms of number of slots between the sides. If S be the total number of slots and P be the total number of poles then coil span is S/P for a full pitched coil. For 12 slots, 2 pole winding, coil span is 6. Let the slots be numbered serially as $1, 2, \dots, 12$. If one coil side is placed in slot number 3, the other coil side of the coil must occupy slot number 9 ($= 3 + 6$).

- A **Double layer winding** means that each slot will house two coil sides obviously belonging to two different coils). Physically one coil side is placed at the bottom portion of the slot while the other is placed above it. It is because of this reason such an arrangement of the winding is called a *double layer* winding. In the n th slot, coil side in the upper deck is numbered as n and the coil side in the lower deck is numbered as n' . In the 5th slot upper coil side is numbered as 5 and the lower coil side is numbered 5'. In the winding diagram, upper coil side is shown with firm line while the lower coil side is shown with dashed line.

Remembering that a coil has two coil sides, for a double layer winding total number of coils must be equal to the total number of slots.

1.4 Numbering a coil

A coil is so *shaped*, that when it is placed in appropriate slots, one coil side will be in the upper deck and the other side will be in the lower deck. Suppose $S = 12$ and $P = 2$, then coil span is 6. Let the upper coil side of a coil be placed in slot number 1, the other coil side must be in the lower deck of slot number 7. The coil should now be identified as $(1 - 7')$. In other words coil sides of a coil are numbered depending on the slot numbers in which these are placed. A typical single turn and multi turn coils are shown in figure 1.

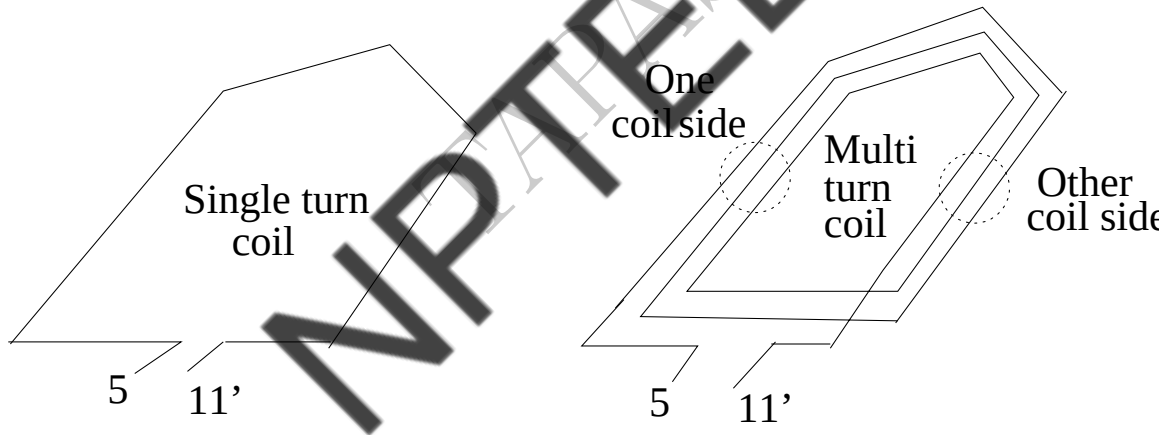


Figure 1: Single turn & Multi turn coil.

1.5 Developed diagram

Instead of dealing with circular disposition of the slots, it is always advantageous to work with the developed diagram of the slots as elaborated in figure 2. In the figure 2, actual armature with 8

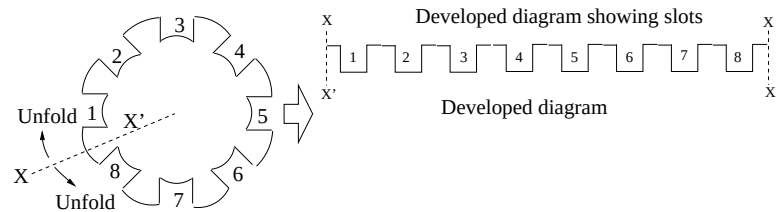


Figure 2: Actual and developed diagram of the slots

slots are shown. Imagine the structure to be cut radially along the line $XX'O$ and unfolded along the directions shown to make it straight.

1.6 An example

Let us try to make 3-phase balanced winding with the following specifications. Total number of slots $S = 12$

Number of poles $P = 2$ Winding should be double layer.

