Industrial Electronics- II

DETCE/S6

AC Motor

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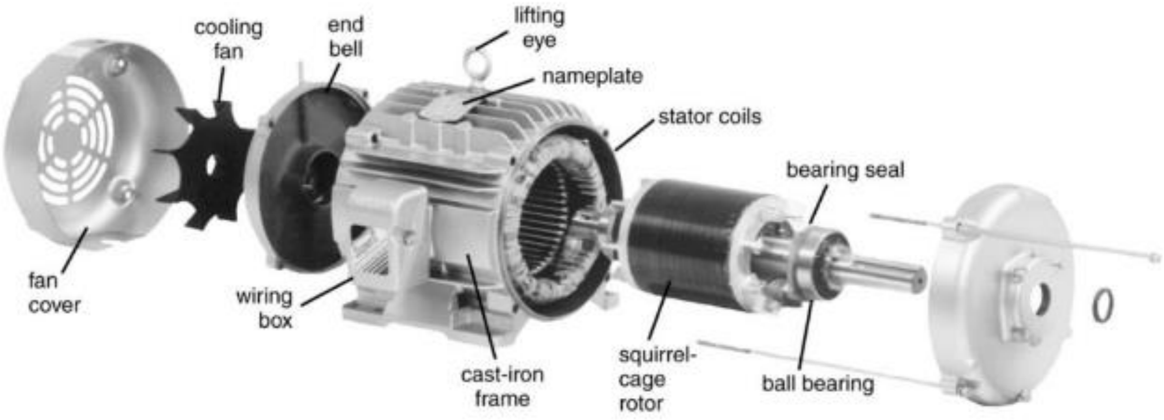


Learning Outcomes:

- Introduction of AC Motor (Three Phase Induction Motor)
- Formation of electrical equivalent circuit of the induction motor
- Starting torque equation generation
- Maximum torque
- Torque slip relationship
- Types of speed control strategies in three phase Induction motor

Introduction

An ac motor which is operated by alternating current is known as **AC Motor**. It is electromechanical device which converts electrical energy into mechanical energy. Most popular ac motor is three phase induction motor which is used for different industrial applications with various speed and load requirements. As three phase inductance motor does not require any additional starting device, so it is also known as **self-starting induction motor**. AC motor consists of two main parts **Stator** and **rotor**. Stator consists of coils and is supplied by Alternating current to produce a rotating **magnetic field**. These coils are wrapped to the **magnetic poles** of the motor which are present on the cover of the AC motor. The rotor is attached to the shaft to produce second rotating magnetic field. The rotor magnetic field is produced with **permanent magnets** or with an exciter.

Operating principles

The two main types of AC motors are induction motors and synchronous motors. The induction motor (or asynchronous motor) always depends on a small difference in speed between the stator rotating magnetic field and the rotor shaft speed called slip. As a result, the induction motor cannot produce torque near synchronous speed where induction (or slip) is irrelevant or ceases to exist. In contrast, the synchronous motor does not rely on slip-induction for operation and uses either permanent magnets, salient poles (having projecting magnetic poles), or an independently excited rotor winding. The synchronous motor produces its rated torque at exactly synchronous speed.

Other types of motors include eddy current motors, and AC and DC mechanically commutated machines in which speed is dependent on voltage and winding connection.

One common example of asynchronous motor is three phase induction motor.

Advantages

- Simple construction.
- Low cost and high reliability.
- Torque is low compared to DC series motor but produces sufficient torque for our need.
- Higher efficiency with less maintenance due to absence of brushes, commutators and slip rings.
- Though it consists of brushes but in normal running condition it does not require any brushes. Hence, frictional loss is minimum.
- Speed control by using SCRs can give wide range of speed.

- Can operate in polluted and explosive environments as they do not have brushes which can produce flux.

Disadvantages

- low starting torque.
- Speed control is difficult.
- During light load condition, the power factor of motor drops to a very value.

Applications

- Leather Industries
- Conveyor Belts
- Fans
- Pumps
- Drilling Machines

Equivalent circuit of induction motor

When ac supply is applied to the stator winding o a three phase induction motor a rotating magnetic field is developed. Due to that rotating magnetic field resulting flux is developed. This flux induced e.m.f. in the rotor winding and this induced e.m.f. produces current in the rotor winding. So applied voltage induces e.m.f. which in turns produces current in the rotor winding like transformer. The equivalent circuit of three phase induction motor acts as a generalised transformer.

