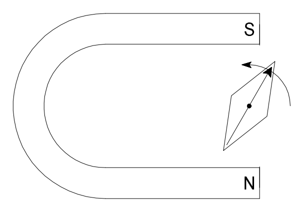
Chapter 10

AC Motors

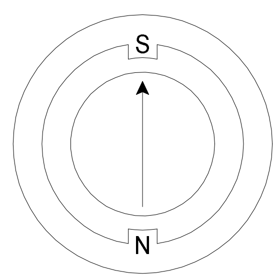
10.1 Alignment Torque

For DC motors we formulated the expression for the torque in terms of the force exerted by the stator field on the current in the rotor winding or, for the slotted armature, the force exerted on the stator itself. Another way of analyzing the torque is to consider the interaction between the magnetic fields of the rotor and stator.

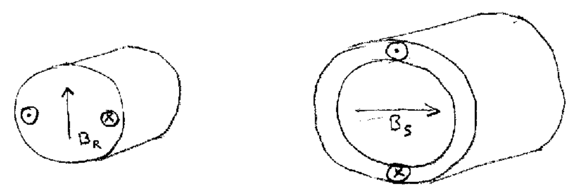
Intuitively, we expect these fields to want to align north pole to south pole, as would happen if we placed a compass between the poles of a horseshoe magnet.



In fact, the compass would align with the magnet even if the needle weren't magnetized, due to reluctance torque. If we replace the needle with a smooth cylinder, there will be a torque only if the cylinder is magnetized. However, in this case there is still a reluctance torque which could align an unmagnetized stator with the magnetized rotor.



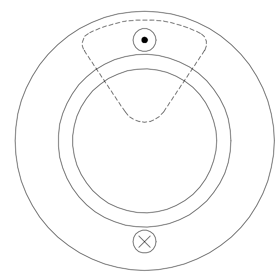
To completely eliminate reluctance torque, both the rotor and stator must be "smooth." The rotor and stator fields can be produced by permanent magnets, current carrying coils, or a mixture of both. For simplicity, we will start by considering the case where both fields are produced by coils.



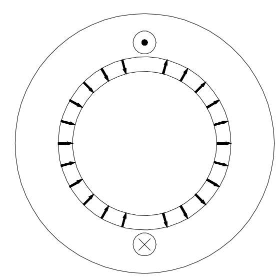
Our technique for determining the alignment torque will be to find the total magnetic energy in the air gap and differentiate with respect to the angle between the rotor and stator. When both the stator and rotor fields are produced by current carrying windings, we can use Ampère's law to find the H field as a function of the winding currents.

10.1.1 Uniform Flux

As an example, consider the idealized field winding configuration shown in the last row of Figure 8.1. By symmetry the H field must be radial, and since any contour of the form in the figure to the right will encircle the same amount of current, it must be uniform.



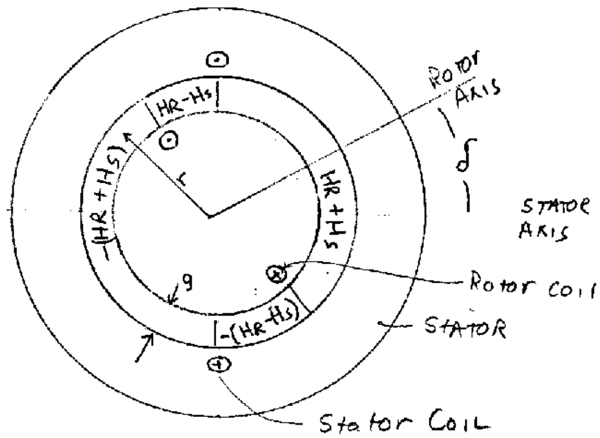
As the integration contour becomes narrower than the coil winding, the inclosed current decreases, so the field drops to zero and changes direction at the top and bottom. The result is a uniform radial field which is directed inward on the left half of the gap and outward on the right half.



The rotor field will also be uniform and radial, but will of course be aligned with the rotor axis and will depend on the rotor current. The total field in the airgap will be the sum of the stator and rotor fields, i.e. $H_t = H_s + H_r$ where

$$H_s = \text{field intensity due to the stator}$$
$$H_r = \text{field intensity due to the rotor}$$

as shown in Figure 10.1.



l = length of rotor and stator
N_s = number of stator turns
N_r = number of rotor turns
i_s = stator current
i_r = rotor current

Figure 10.1: Airgap field with concentrated winding.

Assuming $\mu_{rotor} = \mu_{stator} = \infty$, Ampère's law gives $2gH_s = N_s i_s$ or

$$H_s(\theta) = \begin{cases} \frac{N_s i_s}{2g}, & -\pi/2 < \theta < \pi/2 \\ \frac{-N_s i_s}{2g}, & \begin{array}{l} -\pi < \theta < -\pi/2 \\ \pi/2 < \theta < \pi \end{array} \end{cases}$$

and similarly for H_r. Define $H_S = \frac{N_s i_s}{2g}$ and $H_R = \frac{N_r i_r}{2g}$. Then H_t is as shown in Figure 10.1. To calculate the torque, we will need to know the energy stored in this field and how it varies with δ, the angle between the rotor and stator axes.