Coil span = 180°

Under each pole number of slots = $12/2 = 6$. Therefore, 6 slots corresponds to 180° electrical. Slot pitch = angle between two consecutive slots $\beta = \frac{180^\circ}{6} = 30^\circ$. Under each pole 2 slots each will be allotted to A, B and C phase. When equal number of slots are allotted to each phase, the winding is 60° phase spread winding. Knowing that B-phase winding will start after 120° from the start of A-phase and C-phase will start after 120° from the start of B-phase, we can make a schematic representation of the winding as shown below.

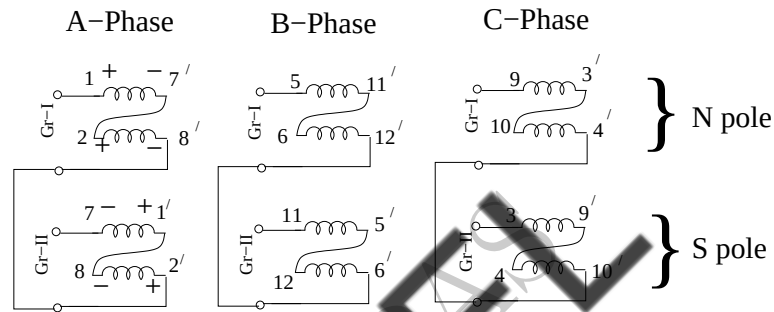


Figure 3: Schematic winding representation

It may be noted that there will be two groups of coil for each phase - one corresponding to N-pole and the other corresponding to S-pole. Groups of a particular phase are connected in series with due regard to the polarity of the induced voltage as detailed in the winding table shown in figure 3. After the winding table is made, actual winding is carried out as shown figure 4. For clarity, only the A-phase winding is shown with its two groups. Windings for B and C-phase will be identical with a mutual displacement of 120° (equivalent to 4 slots)

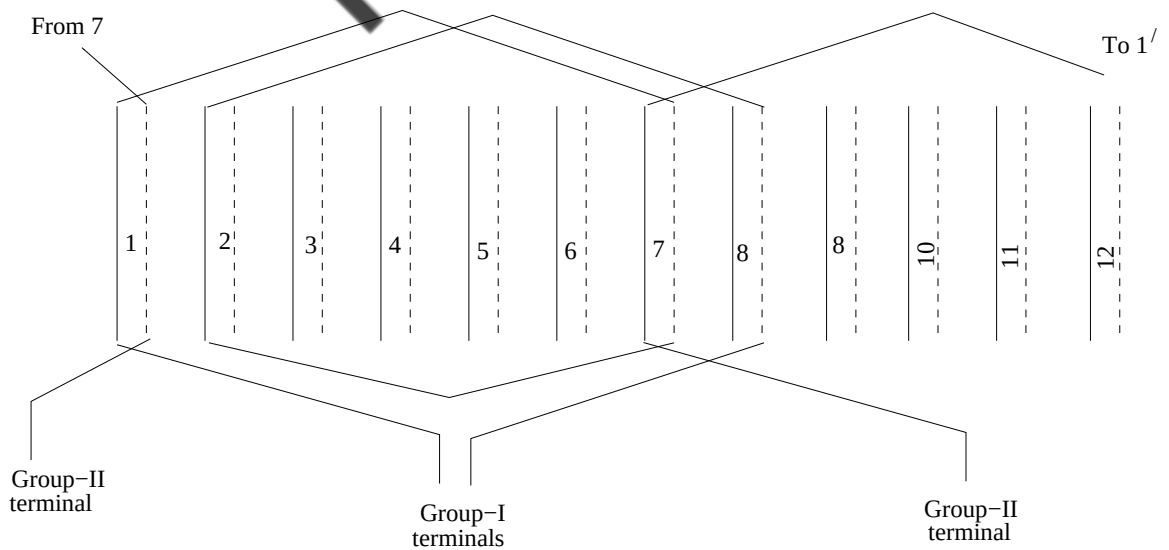


Figure 4: Winding diagram for A-Phase only

1.7 Problems

1. What is pole pitch of a p polar rotating machine in (i) electrical degrees (ii) in mechanical degrees?

Solution

- (i) Pole pitch is 180° in electrical degrees.
- (ii) Pole pitch is $(2/p)180^\circ = 360^\circ/p$ in mechanical degrees.

2. For a full pitched coil, what is the coil span in electrical degrees?

Solution

Coil span = pole pitch = 180° electrical.