Due to air gap in between stator and rotor winding, rotor never acquire the synchronous speed so speed in the primary winding (stator) of the ac motor is different from speed from the secondary winding (rotor) which is the main difference of ac motor from generalised transformer and in case of transformer rotor is static in nature. So, some arrangements have to be made so that ac motor can be acts as generalised transformer by making their speed mathematically similar.

- ❖ The difference in between synchronous speed (Ns) of rotating magnetic field i.e. rotor and actual speed (N) acquire by the rotor is called **slip** (s). It is given by

$$\text{Slip(S)} = \frac{N_S - N}{N_S} \quad \text{.................} \; (1)$$

The speed of the AC motor is determined primarily by the frequency of the AC supply and the number of poles in the stator winding, according to the relation:

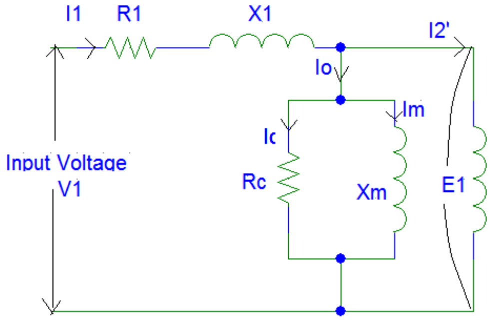
$$\text{Ns} = \frac{120\text{f}}{\text{P}} \quad \text{.........................} \; (2)$$

where

N_s = Synchronous speed, in revolutions per minute
f = AC power frequency
P = Number of poles per phase winding

From the above equation we can say that Ns $\propto$ f. It means speed is directly related to input frequency.

Electrical Equivalent Circuit of Induction Motor



Electrical Circuit of Stator or primary winding of transformer

Where,

I_1 = current flowing through stator/phase
R_1 = Stator resistance/phase
X_1 = stator leakage reactance/phase
R_C = core loss component /phase
X_m =component which is used to produce flux in between stator and rotor i.e. air-gap reactance /phase
I_o = no load current/phase
I_2' = reflected secondary (rotor) current flowing through transformer primary winding (Stator)/phase
E1 = emf induced in the primary winding of the induction motor (Stator) or primary winding of transformer per phase

In case of transformer, secondary winding is static in nature. It means that speed of the secondary winding is same as primary winding or frequency of the primary and secondary is same (as we know **Ns ∝ f)**. But its voltage and current vary according to its turn ratio.

For a three phase induction motor, the frequency (speed) of the rotor winding is changed due to the change in slip value. So, its frequency in the primary and secondary winding is different. Now, if we want to draw the equivalent circuit of the induction motor, then its speed have to be made equal in the primary and secondary winding like transformer by some arrangements for easy representation and analysis.

If we want to make the rotor frequency is same as supply frequency (or frequency of stator) the arrangements are as follows:

Ir2 = current flowing through the rotor winding in rotating condition

$$= \frac{E_{r2}}{Z_{r2}}$$

where,

$$= \frac{sE_2}{\sqrt{R_2^2+(sX_2)^2}}$$

Er2 = induced emf in the rotor winding /phase

E2 = induced emf in the rotor winding /phase in stationary condition

$$= \frac{sE_2}{R_2+jsX_2}$$

Zr2 = impedance of rotor /phase in rotational situation

$$= \frac{E_2}{\frac{R_2}{s}+jX_2} \quad \text{........ (3)}$$

R2 = resistance in the rotor /phase in static condition

X2 = reactance in the rotor /phase in static condition

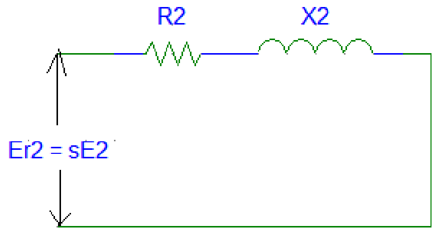
This equation implies that E_2, X_2 terms are Independent of slip(s).

$$X_2 = 2\pi f L_2 \text{ and Slip(S)} = \frac{N_S - N}{N_S}\ ; \quad Ns = \frac{120f}{P}$$

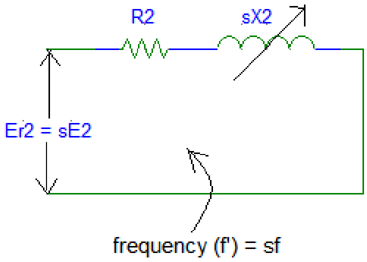
It means that f $\propto N_s$ and $f \propto X_2$. So, if frequency varies then synchronous speed (Ns), reactance(X_2) of the rotor also varies directly with frequency and this variation change the value of slip.

