THREE-PHASE INDUCTION MOTOR

March 2007

IX. THREE PHASE INDUCTION MOTOR

A. PREPARATION

1. Introduction

Galileo Farraris was perhaps the first person to demonstrate a motor of the induction type (1). He made a machine with two pairs of electromagnets as shown in Figure 1 and drove the two windings with two AC voltages 90° out of time phase. The rotor was made of solid copper. Since the machine had a very large effective air gap, it could only develop a very small torque; enough only to cause the copper rotor to rotate at no load.

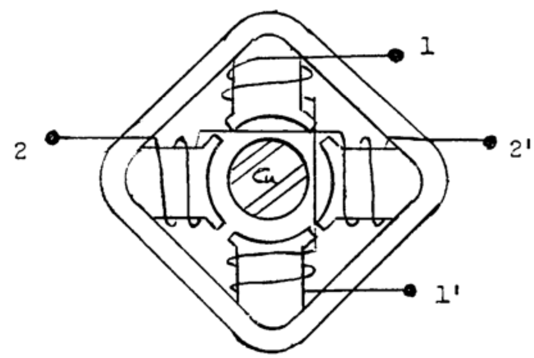


Figure 1.

Nikola Tesla is generally credited with the 'invention' of the induction motor for which he was issued a patent in the United States on 1 May 1888. The validity of the patent was hotly contested in the courts but it was upheld, even though Ferraris could document prior disclosure of substantially similar ideas. Tesla's patent was upheld primarily because he was the first to recognize the commercial importance of the principle of the induction motor and also the first to construct a useful machine. Tesla's invention of the induction motor in 1888, along with the development of the transformer, were two important reasons why the initial use of DC generation and distribution, as espoused by Thomas A. Edison, was superseded by AC generation and distribution, which in the United States was pioneered by George Westinghouse and Co. (2).

Westinghouse immediately realized the commercial possibilities of Tesla's invention and within a few months time in 1888 had acquired the patent rights from Tesla and employed him to develop the motor. A number of people at Westinghouse contributed to improvements in the induction motor. These included C.F. Scott, who helped Tesla substitute slot-embedded coils and a ring wound stator for the original salient pole structure; O.B. Shallenberger, who, also in 1888, invented the AC watt-hour meter, a variant of the induction motor principle; and B.G. Lamme, longtime chief engineer at Westinghouse, who added a completely distributed two-phase stator winding and a distributed rotor winding. Working together, these men achieved a practical induction motor at Westinghouse by 1892.

Early Westinghouse motors, as developed by Lamme, had rotating primary windings with fixed secondary windings on the stator. (3). This was done to avoid sending the heavy secondary currents through slip rings. Lamme and others at Westinghouse later developed the squirrel cage rotor winding, which was cross-licensed by the General Electric Co. in 1896. The cast aluminum rotor was patented by H.G. Reist and H. Maxwell of the General Electric Co. in 1916. It was made by pouring molten metal into a mold surrounding the rotating core of an induction motor. This was essentially the squirrel cage induction motor in its present day form. Many improvements to the motor have been made over the years. 1 to 3 percent of silicon was added to the iron of the motor's magnetic circuit to increase its resistivity and thereby decrease eddy current losses; grain oriented steel was introduced for improved magnetic peremability; and improved mechanical support has allowed smaller air gaps (~ 0.20 in.). Insulating materials have been improved, such that current day maximum winding temperature can be allowed to reach 180° C. These improvements have been such that a 7.5 hp motor of 1897 required a frame size that today accomodates a 100 hp motor.

2. The Rotating Field

Basic to the operation of any induction motor is the production by the motor windings of a magnetic field, approximately sinusoidally distributed over the circumference of the rotor. Depending on the supply frequency and the number of poles on the winding, the field rotates in space about the circumference of the machine at a rate termed the 'synchronous speed'. The rotating field is produced by properly arranging a stator winding such that each phase occupies 360/n electrical degrees of the stator circumference, where n is the number of phases of the exciting voltage. Initially, during the 1890's, motors were 2 phase, but these were displaced as time passed by three phase machines due to wide use of 3 phase for electrical distribution purposes once its advantages for transmission economy were noted.

We will demonstrate the production of a rotating magnetic field for the special case of a 2 pole, 3 phase machine. Consider the superposition of 3 coplanar magnetic field intensities, $\vec{H}_a$, $\vec{H}_b$, and $\vec{H}_c$ at a point in space where the 3 field intensities are displaced 120° in space and 120° in time.

Each of the three components of magnetic field are uniform with respect to the space coordinates, as shown in Figure 2.

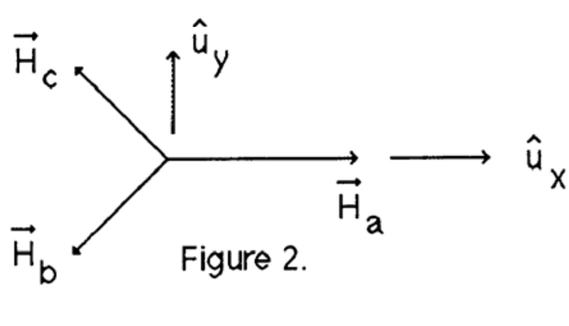


Figure 2.

