

Production of Rotating Magnetic Fields in Polyphase A.C Machines: A Novel Teaching Approach

Seshanna Panthala

**Faculty of Engineering, Assumption University
Bangkok, Thailand**

Abstract

This paper outlines a novel approach for teaching the topic of rotating magnetic fields produced in polyphase a.c machines. The nature of individual phase mmf is described, both graphically and mathematically, and shown to be stationary and pulsating in the air gap of the machine varying sinusoidally in space and time. The resultant of all the phase mmfs is shown to be a rotating mmf wave with constant amplitude and speed. Finally, a demonstration system built by the author is described which can be used in the classroom to show the pulsating nature of the individual phase mmfs and the rotating nature of the resultant mmf wave in polyphase machines.

Keywords: Pulsating magnetic field, rotating magnetic field, polyphase a.c machine, space distribution, time variation, resultant magnetic field.

1. Introduction

The topic, 'rotating magnetic field', is taught generally just before the chapter on induction motors is taken up for teaching. However, the concept of rotating magnetic field and its production can be taught as an independent topic without reference to any other topics, but prior to polyphase machines are taken up.

The fact that rotating magnetic field can be produced, either by rotating a permanent magnet or an electromagnet, is easy to understand. In fact, one can recall as example a cycle dynamo or a hydro-alternator (salient pole rotor). The speed in rpm of the rotating magnetic field is the same as the speed with which the polar structure moves in these cases.

We are interested in this article to discuss the idea of producing rotating magnetic fields without the physical rotation of any member or part. It was realized that a rotating magnetic field could be produced by stationary polyphase windings carrying polyphase currents by Nikola Tesla and others around 1885. This idea is central to the rotating field theory of a.c machines. This is very interesting and at the

same time difficult to conceive the phenomenon leading to the production of rotating magnetic field without any visible physical rotation.

The first conception (rather misconception) to be cleared is that, a magnetic pole need not be a physical projected pole. This clarification is necessary because students are thus far introduced to bar magnets, their flux plots, and d.c machine polar structures wherein the poles are salient poles (i.e., the poles are standing out). It is to be noted that the magnetic field coming out of a surface constitutes a north pole, and the surface where the magnetic field enters is considered as a south pole. There is no need for any projected poles from the stator surface.

2. Nature of Phase mmf in A.C Machines

We shall begin the topic by first investigating the nature of magnetic field (mmf rather) produced by a distributed winding carrying d.c. Simply speaking when one phase of an induction motor is excited by d.c – what is the nature of mmf in the air gap, all other windings being open circuited? For the sake of simplicity, we shall assume a two-phase

winding on the stator and the rotor being simply a laminated cylinder carrying no winding. This is shown in Fig. 1. Only 'a' phase winding is shown. The conductors marked 'x' (into) carry the current into the paper and others marked '.' (dot) carry the current out of the paper.

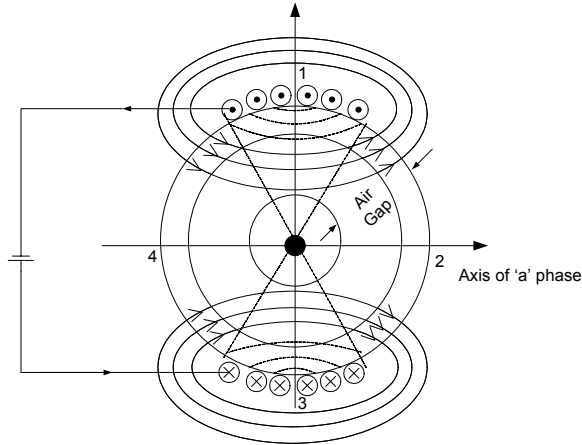


Fig. 1

When a battery is connected to the winding, a direct current flows through the winding and a magnetic field is produced. If the current remains constant, the magnetic field also remains constant. But, will the magnetic field intensity be the same at each point in the air gap? Let us find out. To do this, let the stator surface be spread out as shown in Fig. 2.