3. A balanced three phase, 6-pole, 60° phase spread, distributed winding is housed on 54 number of slots. A-phase winding starts from slot number 1. Now answer the following:
 - (a) Start of B-phase and C-phase will begin from what slot numbers?
 - (b) Each phase will have how many groups?
 - (c) Specify the number of the slots from where the groups of A-phase will start?

Solution

$$\begin{aligned}\text{slots per pole} &= 54/6 = 9 \\ \text{angle between two slots} &= 180/9 = 20^\circ \\ \text{Now } 120^\circ \text{ corresponds to} & \quad 120/20 = 6 \text{ slots}\end{aligned}$$

B-phase will start from slot number 7 ($= 1 + 6$) and C-phase will start from slot number 13 ($= 7 + 6$). Since it is a 60° phase spread winding, number of groups of coil belonging to each phase will be equal to the number of poles i.e., 6. The 6 groups of A-phase will start from slot numbers 1, 10, 19, 28, 37, 46 respectively.

4. Repeat problem 3, if the phase spread is 120° . Other specifications same as before.

Solution

The answers of parts (a) is same as that of problem 3. Since it is a 120° phase spread winding number of groups of coil for each phase will be $p/2 = 6/2 = 3$. The 3 groups of A-phase will start from slot numbers 1, 19 and 37 respectively.

5. Make a winding table in order to make a balanced, 3-phase, 4-pole distributed winding with the following specifications:

Total number of slots $S = 36$	Winding should be double layer
Coil to be used is full pitched	Winding should have a phase spread σ of 60°

Solution

$$\text{Slots per pole} = 36/4 = 9$$

$$\text{Slot pitch } \beta = 180/9 = 20^\circ$$

$$\text{Since coils are full pitched, coil span} = 9 \text{ slots}$$

$$\text{No. of slots to be allotted to each phase /pole/phase} = 36/(4 \times 3) = 3$$

Let slot numbers 1, 2 and 3 be allotted to A-phase, then the first group of A-Phase coils will be 1 – 10', 2 – 11' and 3 – 12' since coil span is 9 (full pitched). First group of B-phase has to begin from slot number 7 i.e., 120° apart from start A-phase. Refer to the winding problem discussed in *suggested material*. Since it is a 4-pole winding with 60° phase spread, there will be 4 groups for each phase as shown in the winding table (figure 5). This figure also shows the interconnections of the groups.

