EEE108 Electromagnetism and Electromechanics

Lecture 22

Synchronous/Induction Motors

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Recall

Electrical Machines

- AC Machines
  - Synchronous
    - Generators (popular)
    - Motors
      - Operation Principle
      - Equivalent Circuit
      - Torque-Speed Characteristic
      - Starting Problem
  - Induction
    - Motors (Three-phase)
      - Construction
      - Basic Induction Motor Concepts
      - Powers and Torques
      - Torque-Speed Characteristics
      - Speed Control
- DC Machines
  - Generators
  - Motors

Synchronous Motors

Synchronous motors convert electrical power to mechanical power.

A synchronous motor is the same physical machine as a synchronous generator, except that the direction of real power flow is reversed.

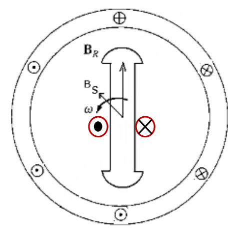
A synchronous motor is composed of two parts:

The **stator** is the outer shell of the motor, which carries the armature winding. This winding is spatially distributed for poly-phase AC current.

The **rotor** is the rotating portion of the motor. It carries field winding, which may be supplied by a DC source.

Operation Principle of Synchronous Motors

Two magnetic fields are present in the machine, and the rotor field tends to align with the stator magnetic field.

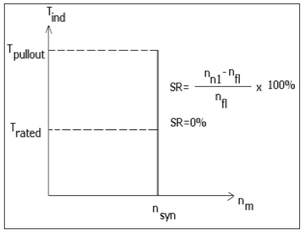


- The field current of a synchronous motor produces a steady-state magnetic field $\mathbf{B}_R$
- A three-phase set of voltages is applied to the stator windings of the motor, which produces a three-phase current flow in the windings. This three-phase set of currents in the armature winding produces a rotating magnetic field of $\mathbf{B}_s$
- Therefore, there are two magnetic fields present in the machine, and *the rotor field will tend to line up with the stator field*, just as two bar magnets will tend to line up if placed near each other.
- Since the stator magnetic field is rotating, the rotor magnetic field (and the rotor itself) will try to catch up.
- As long as the two magnetic fields are "locked in" and rotate in synchronism, a torque is developed.
- The larger the angle between the two magnetic fields (up to certain maximum), the greater the torque on the rotor of the machine

Operation Principle of Synchronous Motors

Steady State Operations

Once the motor is in operation, the speed of the motor is dependent only on the supply frequency. Its torque speed characteristic is constant speed as the induced torque increases. Hence $S_R = 0\%$.



$$\tau_{ind} = kB_R B_{net} \sin\delta$$

where δ is the angle between $\mathbf{B}_R$ and $\mathbf{B}_{net}$.

Maximum torque (pullout torque) is achieved when $\sin\delta = 1$.

Full load torque is much less than that, may typically be 1/3 of pullout torque.

- Synchronous motors find applications in all industrial applications where constant speed is necessary.
- If load exceeds the pullout torque, the rotor will slow down and can not remain locked to stator magnetic field.

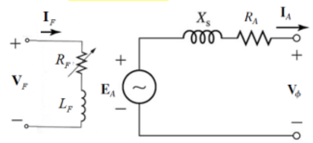
Equivalent Circuit of Synchronous Motors

Single-Phase

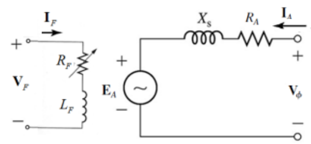
A synchronous motor has the same equivalent circuit as synchronous generator, except that the direction of power flow (and the direction of $\mathbf{I}_A$) is reversed.

