Introduction:

Induction machines are perhaps the most widely used of all electric motors.

They are generally simple to build and rugged, offer reasonable asynchronous performance: a manageable torque-speed curve, stable operation under load, and generally satisfactory efficiency.

An induction machine is a machine having a wound winding on the stator and a wound or cage type rotor.

Both windings carry a/c. , single or 3-phase depending on how they are constructed.

Three-phase induction machine.

There are two basic types; **wound rotor** and **cage rotor**.

A three-phase induction motor may be operated in <u>three different ways.</u>

(i) As an induction motor to drive a mechanical load. The stator winding is driven from a 3 ph supply and the rotor winding is short circuited. 98 - 99% of applications.

(ii) As an induction generator to supply power to a/c. networks. The short-circuited rotor is driven by a prime mover. The stator winding is connected to the grid or network.

(iii) As an induction transformer, (regulator) to supply electrical power at required potential and phase shift. The stator is connected to the supply and the rotor to the load and held stationary. There is no electromechanical power conversion. It is not applicable to cage rotors because of the connections.

Important concepts.

(1) 3-phase rotating magnetic field

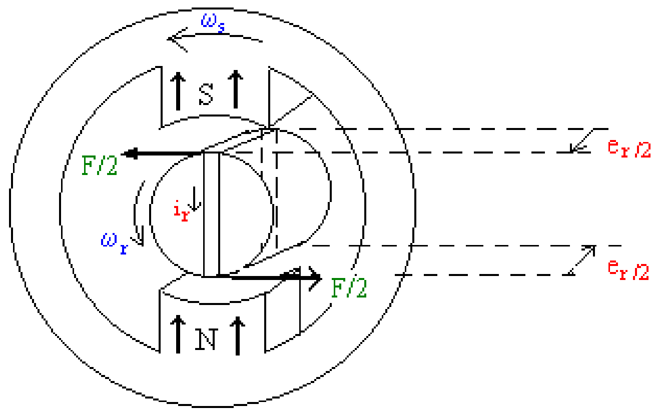
(2) Slip frequency

(3) Equivalent circuit

(4) Torque/speed characteristics.

Principle of Operation.

Consider a machine with, (i) a 2 pole stator , and (ii) a rotor carrying a single short-circuited coil.



If the stator is driven by a torque T_s at speed w_s , then magnetic flux ϕ of its poles cuts both sides of the rotor coil inducing emf e_r .

$$e_r = Bl\omega_s r \quad \text{volts.} \quad (1)$$

e_r produces current i_R around coil..

Since there is no power loss ,

$$T_s \omega_s = e_R i_R \text{watts.} \quad (2)$$

The sides of the coil experience forces,

$$F = B\, l\, i_R \quad \text{N.} \quad (3)$$

This force tends to turn the coil in the same direction as the stator, i.e. clockwise. Hence te stator turns at say ω_r , with torque T_R transmitted to mech. Load. The emf e_R in the rotor is reduced to a new value since the flux cutting speed is now $(\omega_s - \omega_R)$ instead of ω_s.

$$e_r = Bl(\omega_s - \omega_R)\, r \quad \text{volts}$$

Hence the power equation

$$e_R i_R = Bl\omega_s r\, i - Bl\omega_R r\, i$$

$$= T_s \omega_s - T_R \omega_R$$

$$\therefore \quad T_s \omega_s = e_R i_R + T_R \omega_R$$

Mech. Power input to stator = Elect. Power loss + mech. output of rotor .

coil res.

Most of the mech. power to the stator is transferred to mech. power output of the rotor, the balance being lost in the coil resistance.

The coil loss can't be omitted since no transfer would happen without e_R and i_R . Also e_R depends on ω_s being > ω_R …..eq. (4)
e_R and i_R . are a .c. and undergo a complete cycle when the coil is swept once by N and S poles . This occurs $(\omega_s - \omega_R)/2\pi$ times per second.

The only modification from in an actual motor from the above is that the "rotating stator"
is produced electrically by a distributed 3 ph winding as in a synchronous machine. Then
$T_s \omega_s$ is replaced by Pe , the electrical input to the stator.

$$Pe = e_R i_R + T_R \omega_R$$

The rotor winding consists of a large no. of short circuited coils.