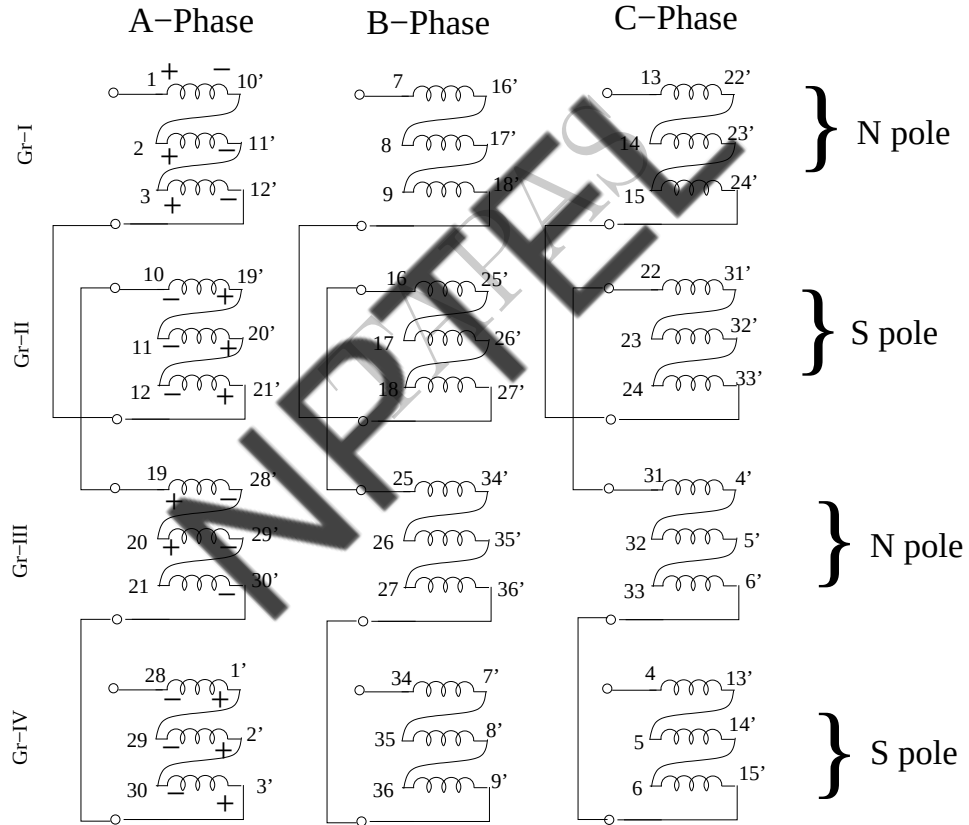


Figure 5: Schematic winding representation

6. Repeat problem 5, with phase spread σ of 120° . Other specifications remaining same.

Solution

$$\text{Slots per pole} = 36/4 = 9$$

$$\text{Slot pitch } \beta = 180/9 = 20^\circ$$

$$\text{Since coils are full pitched, coil span} = 9 \text{ slots}$$

$$\text{Here note, phase spread, } \sigma = 120^\circ$$

$$\text{No. of slots to be allotted to each phase /pole-pair/phase} = 36/(2 \times 3) = 6$$

Let slot numbers 1,2,3,4,5 and 6 be allotted to A-phase, then the first group of A-Phase coils will be 1 – 10', 2 – 11' and 3 – 12' ... 6 – 15' since coil span is 9 (full pitched). First group of B-phase has to begin from slot number 7 i.e., 120° apart from start of A-phase. Refer to the winding problem discussed in *suggested material*. Since it is a 4-pole winding with 120° phase spread, there will be 2 groups for each phase as shown in the schematic winding representation (figure 6). This figure also shows the interconnections of the groups.

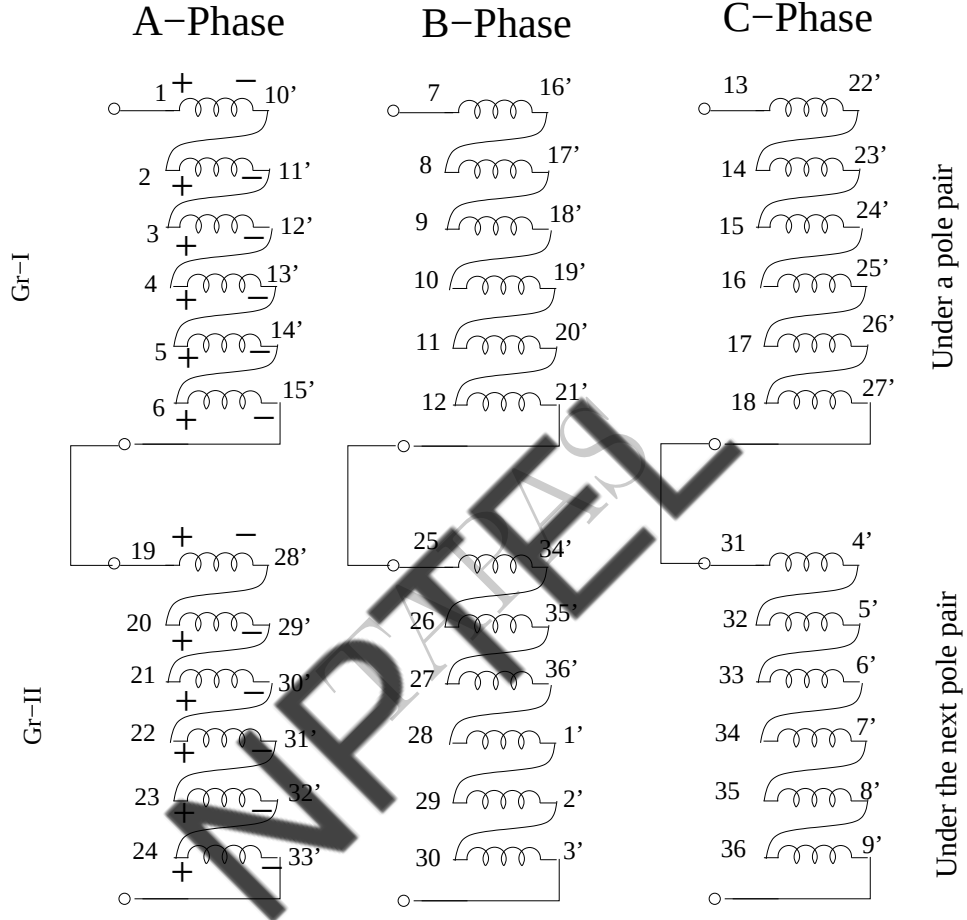


Figure 6: Schematic winding representation