When rotor starts, rotor speed (N) = 0 i.e. s=1 at the time of starting. But when rotor catches the speed slip value starts reducing which in turns decrease the value of frequency (f). In equation (3) X_2 is independent of frequency so speed of rotor is constant. As rotor frequency is same as supply frequency i.e. stator frequency then we can represent induction motor as transformer equivalent circuit.

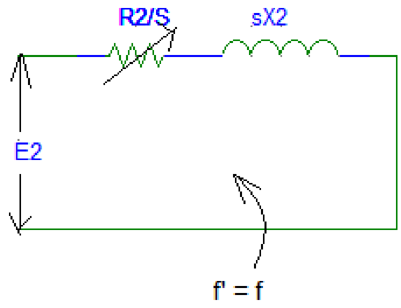
Now we have to redraw the rotor equivalent circuit



Here, electrical load is not connected i.e. load is short circuited.



As, R_2 does not depends upon frequency so R_2 is constant. But X_2 varies with frequency which in turns varies with slip.



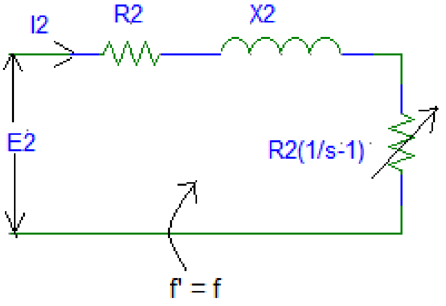
According to equation (3), $Ir_2 = \frac{E_2}{\frac{R_2}{s} + jX_2} = I_2$

Now, rotor frequency is constant with supply frequency.

Another arrangements is $\frac{R_2}{s} = \frac{R_2}{s} + R_2 - R_2$

$$= R_2 + R_2\left(\frac{1}{S} - 1\right)$$

Here, 1^{st} part is independent of slip or frequency and 2^{nd} part depends on slip. Rotor Resistance/phase is varying in nature and also equivalent to electrical load. That means electrical equivalent of mechanical load. So, the modified electrical circuit is given as follows



Equivalent circuit of rotor

Finally, the equivalent circuit of induction motor is similar to transformer equivalent circuit as rotor frequency is same as stator.

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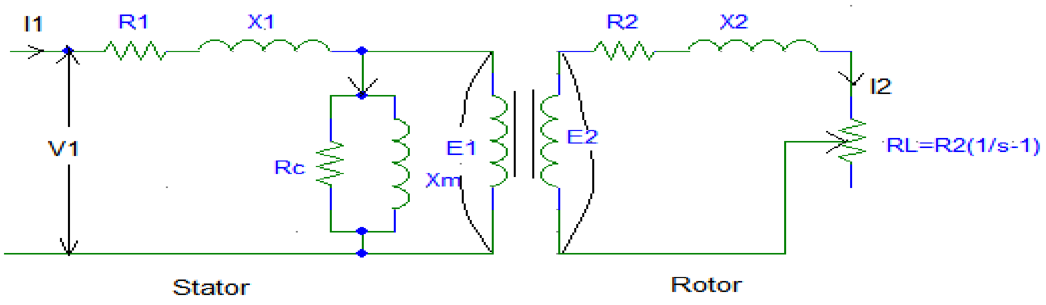
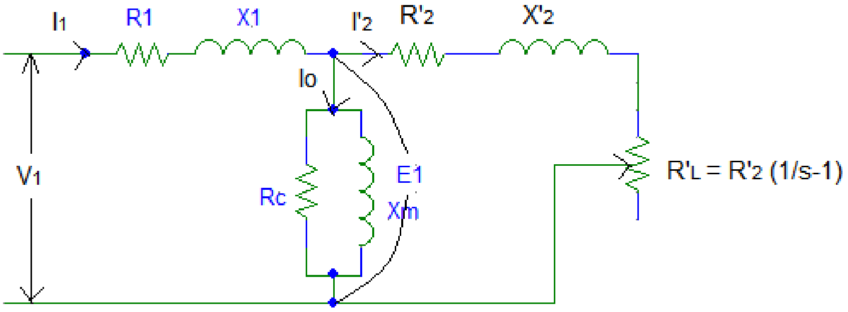