Induction Generator.

Consider the machine from above.
For operation as an induction generator there are 2 requirements;

(i) the stator must be connected to 3 ph supply to provide rotating stator field.
(ii) S/c rotor must be driven faster than the rotating stator field.

When the rotor revolves faster than the mag. Field, its conductors "cut" flux in the opposite sense to that of the motor. Hence emf and currents in the rotor are 180^o out of phase in comparison with the motor case. Therefore due to transformer action currents in the stator are also 180^o out of phase with the motor case.
Hence since the stator emf's are the same, the direction of power flow through the m/c is reversed and mech. power from the prime mover is fed thro. magnetic link into the a.c. network.

Slip speed and slip

In the case of machine with rotor, the speed difference

$\omega_s - \omega_R$ is called the SLIP SPEED

Slip is defined as

$$s = (\omega_s - \omega_R)/\omega_s = (n_s - n_R)/n_s$$

For motors $\omega_s > \omega_R$ and the slip is positive.

Generators the $\omega_s < \omega_R$ and the slip is neg.

Typical values are;

motor, free running at no load:	about + 0.005
full load	+0.03 to +0.07
generator: full load	-0.03 to -0.05

Frequencies of currents and emf's

In the stator the freq. is the supply freq. and related to the speed of the rotating field by the eqn.

$$\omega_s = 2\pi f / p \text{ rad/sec.}$$

$$\text{Hence } f = p\,\omega_s / 2\pi$$

In the rotor the freq. depends on the difference between rotor speed ω_R and the speed of the mag. field ω_s

$$f_R = (\omega_s - \omega_R)/2\pi \qquad \text{for a 2 pole machine as above.}$$

For p pole pairs

$$f_R = (\omega_s - \omega_R)\, p/2\pi = (p/2\pi) \,.\, s \,.\, 2\pi f/p$$

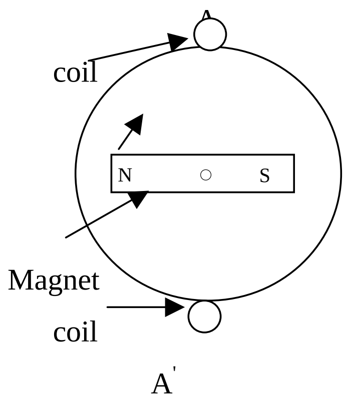
$$= s \,.\, f$$

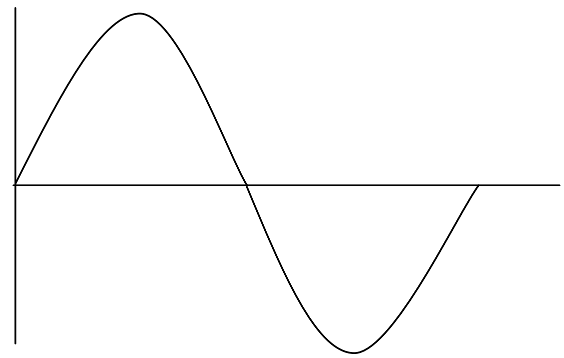
Therefore f_R varies from f (at s = 1 standstill) to 0 (at s = 0 synchronous speed.)

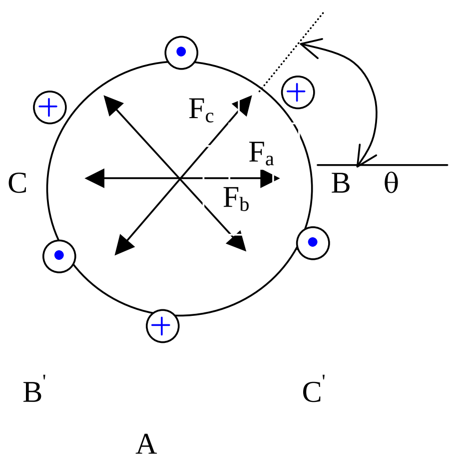
The machine operates at speeds between standstill and synchronous speed, with positive slip between 1 and 0. If the machine runs on no load, with a slip typically less than 0.01 p.u. the rotor e.m.f. is very small, the rotor circuit impedance is almost purely resistive, and a current sufficient to develop a torque to maintain rotation is developed. If a mech. load is now applied to the shaft, the rotor slows increasing the slip. The rotor e.m.f. rises in magnitude and freq., producing more current and torque. Greater load results in more torque up to a maximum pull-out value and then the motor stalls.