We may write, using complex notation,

$$\vec{H}_a = \text{Re}\,[H_m e^{j\omega t}\, \hat{u}_x]$$

$$\vec{H}_b = \text{Re}\,[H_m e^{j(\omega t - 120°)} (-\frac{1}{2}\, \hat{u}_x - \frac{\sqrt{3}}{2}\, \hat{u}_y)]$$

$$\vec{H}_c = \text{Re}\,[H_m e^{j(\omega t - 240°)} (-\frac{1}{2}\, \hat{u}_x + \frac{\sqrt{3}}{2}\, \hat{u}_y)] \quad .$$

The sum, H_t , is,

$$\vec{H}_t = \vec{H}_a + \vec{H}_b + \vec{H}_c \ ,$$

or, $\vec{H}_t = H_1\, \hat{u}_x + H_2\, \hat{u}_y$, where

$$\vec{H}_1 = \text{Re}\,[H_m e^{j\omega t} - \frac{1}{2}\, H_m e^{j(\omega t - 120°)} - \frac{1}{2}\, H_m e^{j(\omega t - 240°)}\,] \ ,$$

$$= \text{Re}\ [\ \frac{3}{2}\ H_m e^{j\omega t}\ ] \ ;$$

and

$$\vec{H}_2 = \text{Re}\,[\ -\frac{\sqrt{3}}{2}\ H_m e^{j(\omega t - 120°)} + \frac{\sqrt{3}}{2}\ H_m e^{j(\omega t - 240°)}\,] \ ,$$

$$= \text{Re}\ [\ \frac{3}{2}\ H_m e^{j(\omega t + 90°)}\ ] \ .$$

This gives,

$$\vec{H}_t = \frac{3}{2}\ H_m\ \cos \omega t\, \hat{u}_x + \frac{3}{2}\ H_m\ \sin \omega t\, \hat{u}_y \ ;$$

and we may easily verify that this represents a vector of constant amplitude, $3/2\ H_m$, rotating in space, counterclockwise, at an angular velocity of ω radians/second. We should note that if the phase sequence were reversed from the a-b-c sequence shown in Figure 2 to an a-c-b phase sequence, then the field intensity components would become,

$$\vec{H}_a = \text{Re}\,[H_m e^{j\omega t}\,\hat{u}_x]$$

$$\vec{H}_b = \text{Re}\,[H_m e^{j(\omega t - 240°)}\,(-\,1/2\,\hat{u}_x - 3/2\,\hat{u}_y\,)]$$

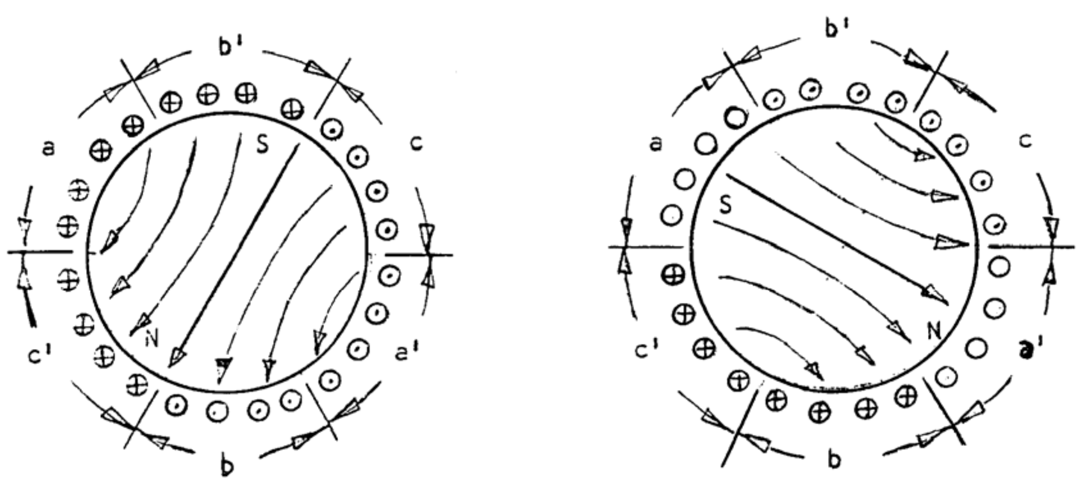
$$\vec{H}_c = \text{Re}\,[H_m e^{j(\omega t - 120°)}\,(-\,1/2\,\hat{u}_x + 3/2\,\hat{u}_y\,)]\,.$$

For this case, the resultant, H_t would be,

$$\vec{H}_t = 3/2\;H_m \cos \omega t\,\hat{u}_x - 3/2\;H_m \sin \omega t\,\hat{u}_y\,,$$

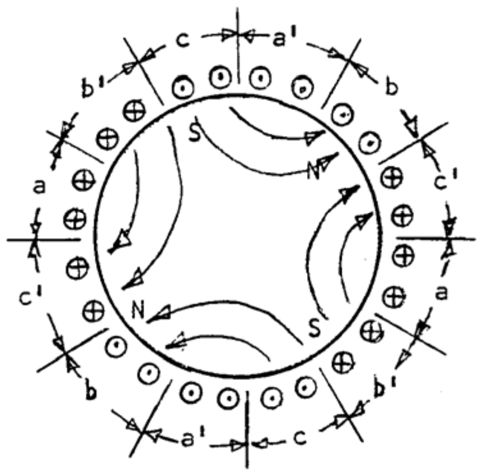
which has the same amplitude as with the a-b-c phase sequence except that the rotation is now clockwise instead of counter-clockwise. **From this we see that the direction of rotation of the magnetic field, and also of a 3 phase induction motor, can be reversed by reversing the phase sequence. Practically, this can be done by interchanging any two of the 3 phase supply lines.**