The magnetic coenergy density is $w' = \frac{1}{2}\mu_0 {H_t}^2$, so the total magnetic coenergy is

$$\begin{aligned} W'_f &= \int_{V_{gap}} w'\,dv \\ &= \int_{\theta=-\pi}^{\pi} \frac{1}{2}\mu_0 {H_t}^2 glr\,d\theta \\ &= \frac{1}{2}\mu_0 glr \int_{\theta=-\pi}^{\pi} {H_t}^2\,d\theta \\ &= \frac{1}{2}\mu_0 glr[2\delta(H_R - H_S)^2 + 2(\pi - \delta)(H_R + H_S)^2] \end{aligned}$$

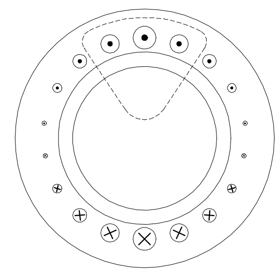
So the torque is

$$\begin{aligned} T &= \frac{\partial W'_f}{\partial \delta} \\ &= -4\mu_0 lrgH_R H_S \end{aligned}$$

for $0 < \delta < \pi$. Note that this is the torque for a single coil rotor in a single coil stator, with no commutation.

10.1.2 Distributed Winding

Instead of concentrating all of the turns of the stator or rotor winding in a single coil in the vertical plane, we could *distribute* them around the circumference. In this case the field strength will vary as larger integration contours enclose more current.



10.1.3 Sinusoidally Distrubuted Flux

With the proper choice of winding distribution, we can get a sinusoidal distribution of flux around the gap, i.e.

$$\begin{aligned} H_s(\theta) &= H_S \cos(-\theta) \\ H_r(\theta) &= H_R \cos(\delta - \theta) \end{aligned}$$

where

$$\begin{aligned} H_S &= \frac{N_s i_s}{2g} \\ H_R &= \frac{N_r i_r}{2g} \end{aligned}$$

The combined magnetic field intensity in the airgap is

$$\begin{aligned} H_t(\theta) &= H_s(\theta) + H_r(\theta) \\ &= H_S \cos(-\theta) + H_R \cos(\delta - \theta) \end{aligned}$$

corresponding to a coenergy density of

$$w' = \frac{1}{2}\mu_0 {H_t}^2$$

The total field coenergy is

$$\begin{aligned} W_f' = \int_{V_{gap}} w' \, dv &= \int_{\theta=0}^{\theta=2\pi} (\frac{1}{2}\mu_0 {H_t}^2)(glr \, d\theta) \\ &= \frac{1}{2}\mu_0 glr \int_0^{2\pi} {H_t}^2(\theta) \, d\theta \end{aligned}$$

Expanding

$${H_t}^2 = {H_S}^2 \cos^2(-\theta) + 2H_S H_R \cos(-\theta)\cos(\delta - \theta) + {H_R}^2 \cos^2(\delta - \theta)$$

but

$$\int_0^{2\pi} \cos^2(x)dx = [\frac{1}{2}x + \frac{1}{4}\sin 2x]_0^{2\pi} = \pi$$

so

$$\int_0^{2\pi} {H_t}^2\, d\theta \quad = \quad \pi({H_S}^2 + {H_R}^2) + \int_0^{2\pi} 2H_S H_R \cos(-\theta)\cos(\delta - \theta)\, d\theta$$

Using $\cos x \cos y = \frac{1}{2}[\cos(x+y) + \cos(x-y)]$ we get

$$\begin{aligned}
\int_0^{2\pi} {H_t}^2\, d\theta &= \pi({H_S}^2 + {H_R}^2) + \int_0^{2\pi} H_S H_R[\cos(\delta - 2\theta) + \cos(\delta)]\, d\theta \\
&= \pi({H_S}^2 + {H_R}^2) + H_S H_R \int_0^{2\pi} \cos(\delta)\, d\theta \\
&= \pi({H_S}^2 + {H_R}^2) + H_S H_R 2\pi \cos(\delta)
\end{aligned}$$

and

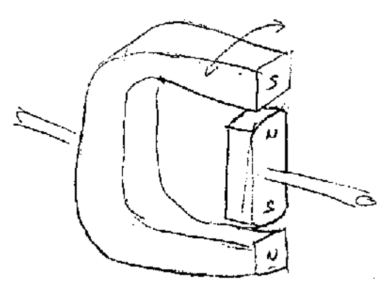
$$\begin{aligned}
W'_f &= \frac{1}{2}\mu_0 g l r \int_0^{2\pi} {H_t}^2(\theta)\, d\theta \\
&= \pi({H_S}^2 + {H_R}^2) + H_S H_R 2\pi \cos(\delta)
\end{aligned}$$

$$\begin{aligned}
T = \frac{\partial W'_f}{\partial \delta} &= -\pi\mu_0 l r g H_S H_R \sin\delta \\
&= -\frac{\pi\mu_0 l r N_s N_r}{4g} i_s i_r \sin\delta
\end{aligned}$$

10.2 Rotating Field

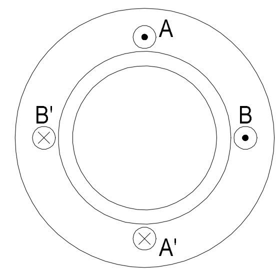
With current flowing in the rotor and stator windings, a torque will be produced which tends to force the magnetic axis of the rotor into alignment with that of the stator.