Single-phase circuit is shown:

Generators



Motors



The internal generated voltage and terminal voltage is:

$$\mathbf{E}_A = \mathbf{V}_\phi + jX_s\mathbf{I}_A + R_A\mathbf{I}_A$$
$$\mathbf{V}_\phi = \mathbf{E}_A - jX_s\mathbf{I}_A - R_A\mathbf{I}_A$$

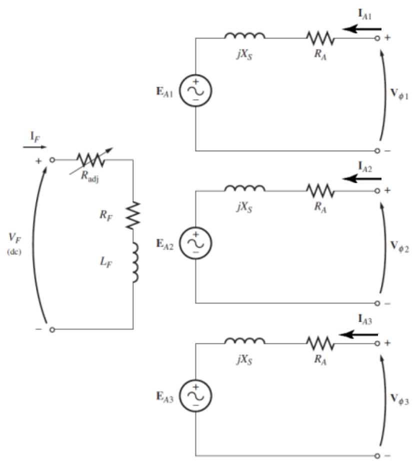
Generators

$$\mathbf{E}_A = \mathbf{V}_\phi - jX_s\mathbf{I}_A - R_A\mathbf{I}_A$$
$$\mathbf{V}_\phi = \mathbf{E}_A + jX_s\mathbf{I}_A + R_A\mathbf{I}_A$$

Motors

Equivalent Circuit of Synchronous Motors

Three-Phase



Starting Synchronous Motors

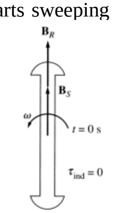
Synchronous motors are not self-starting motors. This property is due to the inertia of the rotor.

Consider a 60 Hz synchronous motor.

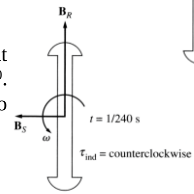
When the power is applied to the stator windings, the rotor (and, therefore its magnetic field $\mathbf{B}_R$) is stationary. The stator magnetic field $\mathbf{B}_S$ starts sweeping around the motor at the synchronous speed.

The induced torque on the shaft:
is zero at $t = 0$ since both magnetic fields are aligned.

$$\boldsymbol{\tau}_{ind} = k\mathbf{B}_R \times \mathbf{B}_S$$

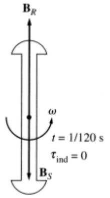


At t = 1/240 s the rotor has barely moved but the stator magnetic field $\mathbf{B}_S$ has rotated by 90^0. Therefore, the torque on the shaft is non-zero and counter-clockwise.

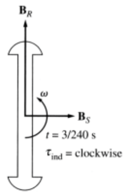


Starting Synchronous Motors

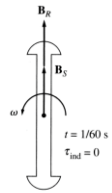
$\boldsymbol{\tau}_{ind} = k\mathbf{B}_R \times \mathbf{B}_S$



At t = 2/240(1/120) s the rotor and stator magnetic fields point in opposite directions, and the induced torque on the shaft is zero again.



At t = 3/240 s the stator magnetic fields point to the right, and the induced torque on the shaft is non-zero but clockwise.



Finally, at t = 1/60 s the rotor and stator magnetic fields are aligned again, and the induced torque on the shaft is zero.

During one electrical cycle, the torque was counter-clockwise and then clockwise, and the average torque is zero. The motor will vibrate heavily and finally overheats!

Starting Synchronous Motors

There are 3 different starting methods available:

a) Reduced speed of stator magnetic field – the aim is to reduce it slow enough as such that the rotor will have time to follow the stator magnetic field. This method used to be impractical due to problems in reducing stator magnetic field.

b) External prime mover to accelerate the synchronous motor. This is a very straightforward method. Use exciters as starting motors to accelerate the synchronous motor up to synchronous speed.

c) Damper windings or amortisseur windings. This is the most popular way to start an synchronous motor. The final effect of this starting method is that the rotor will spin at near synchronous speed.

Synchronous Motor Summary

•A synchronous motor is the same physical machine as a synchronous generator, except that the direction of real power flow is reversed.

•The speed of a synchronous motor is a constant from no load to maximum possible load: $n_m = n_{sync} = 120f_e/P$

•The maximum possible torque a machine can produce:

$$\tau_{ind} = kB_R B_{net}$$

If this value is exceeded, the rotor will not be able to stay locked in with the stator magnetic fields, and the motor will stop.

•A synchronous motor has no net starting torque and so cannot start by itself. There are three main ways to start a synchronous motor:

1. Reduced speed of stator magnetic field
2. Use a prime mover
3. Damper windings or amortisseur windings.

Induction Motors

Induction machines: Induction Generators and **induction motors**

Induction Motors:

- Construction
- Basic Induction Motor Concepts
- Powers and Torques
- Torque-Speed Characteristics
- Speed Control

Induction Motors

Induction machine – the rotor voltage that produces the rotor current and the rotor magnetic field **is induced in the rotor windings** rather than being physically connected by wires. No DC field current is required to run the machine.