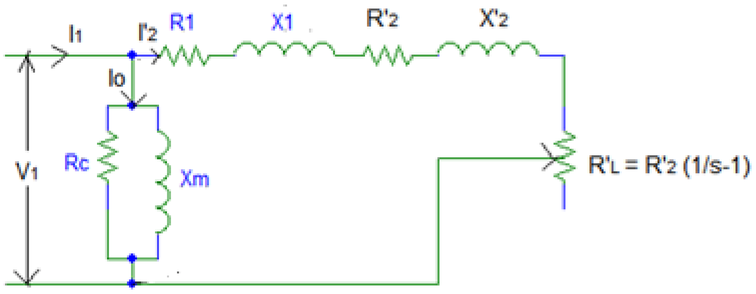
Complete equivalent circuit of induction motor

Here, R_L is electrical equivalent of mechanical load. All other components are same as before. As both side of the induction motor operates at the same frequency so it acts now as generalised transformer.

Now, the equivalent circuit of induction motor referred to stator by shifting the rotor parameter in in stator side by making $R_2 \rightarrow R_2'$; $X_2 \rightarrow X_2'$; $R_L \rightarrow R_L'$. Newly modified circuit is given below



As stator resistance and reactance are so small so voltage drop across them is negligible. Therefore the approximated circuit is given below



Here, $R'_2 = \frac{R_2}{k^2}$

$X'_2 = \frac{X_2}{k^2}$ and

$R'_L = \frac{R_2}{k^2}\left(\frac{1}{S} - 1\right)$

Where, K is transformer turn ratio which is taken 1 for easier Calculation.

Modified equivalent circuit of induction motor

At no load condition,
when N = Ns ; i.e. S=0. If S = 0 then $R_L = \infty$. That means secondary winding is open circuited.
When N=0 i.e. starting condition s = 1. If S = 1 then $R_L = 0$. This means that secondary winding is short circuited. So, no load is connected at the time of starting.

Expression for starting Torque equation

In case of DC motor, T ∝ $\emptyset$Ia (say)

This equation is also valid for Induction motor. But, for three phase induction motor phase angle between induced e.m.f. and rotor current depends on power factor of the rotor circuit.

As torque developed in the rotating part of the induction motor i.e. rotor winding so parameter related to the rotor most be included in the developed torque equation. Therefore, torque equation depends on

(i) stator flux ($\emptyset$)

(ii) rotor current (I_2)

(iii) rotor power factor (cos$\emptyset$)

So, $\mathbf{T} \propto \emptyset \boldsymbol{I_2 cos}\emptyset$

$= K\emptyset \boldsymbol{I_2 cos}\emptyset$ where, K is proportionality constant .... (4)

As $\emptyset$ is the stator flux and flux($\emptyset$) produced by the stator is directly depends on induced e.m.f. then $\emptyset \propto \boldsymbol{V_1}$.

From equation (4) we get, $T = K_1.V_1.I_2.cos\emptyset_2$ .... (5) Here, $K_1 = \frac{3}{2\pi N_S}$ [standard value]

In static condition, rotor current $(I_2) = \frac{V_1}{Z_2}$ where $Z_2 = (R_1+R_2) + j(X_1+X_2)$

and rotor power factor $(cos\emptyset_2) = \frac{R_2}{Z_2}$

By putting the values in equation (5) we get, $T = K_1 \times V_1 \times \frac{V_1}{Z_2} \times \frac{R_2}{Z_2} = K_1\left(\frac{V_1}{Z_2}\right)^2 R_2 = \frac{3}{2\pi N_S} \times \frac{V_1^2}{R_2^2+X_2^2} R_2$

Therefore, at starting time, $\mathbf{T} = \frac{3}{2\pi N_S} \cdot \frac{V_1^2}{R_2^2+X_2^2} \boldsymbol{R_2}$ **...................... (6)**

Torque under running condition

When rotor is in running condition emf induced /phase is V_1

and impedance/phase is $[(R_1 + \frac{R_2}{S}) + j(X_1+X_2)]$.