Returning to our earlier example of the horseshoe magnet and the compass, if we were to spin the magnet about its axis the compass would also spin, being held in alignment with the rotating field. For a practical motor we must be able to produce this rotating field by electrical rather than mechanical means.

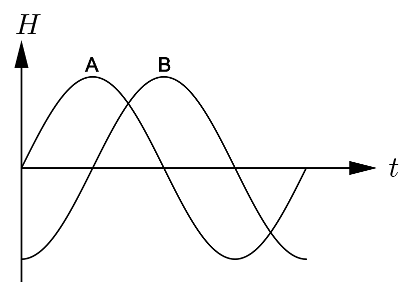


10.2.1 Two Phase Current

With a single stator winding, we can only vary the *magnitude* of the stator field by varying the stator current. If we add a second sinusoidally distributed stator winding, with its axis 90° from the first, then the total stator field will be the sum of the fields produced by the two windings: $H_s = H_a + H_b$, and we can vary the *angle* of the stator field axis by varying the *relative* values of the stator currents. (In the figure these distributed windings are represented by single coils.)



To make this field rotate at a steady rate, we excite the two coils with two sinusoidal currents 90° out of phase, i.e. $H_a = H_S \cos(\theta)\cos(\omega t)$ and $H_b = H_S \cos(\theta - \frac{\pi}{2})\cos(\omega t - \frac{\pi}{2})$ so



$$
\begin{aligned}
H_s(\theta) &= H_a(\theta) + H_b(\theta) \\
&= H_S \cos(\omega t)\cos(\theta) + H_S \cos(\omega t - \frac{\pi}{2})\cos(\theta - \frac{\pi}{2})
\end{aligned}
$$

Using $\cos x \cos y = \frac{1}{2}[\cos(x+y) + \cos(x-y)]$

$$
\begin{aligned}
H_s(\theta) &= \frac{1}{2} H_S[\cos(\omega t + \theta) + \cos(\omega t - \theta) + \cos(\omega t - \frac{\pi}{2} + \theta - \frac{\pi}{2}) + \cos(\omega t - \frac{\pi}{2} - \theta + \frac{\pi}{2})] \\
&= \frac{1}{2}[2\cos(\omega t - \theta) + \cos(\omega t + \theta) + \cos(\omega t + \theta - \pi)]
\end{aligned}
$$

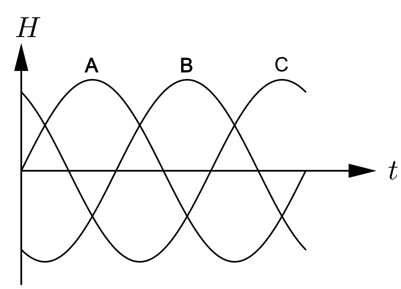
But the sum of the last two terms is zero, so

$$H_s(\theta) = H_S \cos(\omega t - \theta)$$

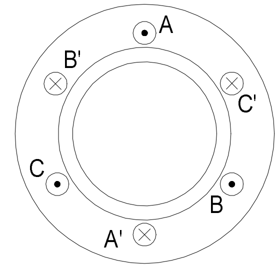
This is a sinusoidally distributed flux wave with a peak value of H_S which is rotating with an angular velocity of ω (while the stator itself remains stationary).

10.2.2 Three Phase

Two phase motors such as this have been used in some servo control systems, but far more common are *three phase* systems. Three phase power consists of three voltages (and currents) of the same frequency, with phases 120° apart.



As for the two phase case, the stator contains one winding for each phase, in this case three windings 120° apart. Again, though the figure represents these as single, concentrated coils, each winding will be distributed around the circumference of the stator so that the windings will overlap.



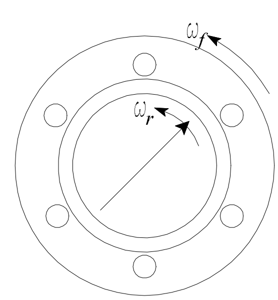
The total stator field is the sum of the fields due to each winding. Each winding produces a sinusoidal variation of the field with angle, and each current produces a sinusoidal variation with time. The total stator field is

$$
\begin{aligned}
H_s(\theta, t) &= H_a + H_b + H_c \\
&= H_S \cos(\omega t)\cos(\theta) + H_S \cos(\omega t - \frac{2\pi}{3})\cos(\theta - \frac{2\pi}{3}) + H_S \cos(\omega t - \frac{4\pi}{3})\cos(\theta - \frac{4\pi}{3}) \\
&= \frac{1}{2} H_S[\cos(\omega t + \theta) + \cos(\omega t - \theta) + \cos(\omega t - \frac{2\pi}{3} + \theta - \frac{2\pi}{3}) + \cos(\omega t - \frac{2\pi}{3} - \theta + \frac{2\pi}{3}) \\
&\quad + \cos(\omega t - \frac{4\pi}{3} + \theta - \frac{4\pi}{3}) + \cos(\omega t - \frac{4\pi}{3} - \theta + \frac{4\pi}{3})] \\
&= \frac{3}{2} H_S \cos(\omega t - \theta) + \frac{1}{2} H_S[\cos(\omega t + \theta) + \cos(\omega t + \theta - \frac{4\pi}{3}) + \cos(\omega t + \theta - \frac{8\pi}{3})] \\
&= \frac{3}{2} H_S \cos(\omega t - \theta)
\end{aligned}
$$