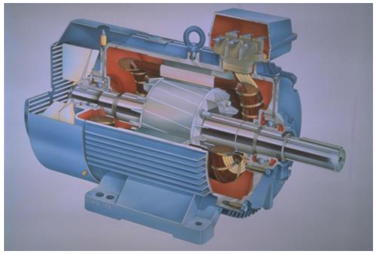
Its characteristic features are:

•Simple and rugged construction

•Low cost and minimum maintenance

•High reliability and sufficiently high efficiency

•Need no extra starting motors and need not be synchronized



Construction

Stator

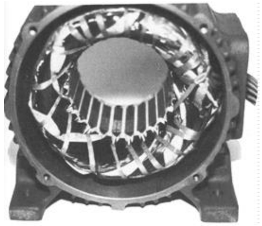
An induction motor has basically two parts – Stator and Rotor

Stator:

•consisting of a steel frame that supports a hollow, cylindrical core

•core, having a number of evenly spaced slots, providing the space for the stator winding

•the windings geometrically spaced 120 degrees apart



The stator of a induction motor

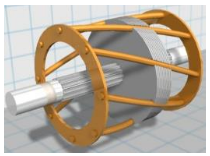
Construction

Rotor

An induction motor is different from a synchronous motor in its **rotor construction** and the **method of producing torque**:

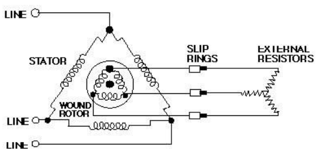
Two types of rotors are used in induction motors:

a) Squirrel Cage - no windings and no slip rings



b) Wound rotor - It has 3 phase windings, usually Y-connected, and the winding ends are connected via slip rings.

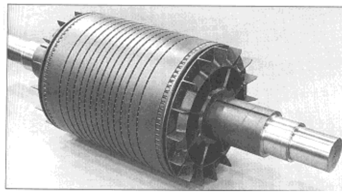
Wound rotor are known to be more expensive due to its maintenance cost to upkeep the slip rings, carbon brushes and also rotor windings.



The squirrel cage rotor is far more common.

Construction

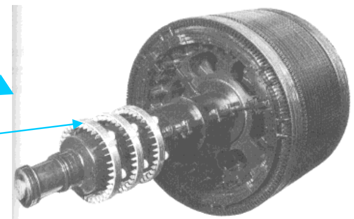
Rotor



Squirrel cage rotor

Wound rotor

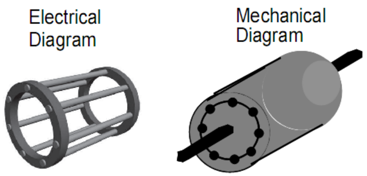
The slip rings



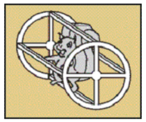
Construction

Squirrel Cage Rotors

- A typical squirrel cage rotor construction is shown on the right
- The cage is constructed from rotor bars (generally copper), typically insulated from and embedded in the rotor body
- The bars are then shorted together with end rings at either end
- There are no slip rings nor any DC excitation supplied to the rotor
- It is a cylindrical not salient rotor

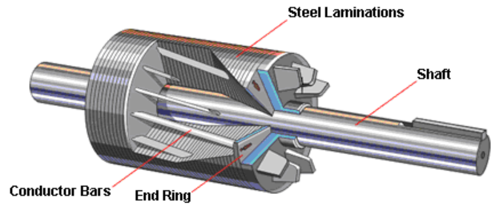


Squirrel Cage Induction Motor Rotor



Construction

Squirrel Cage Rotors



A slight skewing of the bars helps to reduce audible hum caused by vibrations. The rotor and its shaft constitute an integral rotor assembly.

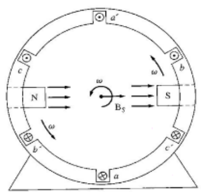
Basic Induction Motor Concepts

The Development of Induced Torque in an Induction Motor

When a current produced by a balanced three-phase source flows in the stator, it will produce a magnetic field in stator as such that $\mathbf{B}_s$ (stator magnetic field) rotating at synchronous speed as determined by the number of stator poles and the applied stator frequency f_e:

$$n_{sync} = \frac{120 f_e}{P}$$

where f_e is the system frequency in hertz and P is the number of poles in the machine.