Rotor current is given by, $I_{r2} = \frac{V_1}{\left(R_1+\frac{R_2}{S}\right)+j(X_1+X_2)}$

Power factor ($cos\emptyset_{r2}$) is $= \frac{\frac{R_2}{S}}{\left(R_1+\frac{R_2}{S}\right)+j(X_1+X_2)}$

By putting all these in equation (5) we get $\mathbf{T} = \frac{3}{2\pi N_S} \times \frac{V_1^2}{\left(R_1+\frac{R_2}{S}\right)+j(X_1+X_2)} \times \frac{R_2}{S}$

Or, $T = \frac{3}{2\pi N_S} \times \frac{V_1^2}{\left(\sqrt{\left(R_1+\frac{R_2}{S}\right)^2+(X_1+X_2)^2}\right)^2} \times \frac{R_2}{S}$ **................ (7)**

Condition for obtaining maximum torque equation under running condition

To obtain maximum torque under running condition, $\frac{dT}{dS} = 0.$

$$T = \frac{3}{2\pi N_S} \times \frac{V_1^2}{\left(R_1+\frac{R_2}{S}\right)^2+(X_1+X_2)^2} \times \frac{R_2}{S}$$

$$\text{So, } \frac{dT}{dS} = \frac{d}{dS}\left[\frac{3}{2\pi N_S} \times \frac{V_1^2}{\left(R_1+\frac{R_2}{S}\right)^2+(X_1+X_2)^2} \times \frac{R_2}{S}\right]$$

$$\text{Or, } 0 = \frac{3}{2\pi N_S} \times V_1^2 \times R_2 \frac{d}{dS}\left(\frac{1}{\left(R_1+\frac{R_2}{S}\right)^2+(X_1+X_2)^2} \times \frac{1}{S}\right)$$

$$\text{Or, } 0 = \frac{-[\{\left(R_1+\frac{R_2}{S}\right)^2+(X_1+X_2)^2\}+S.2(\left(R_1+\frac{R_2}{S}\right).(-\frac{R_2}{S^2}))]}{S^2(\left(R_1+\frac{R_2}{S}\right)^2+(X_1+X_2)^2)^2}$$

As formula stated $\frac{dU}{dV} = \frac{U.dV-V.dU}{V^2}$

$$\text{Or, } 0 = \left(R_1 + \frac{R_2}{S}\right)^2 + (X_1 + X_2)^2 - 2(R_1 + \frac{R_2}{S})\frac{R_2}{S}$$

$$\text{Or, } 0 = R_1^2 + \cancel{2R_1\frac{R_2}{S}} + \left(\frac{R_2}{S}\right)^2 + (X_1 + X_2)^2 - \cancel{2R_1\frac{R_2}{S}} - 2\frac{R_2^2}{S^2}$$

$$\text{Or, } R_1^2 + (X_1 + X_2)^2 = \frac{R_2^2}{S^2}$$

$$\text{r, } S^2 = \frac{R_2^2}{R_1^2 + (X_1+X_2)^2}$$

Therefore, S_{max} = $\boldsymbol{\frac{R_2}{\sqrt{R_1^2 + (X_1+X_2)^2}}}$ for **S_{max}** we will get **T_{max}**

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Now putting the value of S_{max} in equation (7) we get,

$$T_{max} = \frac{3}{2\pi N_S} \times \frac{V_1^2\sqrt{R_1^2 + (X_1+X_2)^2}}{(R_1+\sqrt{R_1^2 + (X_1+X_2)^2})^2+(X_1+X_2)^2}$$

As $\frac{R_2}{S} = \sqrt{R_1^2 + (X_1 + X_2)^2}$

$$= \frac{3}{2\pi N_S} \times \frac{V_1^2\sqrt{R_1^2 + (X_1+X_2)^2}}{R_1^2+R_1^2 + (X_1+X_2)^2+2R_1\sqrt{R_1^2 + (X_1+X_2)^2}+(X_1+X_2)^2}$$

$$= \frac{3}{2\pi N_S} \times \frac{V_1^2\sqrt{R_1^2 + (X_1+X_2)^2}}{2[R_1^2 + (X_1+X_2)^2+R_1\sqrt{R_1^2 + (X_1+X_2)^2}]}$$

$$= \frac{3}{4\pi N_S} \times \frac{V_1^2\cancel{\sqrt{R_1^2 + (X_1+X_2)^2}}}{[\sqrt{R_1^2 + (X_1+X_2)^2}+R_1]\cancel{\sqrt{R_1^2 + (X_1+X_2)^2}}}$$

by taking common $\sqrt{R_1^2 + (X_1 + X_2)^2}$ we get

$$T_{max} = \frac{3}{4\pi N_S} \times \frac{V_1^2}{\sqrt{R_1^2 + (X_1+X_2)^2}+R_1} \quad \text{................ (8)}$$