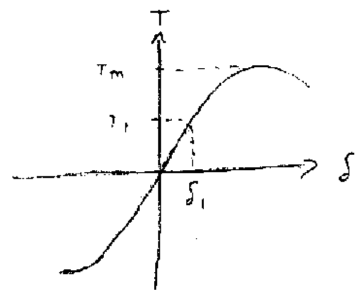
As expected, we once again have a sinusoidally distributed field, rotating with angular velocity ω.

10.3 The Synchronous Motor

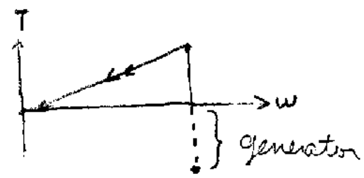
In our development of the expression for alignment torque in Section 10.1.3 the angle δ is the angle between the *fields* of the rotor and stator, not the rotor and stator themselves. If the rotor (and hence its field) and the stator field are both rotating with angular velocity ω then any misalignment between their axes will result in a torque tending to realign them.



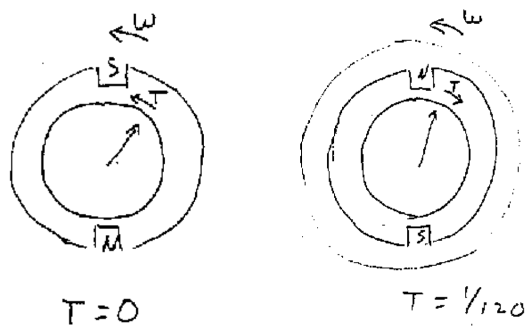
In other words we have a motor, since the torque developed between the rotating field and the rotor can be delivered to a load. As the load torque changes, the angle between the rotor and stator field axes also changes. In the figure, if the load torque is T_1 the rotor will lag behind the stator field by δ_1, but will be rotating at the same angular velocity. Since the rotation of the load is synchronized with the rate of rotation of the field (and hence the frequency of the exciting current) this type of motor is called a *synchronous motor.*



If the load torque exceeds the peak torque T_m the motor will stop. The speed torque curve for a synchronous motor thus shows constant speed for any load torque below T_m with an abrupt, discontinuous transition to zero if the torque exceeds this value.



One annoying characteristic of synchronous motors is that once stopped, they won't restart. Consider what happens if the rotor is stationary while the field is rotating. In the left hand figure below the alignment torque will tend to accelerate the rotor in a counterclockwise direction. Due to inertia of the rotor and attached load, by one half cycle later the rotor will only have reached the position shown in the right hand figure. In this case the alignment torque will accelerate the rotor in a clockwise direction. As a result of this alternating torque, the rotor will vibrate rather than rotate.



More quantitatively, if θ_f is the angle of the stator field axis, and θ_r is the angle of the rotor field axis, then

$$\delta = \theta_f - \theta_r$$

But

$$\begin{aligned} \theta_f &= \omega_f t + \phi_f \\ \theta_r &= \omega_r t + \phi_r \end{aligned}$$

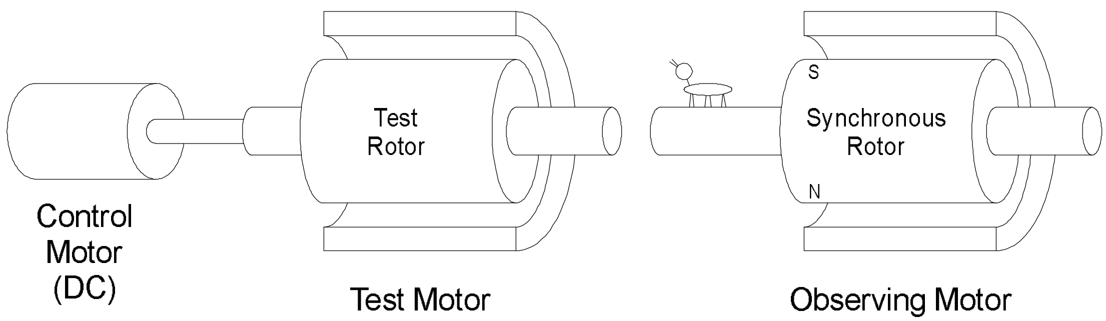
Since the torque is proportional to the angle between the axes

$$T = K \sin \delta = K \sin((\omega_f - \omega_r)t + (\phi_f - \phi_r))$$

The average value of the torque will be zero if $\omega_f \neq \omega_r$.