This rotating magnetic field $\mathbf{B}_s$ passes over the rotor bars and induces a voltage in them. Hence there will be rotor current flow. And this rotor current will produce a magnetic field, $\mathbf{B}_R$. Hence the interaction between both magnetic field would give torque:

$$\boldsymbol{\tau}_{ind} = k\mathbf{B}_R \times \mathbf{B}_S$$

The induced torque would generate acceleration to the rotor, then the rotor will spin.

Basic Induction Motor Concepts

Finite Upper Limit of the Speed

If the induction motor's rotor were turning at synchronous speed → the rotor bars would be stationary relative to the magnetic field → no induced voltage → no rotor current → no rotor magnetic field → ($\boldsymbol{\tau}_{ind} = k\mathbf{B}_R \times \mathbf{B}_S$) Induced torque = 0 → Rotor will slow down due to friction

Conclusion : An induction motor can thus speed up to near synchronous speed but it can never reach synchronous speed. ***The rotor turns at a lower speed.***

Basic Induction Motor Concepts

Slip Speed

The induced voltage at the rotor bar is dependent upon the relative speed between the stator magnetic field and the rotor.

Two terms are commonly used to define the relative motion of the rotor and the magnetic fields: ***slip speed*** and ***slip***

Slip speed:

$$n_{slip} = n_{sync} - n_m$$

Where n_{slip} = slip speed of the machine
n_{sync} = speed of the magnetic field.
n_m = mechanical shaft speed of the motor.

Basic Induction Motor Concepts

Slip

Apart from slip speed we can describe this relative motion by using **slip** -- the % difference of the speed :

$$Slip,\ s = \frac{n_{slip}}{n_{sync}} \times 100\% = \frac{n_{sync} - n_m}{n_{sync}} \times 100\%$$

Slip may also be described in terms of angular velocity, ω

$$s = \frac{\omega_{sync} - \omega_m}{\omega_{sync}} \times 100\%$$

under normal operating conditions, s = 0.01 ~ 0.05, which is very small and the actual speed is very close to synchronous speed.

***s* is not zero, not negligible.**

Using the slip, the mechanical speed of the rotor shaft can be expressed in terms of synchronous speed and slip:

$$n_m = (1 - s)\,n_{sync} \qquad or \qquad \omega_m = (1 - s)\,\omega_{sync}$$

Basic Induction Motor Concepts

Example 1

A 208V, 4 pole, 60Hz, induction motor has a full-load slip of 5%.

(a) What is the synchronous speed of this motor?
(b) What is the rotor speed of this motor at the full-load?

Solution

(a) The synchronous speed:

$$n_{sync} = \frac{120 f_e}{P} = \frac{120 \times 60}{4} = 1800 \text{ r/min}$$

(b) The rotor speed:

$$n_m = (1 - s)n_{sync} = (1 - 0.05)(1800) = 1710 \text{ r/min}$$

Basic Induction Motor Concepts

Electrical Frequency on the Rotor

If the rotor is locked (cannot move), like a transformer, the rotor would have the same frequency as the stator. Another way to look at it is to see that when the rotor is locked, rotor speed drops to zero, then slip is 1. We have:

$$f_{re} = f_{se}$$

f_{re} called the slip/rotor frequency, electrical frequency on rotor

When the rotor move at speed, $n_m = n_{sync}$ (rpm), the rotor frequency is zero, and the slip $s = 0$.

For the speed in between, the stator flux will circulate the rotor conductor at a speed of (n_{sync} - n_m) (rpm). The frequency of the rotor can be written as:

$$f_{re} = sf_{se}$$

With $n_{sync} = \dfrac{120 f_{se}}{P}$ $\qquad \therefore\ f_{se} = \dfrac{n_{sync} P}{120}$

$s = \dfrac{n_{sync} - n_m}{n_{sync}}$ $\qquad \therefore\ f_{re} = \dfrac{(n_{sync} - n_m)P}{120}$

Basic Induction Motor Concepts

Example 2

A 208V, 4 pole, 7460W, 60Hz, induction motor has a full-load slip of 5%.

(c) What is the rotor frequency of this motor at the full-load?
(d) What is the shaft torque of this motor at the full-load?