Torque – Slip characteristics of three phase induction motor

We know that, $T=\frac{3}{2\pi N_S} \times \frac{V_1^2}{\left(R_1+\frac{R_2}{S}\right)^2+(X_1+X_2)^2} \times \frac{R_2}{S}$; **S_{max}**$=\frac{R_2}{\sqrt{R_1^2 + (X_1+X_2)^2}}$ and $T_{max}= \frac{3}{4\pi N_S} \times \frac{V_1^2}{\sqrt{R_1^2 + (X_1+X_2)^2}+R_1}$

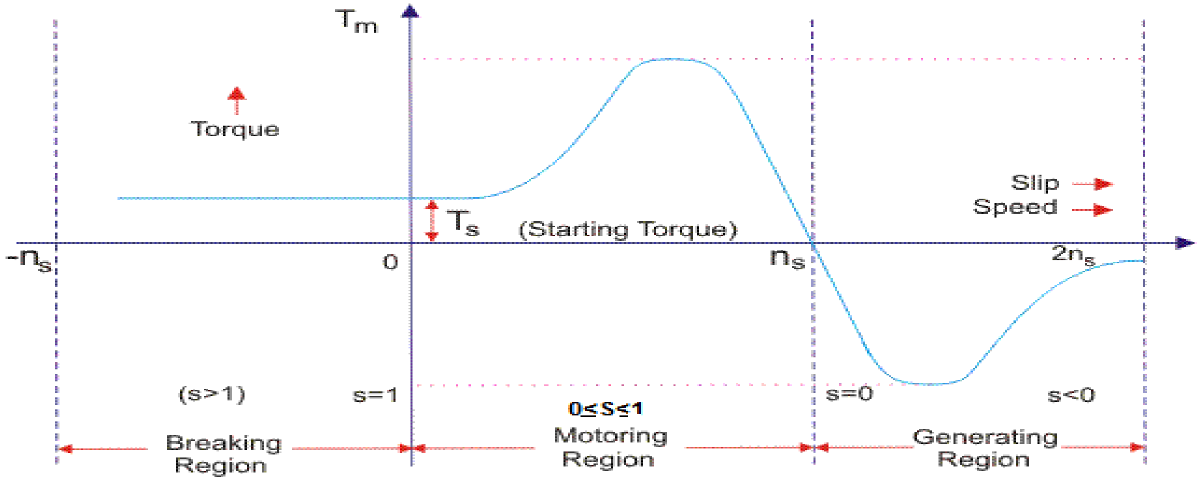
As the induction motor operates from no load to full load, its speed decreases hence slip value increases. Due to the increment of load motor has to produce more torque to satisfy the load demand. So, torque depends on slip.

Motoring Region : This region is divided into two parts. I) Low slip region and ii) high slip region.

In low slip region, the value of **S** is very small. Hence, $T \propto S$. So, if load increases speed decreases which in turn increases slip. This increases torque to satisfy load condition. Hence, the graph is straight line in nature. At, N = Ns, S = 0. Hence, T = 0. So, motor stops rotating when it tries to achieve synchronous speed (Ns). Every motor has its own limitations to produce certain amount torque. When load increases, the rotor can produce maximum rated torque (T_{max}) at s= S_{max}. So, linier behaviour continues till S=S_{max}. Therefore, the operation of motor in this region is known as **stable operation region**.

In high slip region, the value of S is high i.e. S →1 then $T \propto \frac{1}{S}$. Then the nature of the graph is rectangular hyperbola. If load increases now, speed decreases which in turns increases slip. At S = 1, motor acquire synchronous speed (N = 0) i.e. motor becomes standstill and the value of torque is now known as starting torque (T_{start}). After obtaining maximum torque, toque gets reduces to a value called starting torque (T_{start}). As the rotation of motor is not uniform so it is known as **unstable region**.