10.4 The Induction Motor

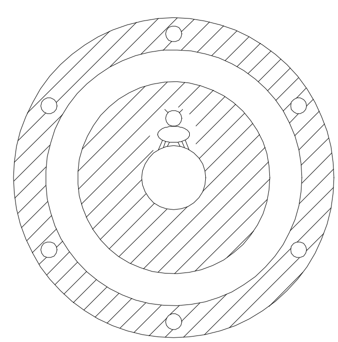
Consider the following experimental apparatus:



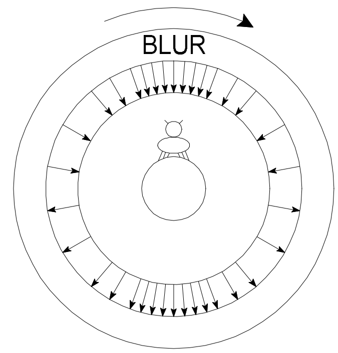
It consists of three motors with their axes of rotation collinear. The motor on the left is a DC motor driven from a variable power supply so that its speed (or torque) may be adjusted to any desired value. The motor in the center is the "test motor." It consists of a stator with a three phase, distributed winding which produces a sinusoidaly distributed field rotating at the power line frequency (60 Hz or 3600 rpm). The direction of rotation is clockwise when viewed from the right. The rotor may be removed and replaced with a variety of different structures depending on the experiment being performed. The rotor of the test motor is connected to the DC control motor and rotates with it.

The motor on the right is the "observing motor" it is a synchronous motor with a stator identical to that of the test motor so that its rotor will exactly follow the rotating field of the test motor. On the shaft nearest the test motor is a perch for the observer, a small bug. This bug has been genetically engineered so that he can see magnetic fields. The bug is wearing a backpack containing a variety of tools and a walkie-talkie so that he can radio his observations to us.

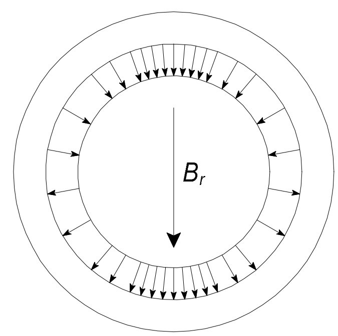
With everything at rest and no current in the test motor windings, here's what the bug sees.



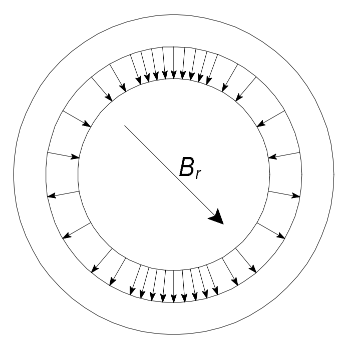
With the observing motor running and the test motor stator energized, the mechanical components of the motor appear as a blur, but the stator field appears stationary, since the bug is rotating synchronously with it.



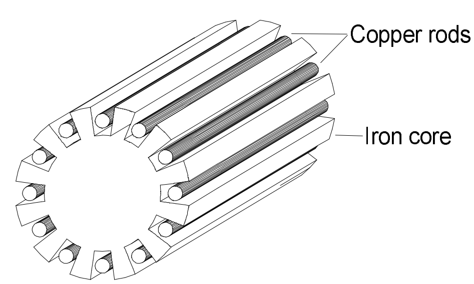
If we place a permanent magnet rotor into the test motor, bring it up to speed with the control motor, and then disconnect the control motor so that there is no load torque, the rotor will appear stationary to the spinning bug with its magnetic axis aligned with the maximum of the stator field.



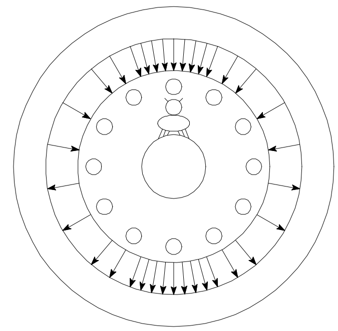
If we now connect the control motor to an adjustable current source we can vary its torque and hence the load seen by the test motor. As we increase the load torque, the axis of the test motor rotor slides further and further behind the axis of the stator field.



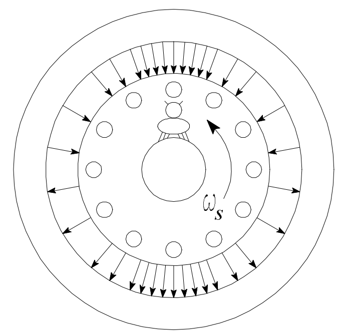
Now we stop the test motor, remove the synchronous rotor and replace with a specially constructed one. This rotor is an iron cylinder with slots along the periphery into which we place copper rods.



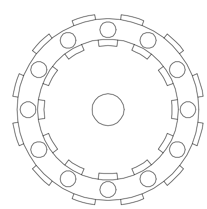
After placing the new rotor into the test motor, we start the observing motor, turn on the test motor field, and adjust the voltage on the control motor so that the test motor rotor is rotating exactly at synchronous speed. To the bug both it and the stator field will appear to be at rest.