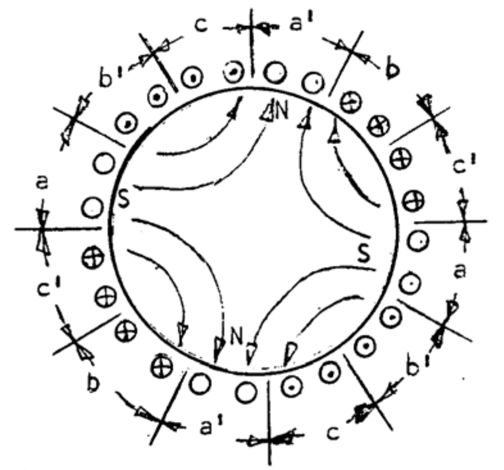
Production of the 3 required components of field intensity in the 3 phase induction motor is done by properly arranging the windings on the motor stator. Figure 3a shows a simple, one layer winding for a 2 pole motor. Diametrically opposite conductors in the belt a - a' represent the two sides of a coil that spans the diameter of the stator. In this diagram each phase coil has one conductor/slot, 4 turns/coil, and one coil/phase. Figure 3a also shows the approximate magnetic field in the motor interior at the instant of time when the current phase 'a' is maximum in the direction indicated. It may easily be verified that the resultant from phases 'b' and 'c' , since they are at negative half maximum when 'a' is at positive maximum, is also in the direction shown. Assuming an a - b - c phase sequence, 90° later, when phase 'a' is at zero current, phase 'b' will be $\sqrt{3/2}\;I_{max}$, and phase 'c' will be $-\,\sqrt{3/2}\;I_{max}$. The resultant magnetic field will then have rotated 90° in position as shown in Figure 3b.



3a Figure 3. 3b

A 4 pole motor with the same number of conductors would have one conductor/slot, 2 turns/coil, and one coil/phase, as in Figure 4a. Here, again, the field interior to the motor is shown at the instant of time when phase 'a' is at its positive maximum and phases 'b' and 'c' are at half their negative maximum values. For this 4 pole machine, 90 electrical degrees later, a time equal to 1/4 of the period of the supply frequency, the field pattern will have rotated 45° CCW in geometric position (assuming a - b - c phase rotation), as shown in Figure 4b.





4a Figure 4. 4b

Actual motors will employ many conductors per slot and many turns per coil. Additionally, it is common to have two coil sides occupy the same slot. Windings may also be short pitch, where the two sides of a coil do not span 180 electrical degrees; and the winding progression around the machine may be either of the lap or wave type. Further, it is possible to arrange either a star or a delta connection of the windings. Finally, if sufficient slots are available, motors may be wound for an arbitrary number of poles. In all cases, however, the fundamental nature of the rotating field is as shown in Figures 3 and 4, except as modified for a larger number of poles.

We have seen that, for a two pole machine, the field makes one complete revolution in a time such that $\omega t = 2\pi$. This implies that the time for one revolution is $T = 1/f$, and so the number of field revolutions per minute is (60) f, where f is the frequency of the 3 phase supply. For the 4 pole motor, the time for one revolution of the field is doubled, and so the revolutions per minute is (30) f. **In this way, if p = number of poles on the winding, the field will rotate at a speed of (120) f/p, which is the synchronous speed of the machine and is denoted by the symbol 'n_s'.**

3. Rotor Currents

The squirrel cage rotor consists of bars parallel to the motor axis, all connected together by end-rings; see Figure 5. One method of obtaining the rotor currents is to assume a rotating field at the rotor surface in the amount,

$$\vec{B} = B_m \cos\left(\omega t - \frac{p}{2}\theta\right)\hat{u}_r ,$$

as seen by a stationary observer, where,

p = number of poles ,

θ = angle measured positive CCW ,

$\hat{u}_r$ = unit vector in the radial direction ,

$\vec{B}$ = magnetic flux density.

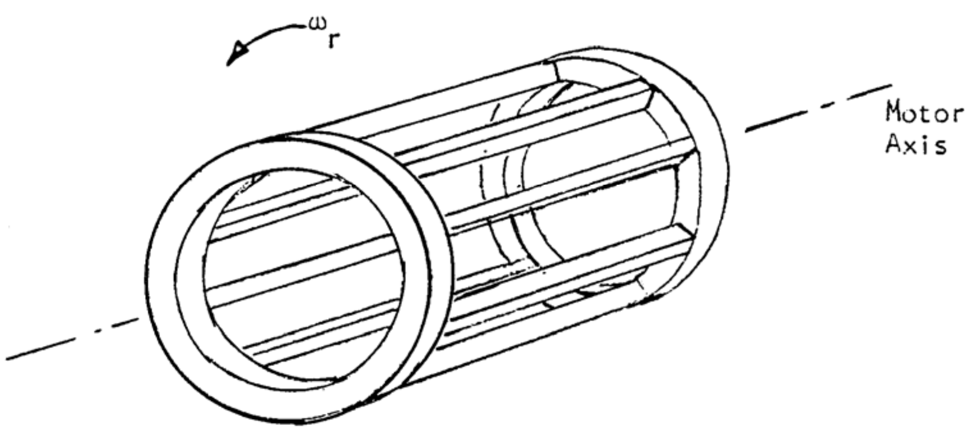


Figure 5.

We have previously seen that this expression for $\vec{B}$ implies a field rotating at the angular velocity, $2\omega/p$ radians/second, or 120 (f/p) revolutions/minute. We define $\omega_s = 2\omega/p$, where ω_s = synchronous angular velocity.

The magnetic field seen at a fixed point on the rotor is obtained by setting $\theta = \omega_r t + \theta'$, where ω_r is the angular velocity of the rotor, and θ' is angle as measured on the rotor. This gives the magnetic field as seen by the rotor,

$$\vec{B}_r = B_m \cos\left[\left(\omega - \frac{p}{2}\omega_r\right) t - \frac{p}{2}\theta'\right] \hat{u}_r .$$

It is common to define a quantity termed the 'slip', s, such that,

$$s = 1 - \omega_r/\omega_s = 1 - n/n_s \text{ , where ,}$$

$$n = \text{motor speed ,}$$

and using this in the expression for B_r gives,

$$\vec{B}_r = B_m \cos\left[s\omega t - \frac{p}{2}\theta'\right] \hat{u}_r .$$

From this we see that a point of constant magnetic field moves over the rotor at an angular velocity found by setting $(s\omega t - \frac{p}{2}\theta') = 0$, which gives the field speed relative to the rotor to be $s\,(2/p)\omega = s\omega_s$, whose distribution is otherwise the same as viewed from the stator. Each bar in the rotor can be imagined as having a voltage induced in it in the amount $|\vec{B}_r|\,Lv$, where

L = length of rotor bar,

v = velocity of rotating field relative to the bar.