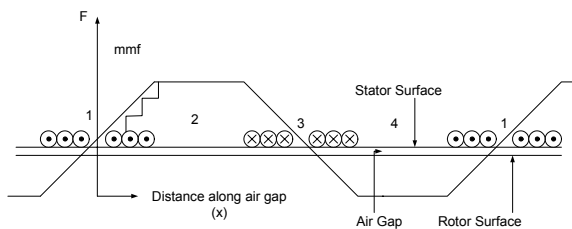


Fig.2

Now, by applying the circuital law ($\oint H \cdot dl = I$) of magnetism, the mmf variation can be graphically represented along the air gap as shown in Fig. 2. The trapezoidal distribution of mmf in space is an approximation – actual variation being stepped. We shall further approximate this trapezoidal distribution to a sine variation to simplify matters. (For rigorous understanding, this means that the fundamental

of the trapezoidal variation is taken and other harmonics are neglected time being.)

Therefore, when one of the stator phase of the machine is excited by d.c, the variation of mmf *along the air gap* will be a sinusoid. Please bear in mind this mmf variation is time independent as long as the current in the winding is constant.

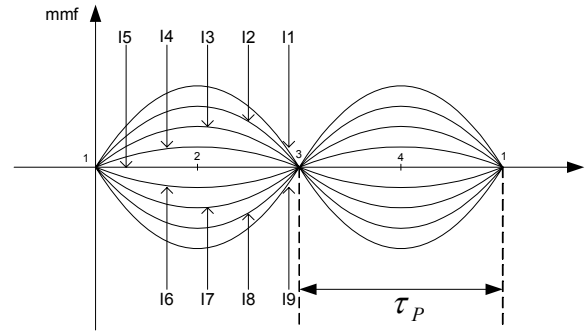


Fig. 3(a)

Fig. 3(a) shows the mmf variation for different direct currents through the winding. When the d.c current through the winding is reduced to I_2 , the variation of mmf will still be a sinusoid but the amplitude will be reduced. As the current magnitude is progressively reduced and then reversed, the mmf distribution undergoes variations as shown in Fig. 3(a). That means, as the current through the winding varies from positive maximum to the negative maximum, the mmf wave reverses polarity once and magnitude will be proportional to the current.

The winding normally carries sinusoidal time varying a.c. The instantaneous values of the current can be regarded as d.c currents and hence, as the current alternates in the winding, the mmf also alternates, but *fixed in space*. The graphical representation looks like a standing wave. The mmf due to a winding carrying a.c does not rotate but alternates only. That means the mmf (flux) of the individual windings of a polyphase machine only alternate with time, but fixed in space with sinusoidal distribution along the air gap of the machine.

It may be worthwhile to represent the mmf waves mathematically. When the winding carries a maximum current (I_1) the distribution is represented as:

$$F(x) = F_1 \sin\left(\frac{\pi}{\tau} x\right) \quad (1)$$

Where x is the distance along the air gap measured from point 1.

F_1 = amplitude of mmf

$\frac{\pi}{\tau}$ = factor which converts distance into angle

τ = pole pitch in meters.

Now, as the current in a phase winding alternates sinusoidally with time, as shown in Fig. 3(b), the amplitude of the mmf wave becomes a function of time.

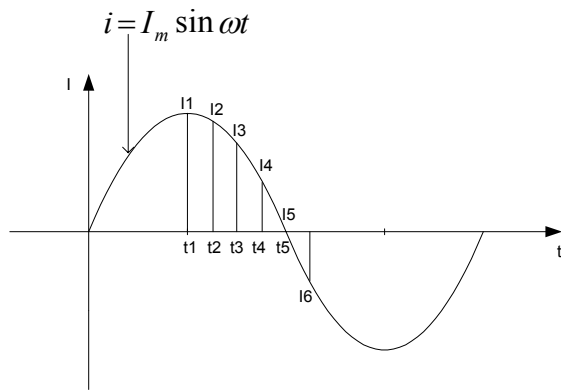


Fig.3 (b)

Therefore,

$$F_a(x, t) = F_1(t) \sin\left(\frac{\pi x}{\tau}\right) \quad (2)$$

The amplitude variation with time is going to be the same function as the variation of current with time. Hence the equation for the phase mmf becomes:

$$F(x, t) = F_m \sin \omega t \left(\sin \frac{\pi x}{\tau} \right) \quad (3)$$

Equation (3) describes what is shown in Fig 3(a). Please note that both time (t) and space (x) have entered into our discussion. It is concluded once again that, the mmf of an individual winding carrying a.c does not rotate but pulsates with a space distribution. The mmf wave is fixed in space.

What happens to the mmf variation of 'a' phase winding carrying a.c must also happen for other windings carrying a.c. But there are two basic differences.