Solution

(c) The rotor frequency : $f_{re} = sf_{se} = (0.05)(60) = 3\ \text{Hz}$

$$f_{re} = \frac{P}{120}(n_{sync} - n_m)$$

$$= \frac{4}{120}(1800 - 1710) = 3\ \text{Hz}$$

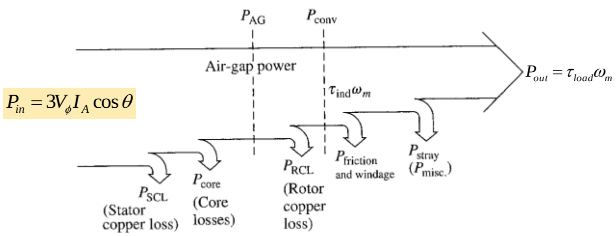
(d) The shaft torque : $\tau_{load} = \dfrac{P_{out}}{\omega_m} = \dfrac{7460}{(1710)(2\pi)(1/60)} = 41.7\ \text{N}\cdot\text{m}$

Principle of Operation

- When a 3-phase stator winding is connected to a 3-phase voltage supply, 3-phase current will flow in the windings.
- A rotating magnetic field $\mathbf{B}_S$ is produced. The magnetic field $\mathbf{B}_S$ induces a voltage in the rotor winding.
- The induced voltage produces rotor current, if rotor circuit is closed.
- The rotor current interacts with the magnetic field $\mathbf{B}_S$, producing torque. The rotor rotates.

Losses and Power Flow

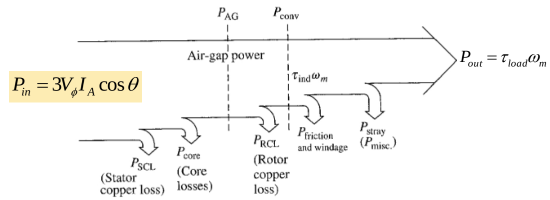
The relationship between the input electric power and the output mechanical power of this motor is shown below:



The core losses of an induction motor come partially from the stator circuit and partially from the rotor circuit.

The rotor core losses are very tiny compared to the stator core losses, all the core losses are lumped together at that point on the diagram.

Losses and Power Flow



The higher the speed of an induction motor, the higher the friction, windage, and stray losses. The higher the speed of the motor, the lower its core losses.

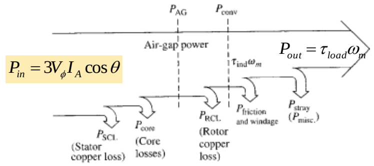
Therefore, these three categories of losses are sometimes lumped together and called *rotational losses*.

The total rotational losses of a motor are often considered to be constant with changing speed, since the component losses change in opposite directions with a change in speed.

Powers and Torques in Induction Motors

If the friction and windage losses and the stray losses are known, the output power:

$$P_{out} = P_{conv} - P_{F\&W} - P_{misc}$$



The developed torque in a machine was defined as the torque generated by the internal electric to mechanical power conversion:

$$\tau_{ind} = \frac{P_{conv}}{\omega_m}$$

This torque differs from the torque actually available at the terminals of the motor by an amount equal to the friction and windage torques in the machine.

The load torque is:

$$\tau_{load} = \frac{P_{out}}{\omega_m}$$

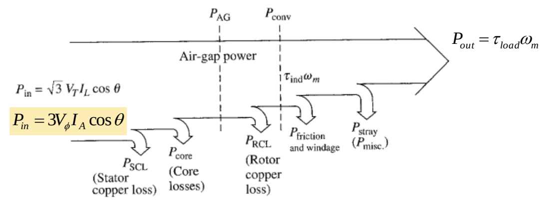
Powers and Torques in Induction Motors

Example 1

Example 6-2

A 480 V, 60 Hz, 50 hp, 3 phase induction motor is drawing 60 A at 0.85 PF lagging. The stator copper losses are 2 kW, and the rotor copper losses are 700 W. The friction and windage losses are 600 W, the core losses are 1800 W, and the stray losses are negligible. Find:

a) The air gap power P_{AG}
b) The power converted P_{conv}
c) The output power P_{out}
d) The efficiency of the motor