The limit to torque production at low slip is the rotor resistance, which should therefore be small. At starting however, the current is limited largely by the leakage reactance. The torque may nevertheless be improved by increasing the resistance, for although this augments the total impedance it reduces the angle of lag and results in more rotor active power shows greater rotor active power means greater torque.

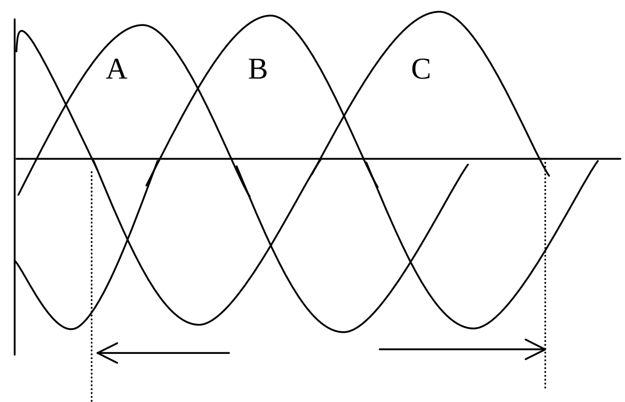
Induction machines.







(Currents)



One cycle

The external stator winding is 3 ph. and this produces a rotating mag. field when connected to a 3 ph. Supply. The 3 ph. Windings, represented by AA', BB' and CC', are displaced from each other by 120 electrical degrees in space, around the inner circumference of the stator.

Balanced 3 ph. supply currents are represented as,

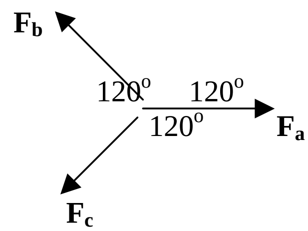
$$i_a = I_m \cos \omega t$$

$$i_b = I_m \cos (\omega t - 120^o)$$

$$i_c = I_m \cos (\omega t + 120^o)$$

Note:

Currents in the stator shown are assumed positive if they flow into the unprimed (A, B,C) and out of the primed ($A^{'}$, $B^{'}$, $C^{'}$) ends of the coil.



Direction of mmf’s with positive currents in the stator coils.

When a current flows through a phase coil, it produces a sinusoidally distributed mmf, (Note: mmf = magnetomotive force $\propto$ NI , i.e. I), wave centered on the axis of the coil representing the phase winding.

If an alternating current flows through the coil, it produces a pulsating mmf wave, whose amplitude and direction depends on the instantaneous value of the current flowing through the coil.

Each coil (i.e. phase winding) will produce similar sinusoidally distributed mmf waves, but displaced 120^o form each other.

At any instant t,

$$F_a(\theta) = F_m \cos\theta$$

$$F_b(\theta) = F_m \cos(\theta - 120^o)$$

$$F_c(\theta) = F_m \cos(\theta + 120^o)$$

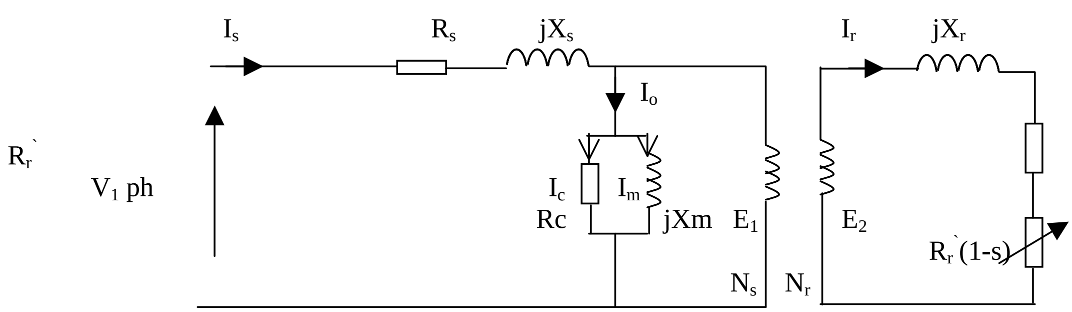
Consider the balanced 3-ph. Currents of fig. Flowing through the 3-ph. Winding of fig…..