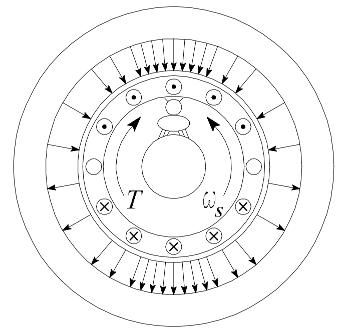
If we reduce the voltage to the control motor so that the test motor is rotating at only 59 Hz, then it appears to the bug that it is rotating *counterclockwise* at 1 Hz. The relative rate of rotation of the rotor with respect to the stator field is called the *slip frequency* ω_s. The copper bars in the grooves of the rotor are being moved at a uniform tangential velocity through a sinusiodally varying magnetic field, so each bar develops a 1 Hz alternating emf between its two ends. The voltage reaches its peak value when the bar crosses the stator field axis and reverses when the bar crosses the horizontal plane.



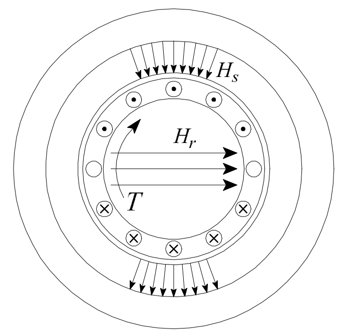
If we now short all the near ends and all the far ends of the copper bars together with copper rings, the emf will produce a current flow in the bars.



The interaction between this current and the stator field produces a force on the bar and the direction of this force for each bar is such that the resulting torque is in the clockwise direction.



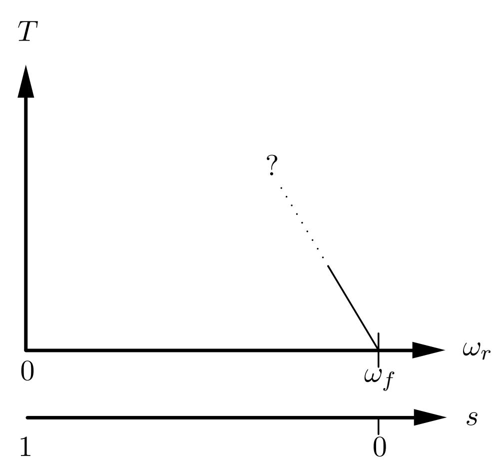
An alternate view is that the current circulating in the loops formed by the bars and the end rings produces a field in the rotor with the alignment torque between the rotor and stator fields being in the clockwise direction.



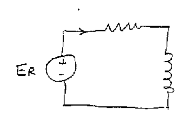
However, recall that although the rotor (and the embeded bars) is rotating counterclockwise (at 1 Hz) with respect to the stator field, the stator field is rotating (at 60 Hz) in the *clockwise* direction with respect to the stator. In other words the torque being produced is in the direction of rotation, i.e. we have a motor. Since the rotor current is induced by the relative motion between the rotor and the stator field, this is called an *induction motor*.

10.4.1 Induction Motor Speed-Torque Curves

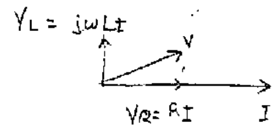
If ω_f is the stator field rotation rate and ω_r is the angular velocity of the rotor, then the slip frequency is $\omega_s = \omega_f - \omega_r$, and the normalized *slip* is $s = \frac{\omega_s}{\omega_f}$. Since the induced emf in the rotor windings is proportional to the slip, and the torque developed is proportional to the rotor current, if the rotor windings were purely resistive, torque would be proportional to slip and the speed/torque curve would resemble that of a DC motor.



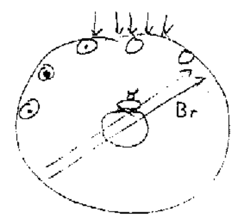
However, since the conductors in the rotor encircle an iron core, they also have a certain amount of inductance.



If we look at the phasor diagram we can see that as ω_s increases, the current decreases and lags further behind the voltage.

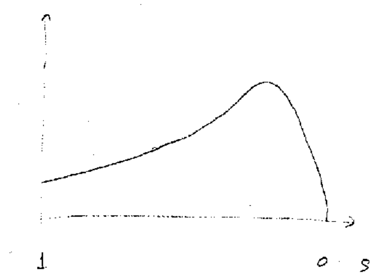


The decreasing current reduces the magnitude of the rotor field and the phase difference between the voltage and current reduces the angle (δ) between the rotor and stator fields.



The decreasing values of rotor current and $\sin(\delta)$ eventually overtake the increasing emf and the torque levels out or decreases with increasing slip (remember that increasing slip means decreasing rotor speed).

If the falloff of torque with slip becomes rapid enough, the *starting torque* (i.e. with $\omega_r = 0$) may be less than the maximum torque. This can cause the embarrassing and potentially damaging situation of a motor being unable to start a load which is well within its rated running capacity.