Power and Torque in Induction Motor

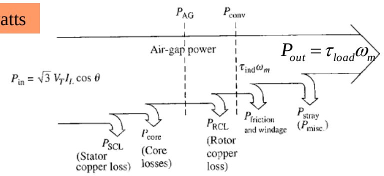
Example 1

Solution:

1 hp = 746 watts

a) The air gap power P_{AG} :

$$P_{in} = \sqrt{3} V_T I_L \cos\theta$$
$$= \sqrt{3}(480)(60)(0.85) = 42.4 \text{ kW}$$
$$P_{AG} = P_{in} - P_{SCL} - P_{core}$$
$$= 42.2 - 2 - 1.8 = 38.6 \text{ kW}$$



b) The power converted from electrical to mechanical form :

$$P_{conv} = P_{AG} - P_{RCL} = 38.6\times10^3 - 700 = 37.9 \text{ kW}$$

c) The output power :

$$P_{out} = P_{conv} - P_{F\&W} - P_{misc} = 37.9\times10^3 - 600 - 0 = 37.3 \text{ kW}$$
$$= 37.3/0.746 = 50 \text{ hp}$$

d) The motor's efficiency :

$$\eta = \frac{P_{out}}{P_{in}}\times100\% = \frac{37.3}{42.4}\times100\% = 88\%$$

Power and Torque in Induction Motor

Example 2

A three-phase, two-pole, 60-Hz induction motor is observed to be operating at a speed of 3502 r/min with an input power of 15.7 kW and a terminal current of 22.6 A. The stator-winding resistance is 0.2 ohm/phase.

Calculate:

1. the power dissipated in the stator winding, the air-gap power,
2. the synchronous speed and the slip.

Solution

1. The power dissipated in the stator winding is :

$$P_{SCL} = 3I_1^2 R_1 = 3(22.6)^2 0.2 = 306 \text{ W}$$

The air - gap power is : $P_{AG} = P_{in} - P_{SCL} = 15.7 - 0.3 = 15.4 \text{ kW}$

If the core losses is ignored.

2. The synchronous speed of this machine is : $n_{sync} = \frac{120}{\text{P}} f_e = \frac{120}{2} 60 = 3600 \text{ r/min}$

The slip : $s = \frac{3600 - 3502}{3600} = 0.0272$

Induction Motor Torque-Speed Characteristics

A typical induction motor torque-speed characteristic curve:

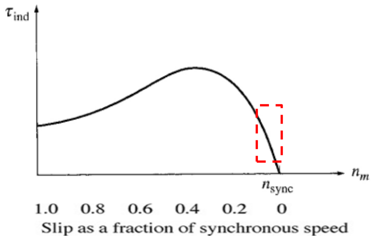
a) Induced torque is zero at synchronous speed.

b) The graph is nearly linear between no load and full load (at near synchronous speeds).

c) The torque increases with increasing slip up to a maximum value and then decreases. Max torque is known as *pull out torque* or *breakdown torque*, typically a factor of 2 larger than the rated torque, limits the short-time overload capability of the motor.

d) Starting torque is very large.

current



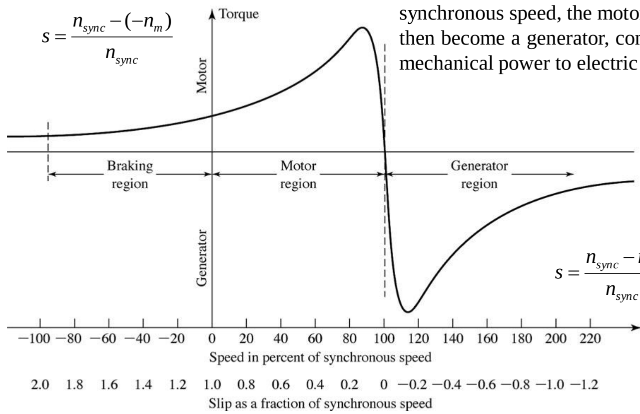
$$s = \frac{n_{sync} - n_m}{n_{sync}}$$

Typical induction-motor torque-speed curve for constant-voltage, constant-frequency operation

Induction Motor Torque-Speed Characteristics

$$s = \frac{n_{sync} - (-n_m)}{n_{sync}}$$

If the rotor were driven faster than synchronous speed, the motor would then become a generator, converting mechanical power to electric power.