This gives the voltage induced in the bar

$$V_{bar} = L\,a\,(\omega_s - \omega_r)\,B_m \cos\left(s\omega t - \frac{p}{2}\theta'\right) ,$$

or,

$$V_{bar} = L\,a\,s\,\omega_s\,B_m \cos\left(s\omega t - \frac{p}{2}\theta'\right) ,$$

where, a = rotor radius.

To find the current in the bars and end-rings would require solving the network problem of Figure 6,

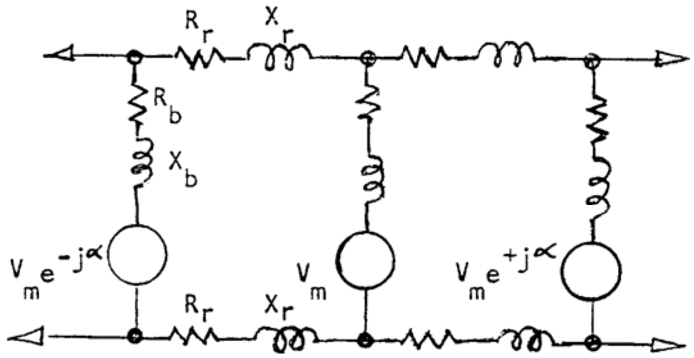


Figure 6.

where, R_b , X_b = resistance and reactance of each bar,

R_r , X_r = resistance and reactance of each segment of end-ring,

$V_m = L\, R\, s\, \omega_s\, B_m$,

$\alpha = (4\pi) / (Z_r\, p)$,

Z_r = number of rotor bars.

We will not attempt a solution of this problem. It is evident that there will be a solution of the form,

$$I_{bar} = V_{bar} / (R + jX) ,$$

where both V_{bar} and I_{bar} are at the slip frequency, $s\omega$.

These events on the rotor are perceived by the stator as an effective impedance. Noting that each bar in the squirrel cage rotor has an induced voltage α degrees out of phase with its neighbor, we may regard the squirrel cage rotor as having m_2 phases where,

$$m_2 = (Z_r) / (p/2) .$$

With this in mind, the rotor voltage per phase is just V_{bar} as previously defined, and the rotor current per phase is,

$$I_2 = \frac{p}{2} I_{bar} .$$

So, if the stator has m_1 phases and Z_1 conductors in series per phase, then the voltage transformation ratio is just Z_1 , while the current transformation ratio is such that,

$$m_1 I_1 Z_1 = m_2 I_2 ,$$

or

$$I_1/I_2 = m_2 / (m_1 Z_1) .$$

Here, we have neglected several factors, including a pitch factor and breadth factor that effectively reduce the number of stator conductors somewhat below the Z_1 value. (4).

4. Induction Motor Equivalent Circuit

The magnetic flux in the machine is a result of the mmf (magnetomotive force) set up by the stator and rotor currents. The mmf of the stator winding is approximately, $m_1 Z_1 i_1$, and the mmf of the rotor winding is $m_2 i_2$. Total mmf is

$$m_1 Z_1 i_1 + m_2 i_2 ,$$

where i_1 and i_2 are phasor representations of the stator and rotor currents.

A phasor diagram can be consructed for the motor as in Figure 7.

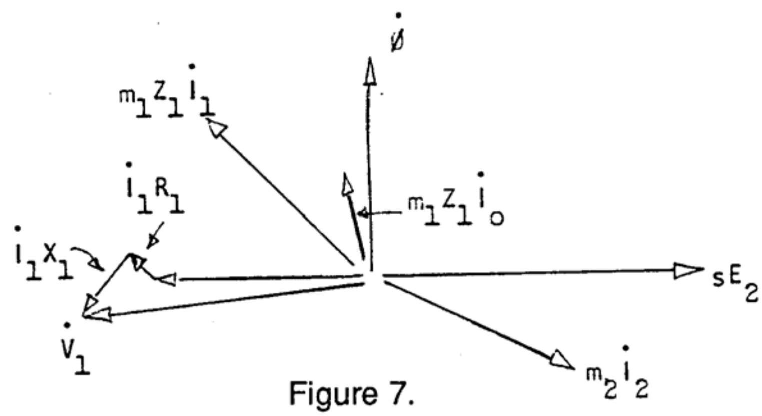


Figure 7.

In this diagram, $m_1 Z_1 i_o$ represents the mmf necessary to maintain the flux, ϕ , which is approximately constant. i_o is then the no-load stator current. $s \dot{E}_2$ is the rotor induced voltage per phase and is just V_{bar} as previously defined. $\dot{E}_2$ and i_2 are related by

$$i_2 = sE_2 / (R_2 + jX_2 s) \ ,$$

where R_2 and X_2 are an equivalent secondary resistance and reactance that can be computed from the circuit of Figure 6. R_1 and X_1 represent the stator winding resistance and leakage reactance, respectively. Note that in this phasor diagram, rotor quantities as viewed from the stator are at the stator frequency.