One place where this can occur is in the compressor of a refrigeration system. If the compressor has been off for a sufficient period of time, the pressures on both sides of the system will be equal and the load will be small. As the compressor runs, high side pressure will increase and low side pressure will decrease until equilibrium is reached. When the compressor stops, the pressure difference will remain high until it can bleed off through the expansion valve. If the compressor tries to restart too soon, the starting torque may be insufficient to overcome the load presented by the higher pressure differential and the motor will stall. This can cause the motor to overheat and possibly become damaged. For this reason, "compressor rated" motors are constructed so that the starting torque is greater than the running torque.

Even though the starting torque of an induction motor may be less than the running torque, it is still greater than zero. In other words an induction motor is self starting, unlike a synchronous motor. This fact combined its simplicity, economy, and ruggedness have made the induction motor the standard choice as a source of mechanical power for applications requiring a few 100ths of a horsepower to several hundred horsepower.

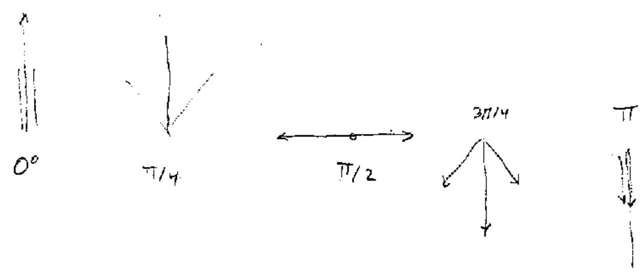
10.5 Single Phase Motors

Unfortunately, creating a rotating field requires polyphase current and nearly all residential and much light commercial wiring is single phase. The fact that at any moment millions of induction motors are happily spinning away inside refrigerators, air conditioners, washing machines, and other appliances plugged into single phase outlets suggests that there is a way around this problem.

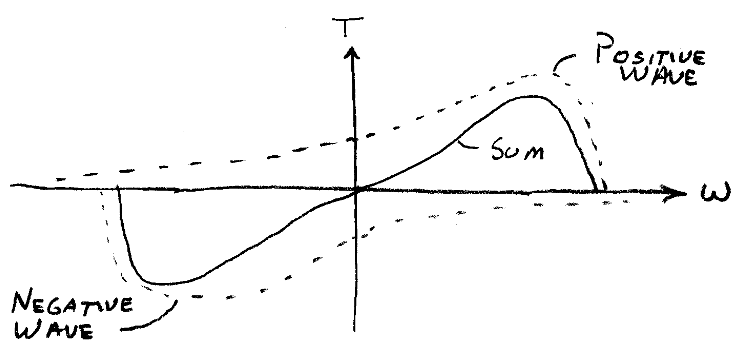
The key to the solution is to think of the flux produced by a single phase winding as the sum of two flux waves rotating in opposite directions.

$$\begin{aligned} H_s &= \cos(\omega t) cos(\theta) \\ &= \frac{1}{2}\cos(\theta + \omega t) + \frac{1}{2}\cos(\theta - \omega t) \end{aligned}$$

where $\frac{1}{2}\cos(\theta+\omega t)$ is the forward flux wave and $\frac{1}{2}\cos(\theta-\omega t)$ is the reverse wave. Graphically:



To find the resulting speed/torque relationship, simply sum the torque produced by each wave for each value of ω_r



There are several significant facts about this curve:

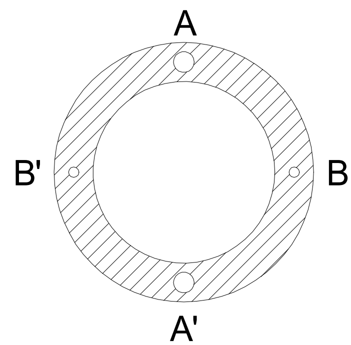
- $T = 0$ for $\omega = 0$, so it won't start.

- $T > 0$ for $\omega > 0$, so it *will* run.
- $T < 0$ for $\omega < 0$, so it will also run backward.

In other words, we have a motor which will run in whichever direction it is started. The only problem is: How do we start it?

10.5.1 The Split Phase Motor

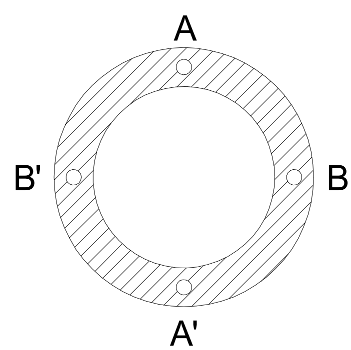
The *split phase motor* has two sinusoidally distributed stator windings, 90° apart. The two windings are different: winding A has low resistance and high reactance; winding B has high resistance but low reactance. As a result the current in winding A lags the applied voltage by close to 90° while in winding B the current and voltage are nearly in phase. Since the strength of the field depends on the current the result is similar to the two phase structure in Section 10.2.1, i.e. there is a rotating component to the field.



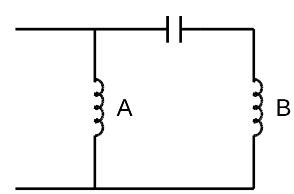
Unlike a true two phase motor, because of the asymmetry of the windings the torque is not uniform. Also, because of the resistive losses in winding B (called the "starting winding") it is usually disconnected once the motor is up to speed.