$$s = \frac{n_{sync} - n_m}{n_{sync}}$$

Induction Motor Torque-Speed Characteristics

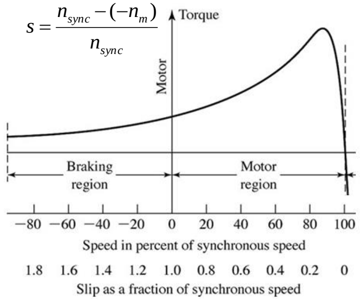
In normal motor region: the rotor rotates in the direction of rotation of the magnetic field produced by the stator currents

Braking region: the motor is driven backward: the motor rotates against the direction of rotation of the magnetic field – by a source of mechanical power capable of counteracting the electromechanical torque.

Usefulness: quick stop the motor

How: interchanging two stator leads in a three-phase motor

$$s = \frac{n_{sync} - (-n_m)}{n_{sync}}$$



Induction Motor

Example

A two-pole, 50-Hz induction motor supplies 15kW to a load at a speed of 2950 rpm.

1. What is the motor's slip?
2. What is the induced torque in the motor in N.m under these conditions?
3. What will be the operating speed of the motor if its torque is doubled?
4. How much power will be supplied by the motor when the torque is doubled?

Solution

1. The motor's slip:

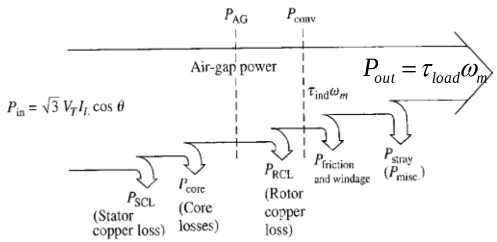
$$n_{sync} = \frac{120 f_e}{P} = \frac{120 \times 50}{2} = 3000 \text{ rpm}$$

$$s = \frac{n_{sync} - n_m}{n_{sync}} = \frac{3000 - 2950}{3000} = 0.0167 \text{ or } 1.67\%$$

Induction Motor

Example

2. What is the induced torque in the motor in N.m under these conditions?



The induced torque in the motor:

If the mechanical losses are ignored, we can have:

$$P_{conv} = P_{load} \text{ and } \tau_{ind} = \tau_{load}$$

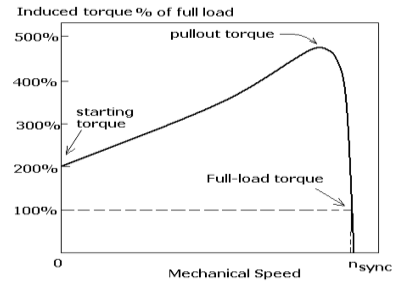
$$\tau_{ind} = \frac{P_{conv}}{\omega_m} = \frac{15\times10^3}{2950\times\frac{2\pi}{60}} = 48.6 \text{ N.m}$$

Induction Motor

Example

3. What will be the operating speed of the motor if its torque is doubled?

In the low-slip region, the torque-speed curve is linear and the induced torque is direct proportional to slip. So, if the torque is doubled the new slip will be 3.33% and the motor speed will be:



$$n_m = (1-s)n_{sync} = (1-0.0333)\times 3000 = 2900 \text{ rpm}$$

4. How much power will be supplied by the motor when the torque is doubled?
The power supplied by the motor:

$$P_{conv} = \tau_{ind}\omega_m$$

$$= (2\times48.6)\times(2900\times\frac{2\pi}{60}) = 29.5 \text{ kW}$$

Speed Control of Induction Motor

Induction motors are not good machines for applications requiring considerable speed control. The normal operating range of a typical induction motor is confined to less than 5% slip, and the speed variation is more or less proportional to the load.

$$\boxed{n_m = (1-s)n_{sync}}$$

There are basically 2 general methods to control induction motor's speed:
a) Varying stator magnetic field speed
b) Varying slip

Varying the magnetic field speed may be achieved by varying the electrical frequency or by changing the number of poles.

$$n_{sync} = \frac{120 f_e}{P}$$

Varying slip may be achieved by varying rotor resistance or varying the terminal voltage.

Speed Control of Induction Motor

Varying Magnetic Field Speed -- By Pole Changing

By applying this method, the number of poles may be maintained (no changes), doubled or halfed, hence would vary its operating speed.

$$n_{sync} = \frac{120 f_e}{P}$$

In terms of torque, the maximum torque magnitude would generally be maintained.