Here, when the slip lies in the region 0 and 1 i.e. when 0 ≤s ≤1, the machine runs as a motor which is the normal operation. The rotation of rotor is in the direction of rotating field which is developed by stator currents. In this region it takes electrical power from supply lines and supplies mechanical power output. The rotor speed and corresponding torque are in same direction.



Torque Slip Curve for Three Phase Induction Motor

Generating Region (S<0):

In this region, S<0 i.e. slip is less than zero means negative. Negative slip indicates that rotor speed is more than synchronous speed. When motor runs above synchronous speed it takes mechanical energy and supplies electrical energy from stator. So, this region is also known as **regenerative braking.**

As slip is negative and generator action takes place so current flows through the rotor in opposite direction of motoring action. So, graph is plotted in the negative direction of Torque-Slip characteristics.

Braking Region (S>1):

In this method, the terminals of supply are reversed then the phase sequence will be changed. This reverses the direction of rotation of magnetic field. As a result the generator torque also reverses which resists the normal rotation of the motor and as a result the speed decreases. So, the motor comes to quick stop due to counter torque which produces braking action. The method by which motor comes to rest is known as **plugging**. During plugging external resistance is also introduced into the circuit to limit the flowing current. The main disadvantage of this method is that here power is wasted.

Induction motor speed control from stator side:

An induction motor is practically a constant speed motor, this means that change in loading range will cause very little change in motor speed. Different speed control strategies are given below:

i) By changing the applied voltage
ii) By changing applied frequency
iii) Constant V/F control of induction motor
iv) Changing the number of stator poles

i) By changing the applied voltage

We know that, T = $\frac{3}{2\pi N_S} \times \frac{V_1^2}{\left(R_1+\frac{R_2}{S}\right)^2+(X_1+X_2)^2} \times \frac{R_2}{S}$. This means that T $\propto sV_1^2$. So, if applied voltage decreases torque will also decrease. Therefore, for obtaining same torque, slip increase and voltage decrease. This method is easiest and cheapest and rarely used because

1. large change in supply voltage is required for relatively small change in speed.
2. large change in supply voltage will result in a large change in flux density, hence, this will disturb the magnetic conditions of the motor.

II) By changing applied frequency

Synchronous speed of induction motor is given by $N_s = \frac{120f}{P}$, where f = supply frequency and P = number of stator poles. Here, $N_S \propto f$ so, synchronous speed will directly change with frequency. Again, actual rotor speed of induction motor is given by, $N = N_s(1\text{-}s)$. At lower frequency, the motor current may become too high due to decreased reactance. And if the frequency is increased beyond the rated value, the maximum torque developed falls while the speed rises. So, this method is not widely used. It may be used where the induction motor is supplied by a dedicated generator (so that frequency can be easily varied by changing the speed of prime mover).

III) Constant V/F control of Induction Motor

This is the most popular method for controlling the speed of an induction motor. As in above method, if the supply frequency is reduced keeping the rated supply voltage unchage, the air gap flux will tend to saturate. This will cause excessive stator current and distortion of the stator flux wave. Therefore, the stator voltage should also be reduced in proportional to the frequency so as to maintain the air-gap flux constant. The magnitude of the stator flux is proportional to the ratio of the stator voltage and the frequency. Hence, if the ratio of voltage to frequency is kept constant, the flux remains constant. Also, by keeping V/F constant, the developed torque remains approximately constant. This method gives higher run-time efficiency. Therefore, majority of AC speed drives employ constant V/F method (or variable voltage, variable frequency method) for the speed control. Along with wide range of speed control, this method also offers 'soft start' capability.

Iv) Changing the number of Stator poles

From the above equation of synchronous speed, it can be seen that synchronous speed (and hence, running speed) can be changed by changing the number of stator poles. This method is generally used for squirrel cage induction motors, as squirrel cage rotor adapts itself for any change in number of stator poles. Change in stator poles is achieved by two or more independent stator windings wound for different number of poles in same slots.

For example, a stator is wound with two three phase windings, one for 4 poles and other for 6 poles. for supply frequency of 50 Hz

i) synchronous speed when 4 pole winding is connected, Ns = 120*50/4 = 1500 RPM

ii) synchronous speed when 6 pole winding is connected, Ns = 120*50/6 = 1000 RPM