We may redraw Figure 7 as Figure 8 where rotor voltage and current

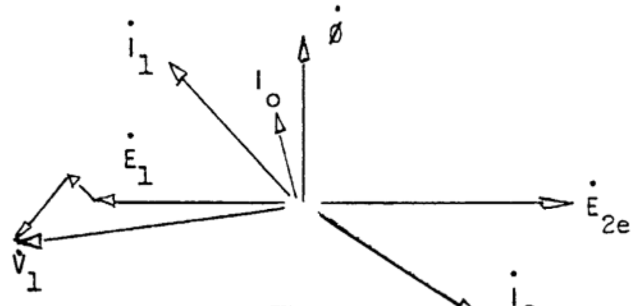


Figure 8.

have been referred to the stator by the factors Z_1 and $(m_2) / (m_1 Z_1)$, respectively, such that,

$$\dot{E}_{2e} = Z_1 \dot{E}_2 \ ,$$

$$\dot{I}_{2e} = (m_2)\,(1/m_1 Z_1)\,\dot{I}_2 \ ,$$

and

$$\dot{I}_{2e} = \frac{\dot{E}_{2e}}{\frac{R_2}{s} + jX_2} \ .$$

An inspection of Figure 7 shows that the relations implied in the phasor diagram can be represented as well by the equivalent circuit of Figure 9. The utility of this equivalent circuit is that all elements

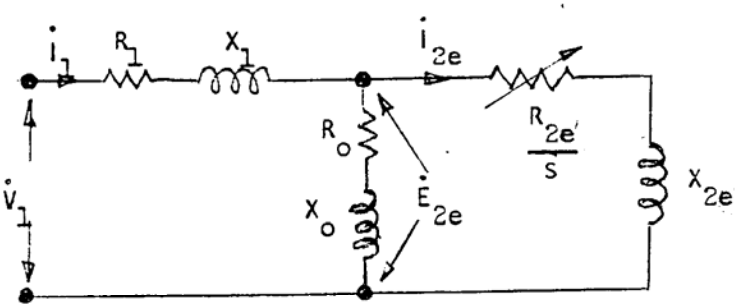


Figure 9.

are effectively constant except R_2/s, which varies from a minimum value, R_2, at standstill to an open circuit at synchronous speed. It is useful to separate R_2/s into two parts, R_2 and $R_2\ (1 - s)/s$. The total power dissipated in the element R_2/s, can be thought of as consisting of two parts. One is

$$I_{2e}^2 R_2 \quad ,$$

which is just the ohmic loss of the rotor. The other part is

$$\boxed{I_{2e}^2 R_2 (1-s) / s} \quad ,$$

which is the mechanical power developed by the motor.

5. Torque and Power Characteristics

In the usual situation the motor has a constant voltage, V_1, applied. The stator quantities, R_1 and X_1, are sufficiently small that the magnetizing current through R_o and X_o causes a negligible voltage drop across R_1 and X_1. This allows approximating the equivalent circuit as in Figure 10.

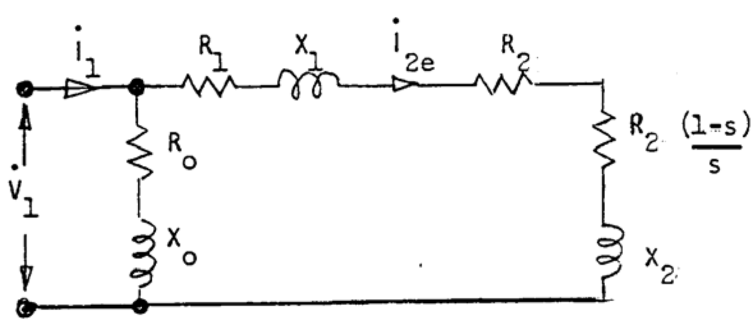


Figure 10.

Mechanical power output, then, is

$$P_o = \frac{m_1 V_1^2}{(R_1 + R_2/s)^2 + (X_1 + X_2)^2} R_2(1-s)/s \ .$$

Output mechanical power and shaft torque are related by

$$P_o = 2\pi nT/60 \text{ watts ,}$$

where T = Torque in newton-meters ,

n = motor speed , revolutions/minute ,

$= (1 - s)\ n_s$.

Using the relation between mechanical power and torque gives

$$T = \frac{30}{\pi n_s} \frac{m_1 V_1^2}{(R_1 + R_2/s)^2 + (X_1 + X_2)^2} (R_2/s) \ .$$

Differentiating to find the motor slip that maximizes the torque gives,

$$s\Big|_{T = T_{max}} = \frac{R_2}{\sqrt{R_1^2 + (X_1 + X_2)^2}} \ .$$

Typical speed-torque curves for induction motors are shown in Figure 11.

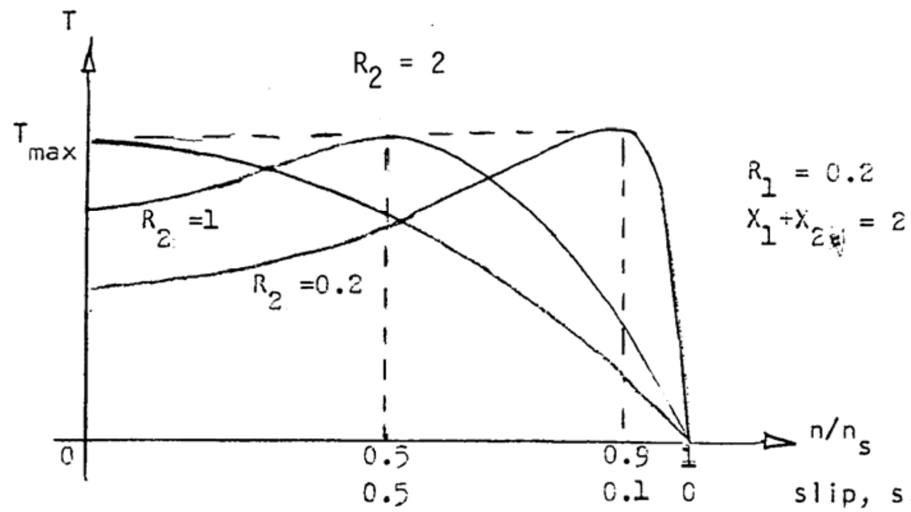


Figure 11.

It is straightforward to demonstrate that the maximum torque is independent of the rotor resistance, although of course, the speed at which the maximum torque occurs is strongly influenced by the rotor resistance.

Curves of output power versus speed will be similar to those of torque versus speed except that power output at zero speed will be zero, and the point of maximum power output will be shifted to a somewhat higher speed than the point of maximum torque.