Disadvantage:

- This method will enable speed changes in terms of 2:1 ratio steps, hence to obtain variations in speed, multiple stator windings has to be applied.
- Multiple stator windings have extra sets of windings that may be switched in or out to obtain the required number of poles. Unfortunately this would be an expensive alternative.

Speed Control of Induction Motor

Varying Magnetic Field Speed -- By Changing the Line Frequency

Changing the electrical frequency will change the synchronous speed of the machine.

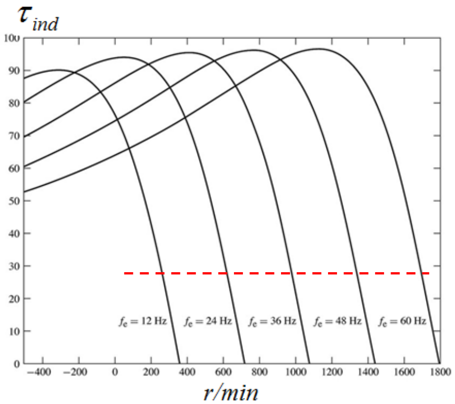
$$n_{sync} = \frac{120 f_e}{P}$$

Changing the electrical frequency would also require an adjustment to the terminal voltage in order to maintain the same amount of flux level in the machine core.

With the arrival of solid-state devices/power electronics, line frequency change is easy to achieved and it is more versatile to a variety of machines and application.

Speed Control of Induction Motor

Varying Magnetic Field Speed -- By Changing the Line Frequency



A family of typical induction-motor speed-torque curves for a four-pole motor for various values of the electrical supply frequency.

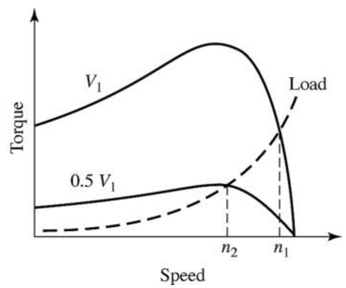
Speed Control of Induction Motor

Varying Slip -- By Changing the Line Voltage

Varying the terminal voltage will vary the operating speed but with also a variation of operating torque.

The torque developed by an induction motor is proportional to the square of the voltage applied to its primary terminals.

In terms of the range of speed variations, it is not significant hence this method is only suitable for small squirrel-cage motors only, such as driving fans.



Speed Control of Induction Motor

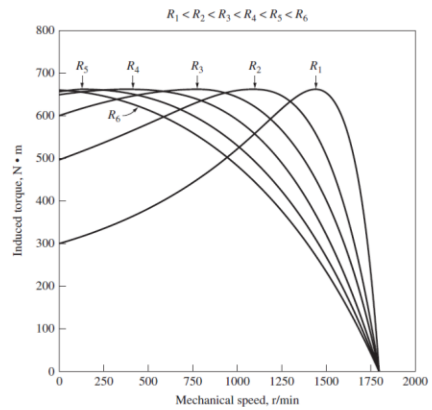
Varying Slip-- By Changing the Rotor Resistance

It is only possible for wound rotor applications. The resistance increases – the speed decreases.

Disadvantages:

- Low efficiency at reduced speeds
- Poor speed regulation with respect to change in load

Normally used only for short periods because of this efficiency problem.



Speed control by varying the rotor resistance of a wound-rotor induction motor

Braking and Starting an Induction Motor

Braking:

Sometimes an induction motor (and its load) needs to be stopped suddenly. This can be achieved by interchanging the phase sequence.

When the direction of the stator magnetic field reverse, the induced torque in the motor will stop the machine very rapidly and will try to rotate it in the other direction. It would act as a braking action to the rotor.

Starting:

The starting current is a few times higher than full load current.

High-inertia loads put a strain on induction motors because they prolong the starting period. The higher current during this interval may cause the problem of overheating.

Wound rotors: Insert extra resistance in the rotor circuit during starting.

Cage motors: Starting circuits

Induction Motor Summary

Induction Motors:

- Construction
- Basic Induction Motor Concepts
- Powers and Torques
- Torque-Speed Characteristics
- Speed Control

Next

Module Revision

Thanks for your attendance