Angle θ can be chosen as the axis of phase A.

At any instant of time all three phases contribute to the air-gap mmf

Induction motor :- Equivalent circuit.

In order to develop performance characteristics, it is necessary to construct an equivalent circuit, which will represent the induction machine in terms of lumped circuit parameters referred to the stator. This may be done by considering the relationships between the magnetic field components, the currents flowing in the stator and rotor windings and the voltages induced in these windings. A per phase equivalent circuit of a three phase induction motor is shown in Fig.1. It is based on the concept of transformer action, which is important for steady-state analysis, and besides, the induction motor is basically a transformer with a rotating secondary winding.



Slip s = $(ns\text{-}n_r)/n_s$ = (1500-1460)/1500 = 0.04 p.u.

Fig. 1

where ; V_1 = Terminal voltage.

R_s = Stator winding resistance.

jX_s = Stator leakage reactance.

jX_m = Magnetising reactance.

R_c = Core loss resistance.

E_1 = Induced voltage in the stator winding.

E_2 = Induced voltage in the rotor winding.

jX_r = Rotor leakage reactance.

R_r = Rotor winding resistance.

N = Ns/Nr Transformation ratio.

The rotating air gap voltage E_1, which is subsequently converted to slip voltage v_r (E_2) = NsE_1 in rotor phase, where N is the rotor to turns ratio and s = slip, [per unit]. The no load excitation current I_o consists of two components, $I_c = \frac{E_1}{R_c}$ (core loss), and a magnetising component $I_m = E_1/jX_m$, where X_m is the magnetising reactance. The rotor induced voltage V_r (E_2) causes rotor current I_r at slip frequency ω_r , which is limited by rotor resistance R_r and leakage impedance $\omega_r L_r$. The rotor current I_s consists of excitation component I_o and the rotor reflected current I_r. Fig.2 shows the per phase equivalent circuit with respect to the stator.

(ii) machine.

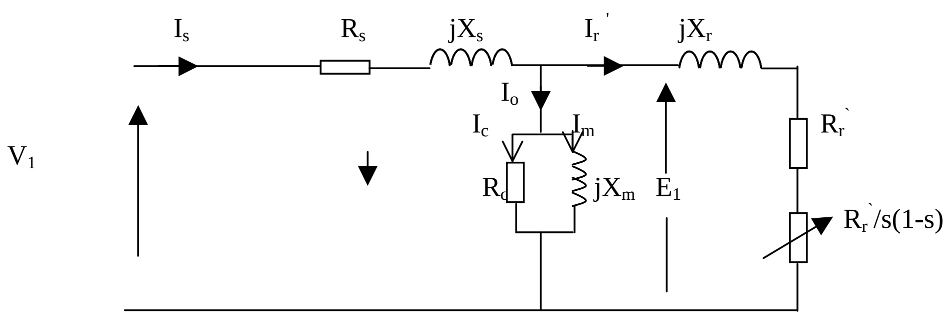


Fig. 2

$R_r` = N^2 R_r$ and is the per phase standstill rotor resistance referred to the stator and $\frac{R'_r}{s}(1-s)$ is a dynamic resistance that depends on rotor speed, and corresponds to the load on the motor.