6. Operation Beyond the Range $0 < s < 1$

Suppose an induction motor is energized by an AC line and is connected to a prime mover, as for example a turbine or a DC motor. Then, if the motor speed is between zero and slightly less than synchronous speed $(0 < s < 1)$, it must of necessity be delivering mechanical power to the prime mover. It is possible, however, by opening the throttle of the prime mover, to reverse the power flow such that the motor is driven above synchronous speed. If this is done, the magnetic field produced by the interaction of rotor and stator currents will still rotate at synchronous speed. In contrast to motor action, the rotor now rotates faster than the rotating field and the slip, s, is negative. The equivalent circuit of Figure 10 still applies, except that the resistance, $R_2 (1 - s)/s$ is now negative and the rotor can generate power.

A synchronous alternator can readily supply power, either to a leading or lagging power factor load; the induction, or asynchronous, generator cannot, of itself, supply a lagging power factor, or inductive, load. This is evident from an inspection of Figure 10 where it is clear that above synchronous speed the motor can be represented at its terminals by an equivalent inductive reactance and negative resistance connected in parallel. If a voltage exists across the motor terminals the motor will still require a current component to supply the equivalent parallel inductive reactance. This quadrature component can only be supplied by a device that appears as a parallel capacitive reactance, either a synchronous motor or alternator, or a static capacitor.

Asynchronous generators have found some application as standby generators in remotely located small power plants. The generator can idle on the line as a motor and drive its own prime mover at almost synchronous speed until the need arises for power generation, which causes the throttle of the prime mover to open until power of sufficient amount is generated. In this way synchronizing problems involved in the start-up of synchronous alternators are avoided. The need for supplying lagging quadrature current to the generator has prevented large scale application of asynchronous generators.

Another situation where the motor may operate as a generator is where the need arises to brake a motor or to stop it quickly. Slowing or stopping a motor that is revolving may be done by connecting the windings to a DC source as in

Figure 12. Although a star connection is shown, the same effect occurs with the delta connection. The DC excitation produces a stationary field relative to the stator, while the rotor experiences a field rotating at aproximately synchronous speed. A torque on the rotor approximately equal to the starting torque is developed in a direction to slow the motor; and the rotating kinetic energy of the rotor and connected load is partially converted to heat in the rotor and electrical power supplied to the DC source.

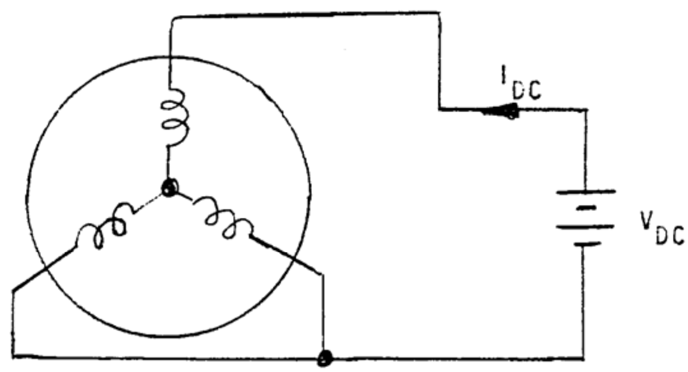


Figure 12.

7. Determination of Motor Constants (4)

The major operating constants of the equivalent circuit of an induction motor can be found in much the same way as with a transformer, which is not surprising considering the general similarity of the two devices. Two tests are made.

The first is a no-load test in which voltage is applied to a motor running with no connected shaft load. A series of voltages is applied ranging from about 25 percent above rated value, down to the point where the motor speed drops perceptibly. For each value of the applied voltage, readings are taken of the motor line current and the power input to the motor.

The second is a blocked-rotor test in which the rotor is mechanically constrained so that it cannot turn. A series of reduced voltages is applied to the motor such that line currents ranging from zero to about 125 percent of full load value are produced. Power input to the motor is simultaneously monitored in this test.

Also, a measurement is made of the DC stator resistance.

Rather than the equivalent circuit of Fig. 10, we choose one more akin to Fig. 9 to yield the result shown in Fig. 13. Based on past experience, the following simplifying assumptions can be made for this model:

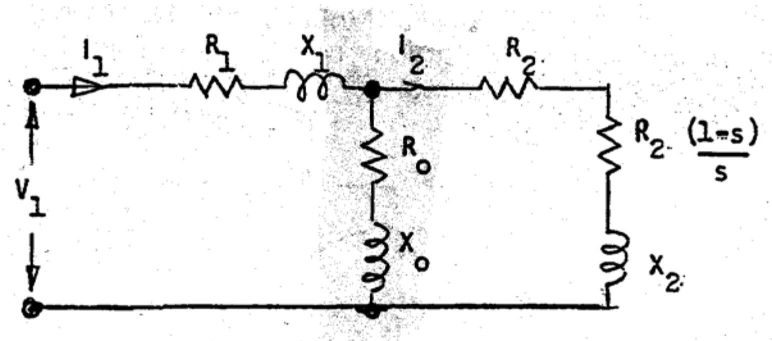


Figure 13.

$X_0 >> X_1$, $|R_0 + jX_0| >> |R_2 + jX_2|$, and $X_1 \approx X_2$. **NOTE WELL: This is based upon a WYE model and therefore represents but one of the <u>three</u> phases.**

For the rotor locked, s = 1 so that the following equations can be written from the equivalent circuit of Figure 13 assuming $|R_0 + jX_0| >> |R_2 + jX_2|$:

$$Z_{11} = (R_1 + R_2) + j(X_1 + X_2),$$
$$|Z_{11}| = V_1/I_1 \text{ , and}$$
$$P_{PH} = (R_1 + R_2)I_1^2$$

These equations can be solved for R2, X_1 , and X_2 as follows:

$$R_2 = (P_{PH}/I_1^2) - R_1$$

and (by assumption)

$$X_1 = X_2 = \tfrac{1}{2}\sqrt{|Z_{11}|^2 - (R_1 + R_2)^2} \text{ .}$$

Assuming that the stator resistance R_1 **is measured at DC** and that phase power P_{PH} , phase voltage V_1 , and phase current I_1 are measured, R_2, X_1, and X_2 can be calculated for the motor from the locked rotor test data.