They are:

- (i) The windings occupy different positions in space along stator surface. Hence, the space variation of mmf is thus shifted.
- (ii) The currents through the windings have phase shift in time and the variations in mmf will be delayed or advanced depending on this phase shift.

We are considering a two-phase winding. Hence, we are now in a position to write an equation for the mmf variation due to the 'b' phase winding carrying a.c. under-balanced condition:

$$F_b(x, t) = F_m \sin\left(\omega t - \frac{\pi}{2}\right) \sin\left(\frac{\pi x}{\tau} - \frac{\pi}{2}\right) \quad (4)$$

The angle $\pi/2$ occurs in Equation (4) because the current in 'b' phase lags (in time) the current in 'a' phase by 90° elec, and the 'b' phase axis is shifted in space behind 'a' phase axis by 90° elec (space).

3. The Resultant mmf Wave

As we are interested in the resultant field produced by the balanced two-phase winding carrying two-phase currents, it is pertinent to add Equations (3) and (4) to get the equation for the resultant field. Hence:

$$\begin{aligned} F_r(x, t) &= F_a(x, t) + F_b(x, t) \\ &= F_m \left[\sin \omega t \sin \frac{\pi x}{\tau} + \cos \omega t \cos \frac{\pi x}{\tau} \right] \\ &= F_m \cos\left(\omega t - \frac{\pi x}{\tau}\right) \end{aligned} \quad (5)$$

4. Speed of the Resultant mmf Wave

The fact that Equation (5) represents a rotating magnetic field with constant amplitude F_m and with speed ω rad/s is shown below.

There are many ways to show the rotating nature of the mmf wave as described by Equation (5) (Panthala 1974). The basis for the method we are going to use is the following:

Suppose you are moving with a speed of 30 km/hr and you observe that a particular object appears to be stationary as far as you are concerned. What does that mean? It means that the object itself is moving and moving in the

same direction as yours and with the same speed as you are moving.

We will assume that the resultant magnetic field is moving in the air gap and is given mathematically by the Equation (5).

Now let us install an *observer* on the rotor and drive the rotor at ω rad/s by an external means (see Fig.4).

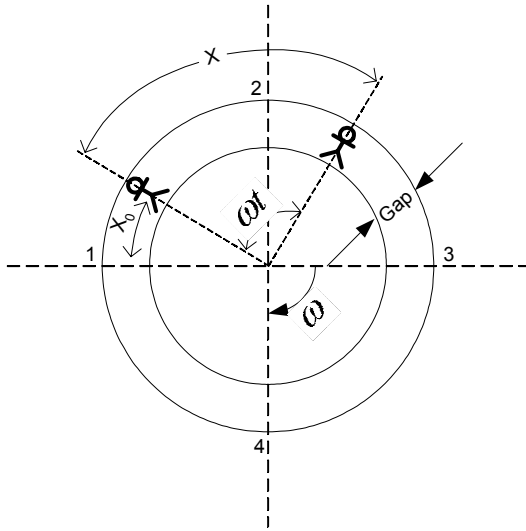


Fig.4

If the observer sees the same magnetic field at all times, then we can conclude that the magnetic field is rotating in the same direction as the observer, and the speed of the field will be ω rad/s.

Let at time $t = 0$, the observer is at a distance x_0 from the origin. Therefore, he sees the magnetic field as:

$$F(t, x)_{t=0, x=x_0} = F_m \cos \frac{\pi x_0}{\tau} \quad (6)$$

After a time " t ", he would have moved by ωt rad. Therefore, at this time, his position from the origin would be:

$$x = x_0 + \omega t * R \quad \text{where:}$$

R = radius of the rotor.

At this time $t = t$, $x = x_0 + \omega R t$ and he sees a magnetic field

$$\begin{aligned} F(x, t)_{\substack{x=x_0+\omega R t \\ t=t}} &= F_m \cos \omega t - \frac{\pi}{\tau} (x_0 + \omega R t) \\ &= F_m \cos \left(\omega t - \frac{\pi x_0}{\tau} - \frac{\pi R}{\tau} \omega t \right) \end{aligned}$$

$$= F_m \cos \left(-\frac{\pi x_0}{\tau} \right) \quad (7)$$

($\frac{\pi R}{\tau} = 1$ because " τ " = pole pitch and " πR " is the half the circumference and for a two pole case it is equal to the pole pitch.)