10.5.2 The Capacitor Start Motor

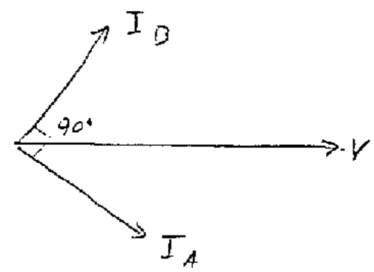
Like the split phase motor, the *capacitor start motor* has two windings 90° apart, but in this case they are more nearly identical.



In this case, as the name suggests, the phase shift between the two windings is provided by a capacitor, often called the *starting capacitor*.



By proper choice of the value of this capacitor, the current in winding B can be made to lead the current in winding A by 90°.



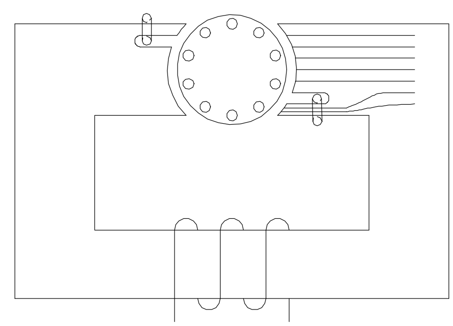
The reduced loss and greater symmetry of the field structure give this motor a larger, smoother torque than the split phase motor. Unfortunately, the phase relationship is correct only at a particular value of speed and load. In some cases this is chosen to occur at low speed to give high starting torque and once the motor is up to speed the second winding is disconnected, as in the split phase motor. Such a motor is called a *capacitor start motor*.

In a *capacitor run motor* the capacitor and second winding are permanently connected, or a different value of capacitor is switched in when running speed is reached. A capacitor run motor has higher and much smoother torque than a split phase or capacitor start motor since it is nearly a true two phase structure without the strong torque pulsations caused by single phase current.

10.5.3 The Shaded Pole Motor

Although the rotor of an induction motor is simple to make, the multiple, distributed windings of are complex and consequently expensive to produce. Where cost is more important than performance, the *shaded pole* structure can be used.

This usually uses a simple rectangular core for the stator. Each pole face has a slot cut in one edge and a copper loop called a *shading ring* is placed around the resulting finger, forming a single turn, shorted winding. With alternating current applied to the stator winding, the current induced in this shading ring works to oppose the change in flux in the portion of the pole which it surrounds. This results in a phase lag between the flux in the shaded portion and the main portion of the pole, giving rise to a rotating component to the flux.



10.6 Speed Control of AC Motors

The steep slope of the speed-torque curve for $\omega_r \approx \omega_f$ means that an induction motor can also provide good speed regulation. However, in applications where *variable* speed is required AC motors aren't quite as easy to control as DC motors, where speed responds directly to changes in voltage or resistance. However, there are several ways to change the speed of an AC motor.

Change the Frequency The speed of an AC motor depends entirely (synchronous motor) or primarily (induction motor) on the speed of the rotating field, which in turn is determined by the frequency of its driving voltage. The best way to change the speed of an AC motor is to change the frequency of the applied voltage. While this appears to be impossible when the AC line voltage is fixed at 60 Hz, improvements in power semiconductor technology have made so called *variable frequency drives* increasingly economical.

A variable frequency drive is essentially a high power variable frequency oscillator. The input line voltage is rectified and filtered to produce DC which is used as the input to three switch-mode power supplies. These are driven by a three phase, variable frequency oscillator to produce three phase, variable frequency current.

In addition to providing speed control, some variable frequency drives are available which accept single phase input, allowing smoother running three phase motors to be used in environments where only single phase is available.

Change the Number of Poles All of the illustrations in this chapter have shown *two pole* structures where the flux wave has only a single maximum (and minimum), i.e. a single pair of poles. It is possible to rearrange the windings so that there are several pairs of poles (e.g. 4-pole, 6-pole, 8-pole) in the field pattern. In this case, the flux wave still advances by one pole pair per cycle of the applied voltage, but since there are more pole pairs per rotation, the rate of rotation is reduced.

For example, with 60 Hz current, a two pole motor will have a synchronous rotation speed of 60 Hz or 3600 rpm. A 4 pole motor would have half that or 1800 rpm, a 6 pole motor would have 1200 rpm, and so on.

It is possible to arrange the stator windings so that the number of poles may be changed by changing the connections of the windings. Thus the same motor may be switched between 2 and 4 poles (3600 and 1800 rpm), 4 and 12 poles (1800 and 600 rpm), etc.

Change the Voltage Although the rate of rotation of the field does not depend on the voltage applied to the stator windings, the strength of the field, and hence the magnitude of the alignment torque do, so that the vertical scale of the speed-torque curve will change with the applied voltage. Depending on the shape of the speed-torque curve for the load, this may allow control of the running speed by varying the voltage. Another way to achieve the same effect is to have several taps on the stator winding. This is the technique used in most portable fans to control their speed.