From the data obtained from the no-load test, we can determine the values for the series circuit elements R_0 and X_0. To find these values, we draw graphs of power and line current versus applied voltage as shown in Figure 14.

First the measured I_1 and the measured phase power P_{PH} are used to calculate

$$P_C + P_{FW} = P_{PH} - I_1^2R_1 \text{ ,}$$

where $I_1^2R_1$ is the copper loss in this no-load case, P_C [W] is the per-phase core loss and P_{FW} [W] is the per-phase friction-and-windage. The derived values are then *appropriately* plotted and a suitable approximating curve put through them; this curve is then cleverly *extrapolated* backwards to the voltage origin, and **because core loss varies as V_1^α**, its intercept gives the friction-and-windage power loss[☺]. This will be explored further on the next page.

[☺] The observant student will note the italicized and bold-face material in this sentence and realize that brainpower may be more important than computer power in getting this right.

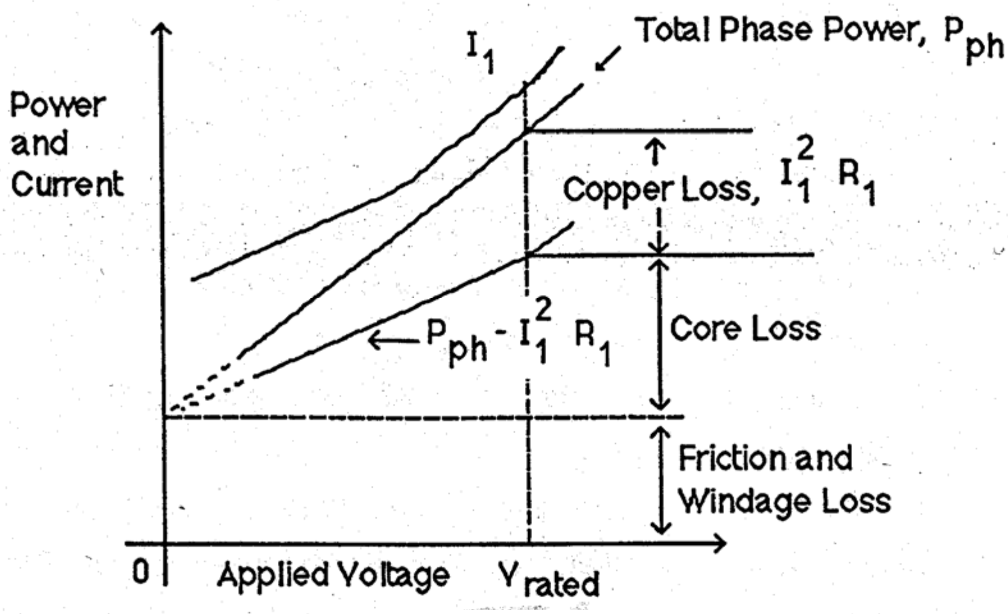


Figure 14

For no load, s = 0 so that the following equations can be written from the equivalent circuit of Figure 13:

$$Z_{IN} = (R_1 + R_0) + j(X_1 + X_0)$$
$$|Z_{IN}| = V_1/I_1.$$
$$P_{PH} = P_{Cu} + P_C + P_{FW} = I_1^2(R_1 + R_0) + P_{FW}\ .$$

Thus:

$$R_0 = [P_{PH} - P_{FW}]/I_1^2 - R_1$$
$$X_0 = \sqrt{|Z_{IN}|^2 - (R_1 + R_0)^2} - X_1.$$

Assuming that phase power P_{PH}, phase voltage V_1, and phase current I_1 are measured and that friction-and-windage loss P_{FW} has been obtained as shown in Figure 14, R_0 and X_0 can also be calculated for the motor from the no-load test data.

8. Bibliography

(1) A.S. Langsdorf, Theory of Alternating Current Machinery, 2nd. ed., New York, McGraw-Hill, 1955.
(2) T.S. Reynolds and T. Bernstein, "The Damnable Alternating Current", Proceedings of IEEE, (64) pgs. 1339-1343, Sept. 1976.
(3) P.L. Alger and R.E. Arnold, "The History of Induction Motors in America", Proceedings of IEEE, (64), pgs. 1380-1383, Sept. 1976.

B. EXPERIMENT

1. Equipment List

    One Instrumentation Rack with the usual test equipment

    One 208 Volt, 0.75 HP, 3-phase induction motor

    One dynamometer with torque controller

    One Phase Sequence Indicator

    One single-phase wattmeter plus miscellaneous apparatus as needed

2. Initial Data

    Record all nameplate information for the induction motor. You should also make a DC measurement of stator winding line-to-line resistance using a DMM.

3. Speed and Direction of Rotation

    The motor is mounted in a test rig that allows one to control the torque applied to the motor shaft and to measure both rpm and torque. The rpm sensor operates on a Hall effect principle and consists of a disk bearing on its periphery two magnetic pole-pairs and a detector that pulses once each time a pole-pair is rotated past it. Observe that, by counting the output of the detector, you will get a frequency, φ [Hz] , that is *twice* the actual rotational frequency of the motor. Therefore

$$\text{motor rpm} = n = 60\times(\tfrac{1}{2}\varphi) = 30\varphi \quad .$$

To observe the rpm sensor in operation, proceed as follows. Energize the detector with –20 VDC ; and attach its output to the oscilloscope, the torque controller, and frequency counter. Power up the motor normally and determine the no-load* rpm when the motor, as viewed from the front, is rotating clockwise (CW); repeat with the motor spinning counter clockwise (CCW).