From Equations (6) and (7), we see that the observer sees the same amount of magnetic field, which confirms that the resultant field is moving with a speed of ω rad/s, and has a constant amplitude.

5. Class Room Demonstration

A portable demonstration model has been built by the author based on the approach adopted in this paper. A photograph of the demonstration system is shown in Fig. 5.

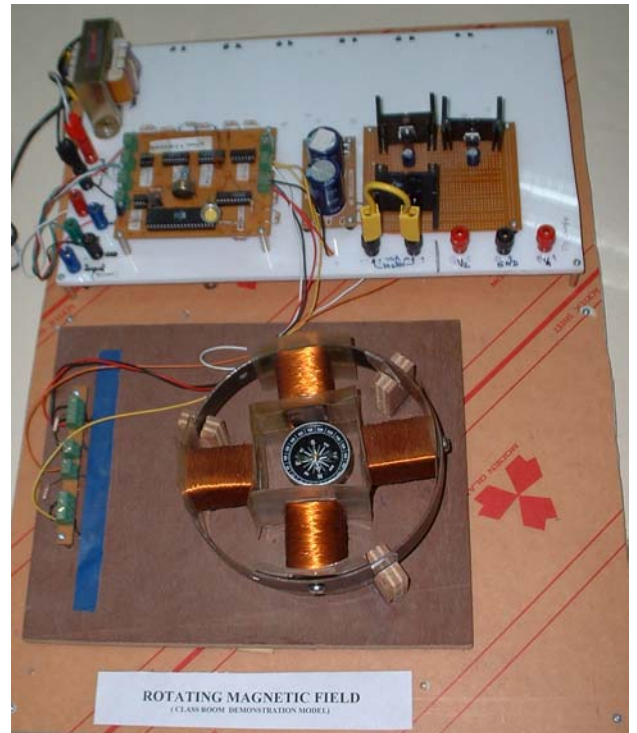


Fig. 5. Rotating magnetic field-classroom demonstration model

The system consists of an electro-mechanical structure representing the stator of an elementary two-phase, two-pole induction motor and a micro-controller based low frequency two-phase a.c generator for exciting the coils of the motor. The electromechanical

structure consists of a circular mild steel ring (160 mm diam.) with four projecting mild steel pieces fixed to it with coils wound on each. The coils are connected such that an elementary two-pole, two-phase arrangement results. A small magnetic compass is located centrally to detect the direction of the magnetic field produced by the coils (see photograph for details). The coils are excited by very low frequency (0.1 Hz) two-phase currents from the low-frequency generator specially constructed for this purpose. It can be observed that the compass needle rotates slowly, confirming the rotating nature of the magnetic field. A center zero ammeter can be used to show the current in each coil. As the current goes through one cycle, the compass needle completes one revolution. The direction of rotation of the field can be reversed easily by interchanging the winding currents. The success of the demonstration depends on the availability of low frequency two-phase generator which was built in the Department of Electrical Engineering using an 8-bit microcontroller (AT89C51) and two digital to analog converters (DAC0800) connected for bipolar operation. The block diagram of the low frequency two-phase a.c generator is shown in Fig.6:

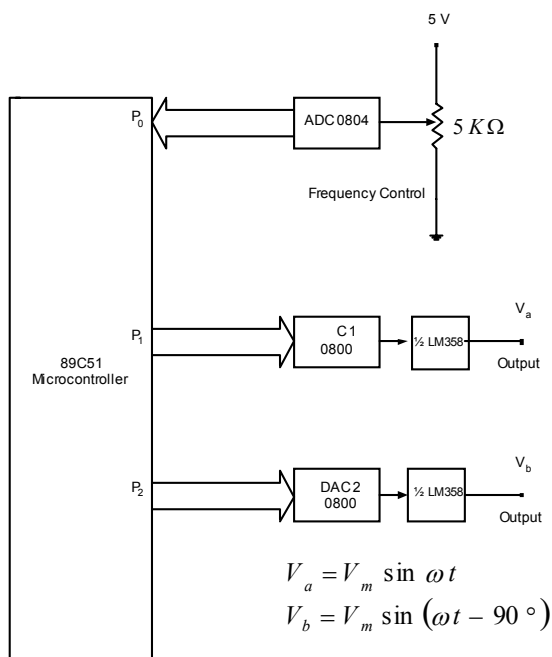


Fig. 6. Block diagram of low-frequency two-phase a.c generator

The readers interested in the details of this generator and the associated software for the microcontroller are advised to contact the author. The required HEX numbers to generate a sine wave were stored in the flash memory of the controller as a look up table. The actual hex numbers-256 in all (Dote and Sakan 1990) that are stored in the flash memory are given in Appendix 1 for those interested to construct the two-phase or three-phase low-frequency sine wave a.c generator using microcontroller and digital to analog converters as shown in the block diagram in Fig.6.