If the core loss is lumped with the windage and friction loss, Rc can be removed form the circuit. Equating $R`_r + \frac{R'_r}{s}(1-s) = \frac{R_r`}{s}$, the equivalent circuit may be redrawn as below in Fig.3, where $jX_r` = N^2 jX_r$

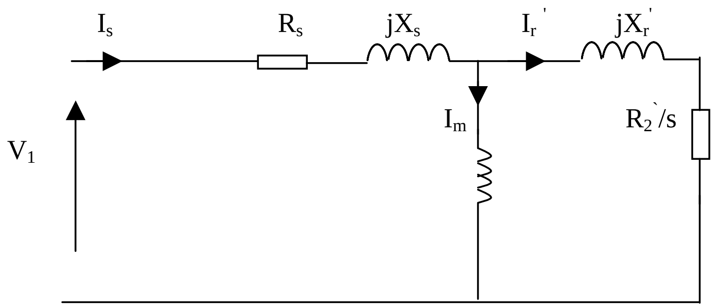


Fig. 3

Where I_r is :

$$I_r' = NI_r$$

$$= \frac{V_1}{\left(\frac{R_r}{s}\right) + jX'_r}$$

.....(1)

Various powers in an induction motor are;

Power across the air-gap, $P_g = \frac{3|I_r'|^2 R_r'}{s}$. ....(2)

Stator copper loss, $P_{cop1} = 3|I_s|^2 R_s$

....(3)

Rotor copper loss $P_{cop2} = 3|I_r'|^2 R_r' = s.P_g$. ....(4)

Shaft power $= \boldsymbol{P_o} = P_g(1 - s)$

$= P_g - P_{cop2} = \frac{3|I_r'|^2 R'_r(1-s)}{s}$.

....(5)

P_{rot} = Rotational losses.

....(6) Shaft power , $T.\,\omega_m = P_o$,

....(7)

where ω_m = angular velocity.

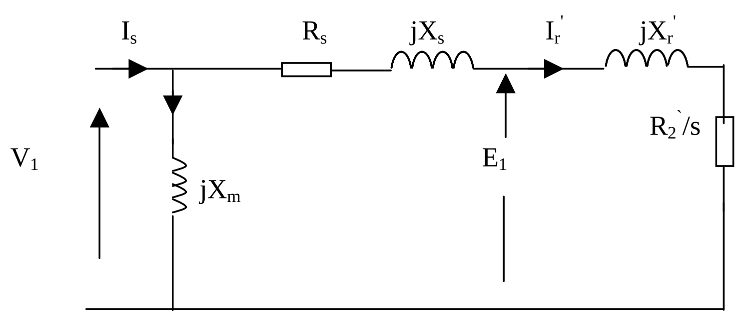
The synchronous speed, $\omega_s = \dfrac{\omega_m}{(1-s)} = \dfrac{2\pi f_1}{p}$.

....(8)

where p = pole pairs and f_1 = frequency.

and therefore the torque $T = P_o / \omega_m = \dfrac{3|I_r`|^2 R'_r(1\text{-}s)}{s} . 1/\omega_m$

$$= \frac{3\,|\,I_r`\,|^2\,R_r}{s} . \frac{p}{2\pi f_1} \qquad ....(9)$$



Approximate equuivalent circuit.

Fig. 3

The rotor current,

$$I_r` = \frac{E_1}{(\frac{R_r}{s})` + jX'_r} = \frac{V_1}{(R_s + \frac{R'_r}{s}) + jXs + jX_r`}$$

The scalar magnitude of the rotor current,

$$= \frac{V_1}{\sqrt{\left(R_s + \frac{R'_r}{s}\right)^2 + \left(Xs + X_r`\right)^2}} \qquad ....(10)$$

From eqn (9) , Torque T $= P_o / \omega_m = P_g(1 - s)/ \omega_s(1\text{-}s)$

$$= P_g / \omega_s \qquad ....(11)$$

from eqn. (2) T $= \dfrac{1}{\omega_s}\dfrac{3\,|\,I_r^{`}\,|^2\; R_r'}{s}.$

$$= \frac{1}{\omega_s}\frac{3V_1^2}{\left\{\left(\mathrm{R}_s+\dfrac{R'_r}{s}\right)^2+\left(Xs+X_r^{`}\right)^2\right\}}\frac{R'_r}{s} \quad \ldots.(12)$$

Power loss and power flow through I.M