BE CAREFUL !!
It can hurt to tangle with a three-phase motor.

A successful salesman for General Electric's motor division once remarked to one of your instructors that, when asked by a customer how a motor

* The "no-load" condition is that which obtains when the controller knob is fully counter-clockwise.

actually worked, he invariably replied "Very well, indeed.". This attitude is typical of a technologically mature discipline: one really can afford to treat the device as if it were a black box. Therefore, in addition to determining the short circuit and open circuit characteristics of your motor you will also have to determine its input and output powers. To this end, it will be assumed that the motor is a **balanced three phase wye** connected load and that you will therefore need to measure only one line-neutral voltage, only one line current, and only one phase power to characterize P_{in} completely. That is,

$$P_{in} = 3P_{line\text{-}neutral} = 3P_{phase} = 3I_{rms}V_{rms}\cos\theta.$$

Take note that V_{rms} is the phase voltage $V_{line\text{-}neutral} = V_{line\text{-}line}/\sqrt{3}$. Further,

$$P_{out} = 2\pi fT = \frac{2\pi n}{60}T = \pi\varphi T,$$

where T is the shaft torque, measured with the dynamometer in-oz, which must be converted to N·m in order to obtain power in watts.

4. Starting Current

Wire up the motor for CW motion so that starting current can be measured accurately using the oscilloscope[#]. With no load on the motor and 120 $V_{rms,\ line\text{-}line}$, turn on the power and observe and record the transient starting current[&].

5. No Load Test.

Precisely 1 h after the scheduled start of the lab, you must be prepared to measure V_{rms} and $\varphi(V_{rms})$, $I_{rms}(V_{rms})$, $P_{phase}(V_{rms})$. Because there is no way to control V_{rms} at the bench, all lab groups are required to take their measurements in synchrony as the line-line voltage is varied at the control panel by the instructor. Line-to-line voltage will be varied from 30 to 210 V in steps of 30 V.

6. Locked Rotor Test.

This portion of the experiment will begin immediately after the NO Load Test is complete. With the motor de-energized, lock the rotor with the wooden clamp-on fixture provided. Turn on the power. Note that V_{rms} will initially be low,

[#] Remember that you are working with polyphase power . Therefore it will be essential for you to distinguish carefully between line-line and line-neutral voltages.

[&] Just how this is done is up to you. But it can be done. It just can't be done swiftly unless you **design** your measurement in advance.

and the instructor will then raise it in steps until $I_{rms}(V_{rms}) = I_{full\text{-}load}$. Measure V_{rms} and $\varphi(V_{rms})$, $I_{rms}(V_{rms})$, $P_{phase}(V_{rms})$. Turn off the power.

7. Torque vs. Speed Curves.

Immediately after the Locked Rotor Test is complete, the instructor will reset the line-to-line voltage to approximately 120 V_{rms}. The dynamometer is a device that allows placing a variable load on the motor. Use the weights provided, and vary the control current to the dynamometer so that the motor will be loaded with a torque roughly proportional to the control current. This control current is feedback regulated by the output from the rpm sensor, *but only if you run the necessary coax*: should you omit this coax, your data will be subtly degraded. Since the product of motor torque (T) and shaft angular velocity ($\pi\varphi$) is power, the dynamometer is absorbing energy. This energy is dissipated primarily as heat, and the dynamometer temperature will therefore rise. It is advisable to feel the dynamometer case occasionally to insure that it is not overheating. Note that the torque exerted upon the motor by the dynamometer is indicated by the appropriate scale on the dynamometer circumference. In using the dynamometer, care should be taken (i) to avoid sudden substantial variations of control current and (ii) to avoid sudden motor starts with the control current on. These can slam the dynamometer against its limit stops. Treat the dynamometer as the sensitive instrument that it is.

Complete the experiment as follows. First, begin at no load and, by gradually increasing the dynamometer control current, measure ϕ, $P_{phase}(\varphi)$, $T(\varphi)$, and $I(\varphi)$ as φ gradually decreases. Continue this until you reach rated current. The motor should not stall[#]. However, if it does stall, quickly reduce the dynamometer current to restart the motor.

[#] Win laurels! Improve your grade! The instructors have a nagging suspicion that these induction motors have a pull-up torque. But, in the entire history of the course, no one has ever been able to detect one. Solve this mystery and garner esteem.

C. REPORT

(a) Based on your data from the no-load and locked-rotor tests, do the following. Plot graphs similar to those described in Figure 14 and find the power lost due to friction and windage. Compute the following: (1) the stator winding phase resistance R_1 from your line-to-line measurement, (2) numerical values of the exciting path elements R_o and X_o at rated voltage, and (3) numerical values of R_2 and X_1 and X_2 at rated current. Assume that X_1 is equal to X_2. Show your final equivalent circuit (Figure 13) for the induction motor using these values,

(b) Use your *equivalent circuit* to calculate the expected starting current of the motor assuming 120 $V_{rms,\ line\text{-}line}$ and no load. Is your calculated value close to the observed value? Comment. [Note: You will have to study Fig. 13 and Section 7 with care to answer this question successfully.]

(c) Use your equivalent circuit to generate smooth theoretical curves of slip (%), torque (ft-lbs), power in (watts), power out (Hp), efficiency (%), line current (Amp), and power factor versus motor speed (rpm). All of these parameters are to be computed at 120 $V_{rms,\ line\text{-}line}$ and six <u>separate</u> graphs are to be made using the same motor speed scale. Next, overlay the experimental points onto these graphs and comment cogently.

(d) Using your equivalent circuit, compute the motor horsepower at rated line-to-line voltage of 208V and rated speed. Compare your result with the 0.75 Hp given as the rated output on the motor nameplate. Is 0.75 Hp a conservative value for this motor?