6. Conclusion

The physical and mathematical approach presented herein, it is hoped, will lead to a better understanding of the nature of the individual phase mmfs and their resultant rotating mmf wave in polyphase a.c machines. In particular the rotating magnetic field demonstration system developed will go a long way in conceptualizing the rotating nature of the magnetic field while the windings producing the field are themselves not moving. Even though a two-phase motor winding is taken for developing the approach, it can easily be extended to a three-phase motor winding on similar lines. It is hoped that the electrical engineering teachers will make use of this approach in their teaching.

7. Acknowledgment

The author acknowledges the help rendered by Mr. Narong Aphiratsakun for drawing the figures and formatting the manuscript.

8. References

- Panthala, S. 1974. An approach to teaching rotating mmf waves. Indian J. Tech. Educ. 3: 11-4.
- Dote, Y.; and Sakan, K. 1990. Brushless Servomotors: Fundamentals and Applications. Clarendon Press, Oxford, UK.

Appendix 1

The 256 hex values stored in the flash memory of the microcontroller AT89C51 as a look up table are given below. These values are sent to the DACs at regular intervals to generate the required sine waves. The required phase shift can be achieved between the sine waves by suitably off setting the pointer.

80H,83H,86H,89H,8CH,8FH,92H,95H,98H,9BH,9EH,0A1H,0A4H,0A7H,0AAH,0ADH,0B0H
 0B3H,0B6H,0B9H,0BBH,0BEH,0C1H,0C3H,0C6H,0C9H,0CBH,0CEH,0D0H,0D2H,0D5H,0D7H
 0D9H,0DBH,0DEH,0E0H,0E2H,0E4H,0E6H,0E7H,0E9H,0EBH,0ECH,0EEH,0F0H,0F1H,0F2H
 0F4H,0F5H,0F6H,0F7H,0F8H,0F9H,0FAH,0FBH,0FBH,0FCH,0FDH,0FDH,0FEH,0FEH,0FEH
 0FEH,0FEH,0FFH,0FEH,0FEH,0FEH,0FEH,0FEH,0FDH,0FDH,0FCH,0FBH,0FBH,0FAH,0F9H
 0F8H,0F7H,0F6H,0F5H,0F4H,0F2H,0F1H,0F0H,0EEH,0ECH,0EBH,0E9H,0E7H,0E6H,0E4H
 0E2H,0E0H,0DEH,0DBH,0D9H,0D7H,0D5H,0D2H,0D0H,0CEH,0CBH,0C9H,0C6H,0C3H,0CH
 0BEH,0BBH,0B9H,0B6H,0B3H,0B0H,0ADH,0AAH,0A7H,0A4H,0A1H,9EH,9BH,98H,95H,92H
 8FH,8CH,89H,86H,83H,7FH,7CH,79H,76H,73H,70H,6DH,6AH,67H,64H,61H,5EH,5BH,58H,5H
 52H,4FH,4CH,49H,46H,44H,41H,3EH,3CH,39H,36H,34H,31H,2FH,2DH,2AH,28H,26H,24H,2H
 1FH,1DH,1BH,19H,18H,16H,14H,13H,11H,0FH,0EH,0DH,0BH,0AH,09H,08H,07H,06H,05H
 04H,04H,03H,02H,02H,01H,01H,01H,01H,01H,01H,01H,01H,01H,01H,02H,02H,03H,04H
 04H,05H,06H,07H,08H,09H,0AH,0BH,0DH,0EH,0FH,11H,13H,14H,16H,18H,19H,1BH,1DH
 1FH,21H,24H,26H,28H,2AH,2DH,2FH,31H,34H,36H,39H,3CH,3EH,41H,44H,46H,49H,4CH
 4FH,52H,55H,58H,5BH,5EH,61H,64H,67H,6AH,6DH,70H,73H,76H,79H,7CH.