Important Characteristics and Speed Control of Induction Motors

Important Characteristics of The Induction Motor

1. EFFICIENCY CHARACTERISTIC:

Efficiency is defined as the ratio of the power taken from the motor shaft to the active power drawn from the supply at nominal stator voltage. The characteristic showing the variation between the efficiency and the mechanical power taken from the motor shaft is called efficiency characteristic ($\eta=f(P_m)$).

2. CURRENT CHARACTERISTIC:

It is the variation between the stator current and mechanical power taken from the motor shaft at nominal stator voltage ($I_s=f(P_m)$).

3. POWER FACTOR CHARACTERISTIC:

It is the variation between $\cos\varphi_s$ value and P_m mechanical power at nominal stator voltage ($\cos\varphi_s=f(P_m)$).

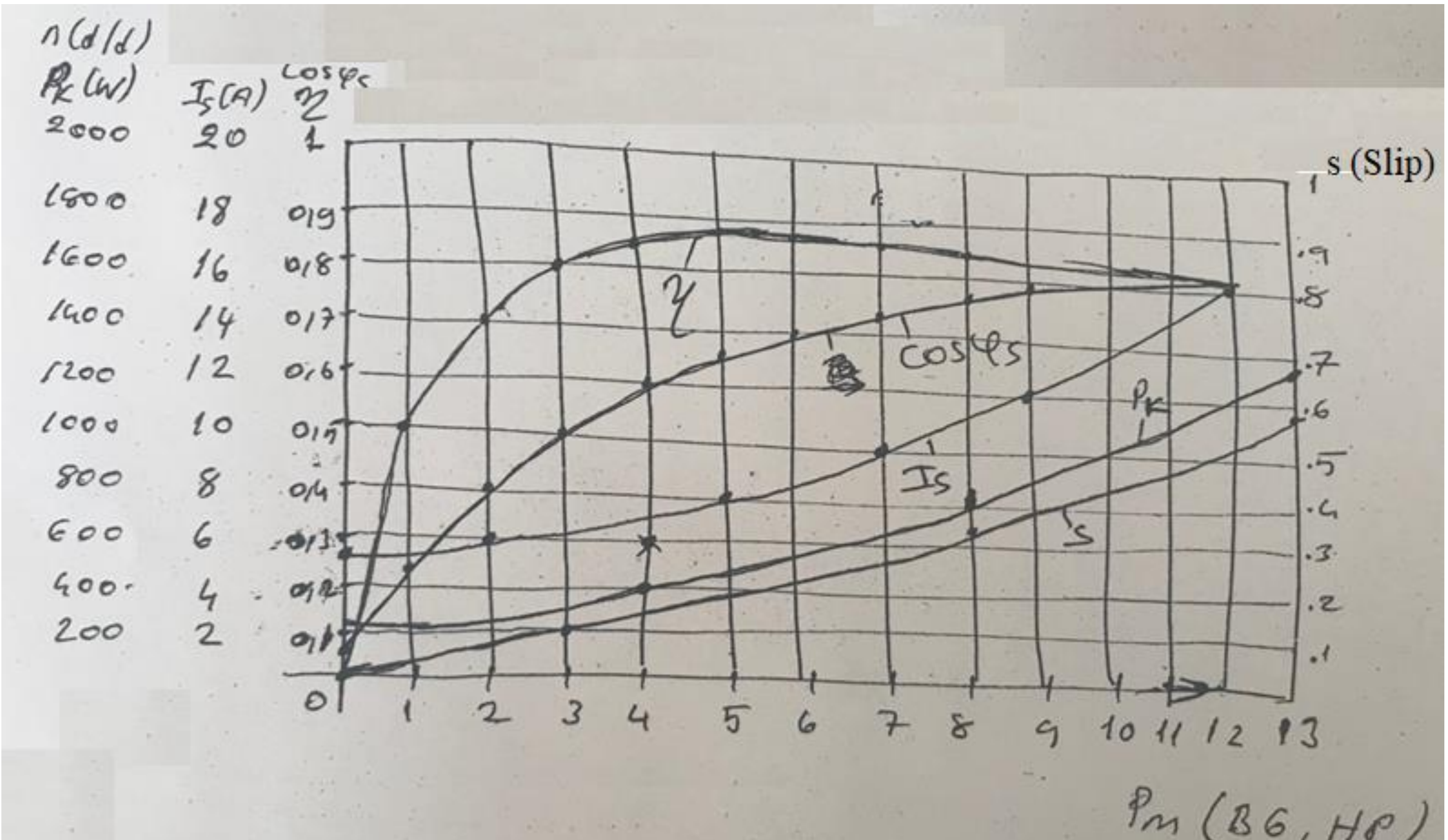
4. LOSS CHARACTERISTICS:

It is the variation between the total power loss of the motor and P_m mechanical power at nominal stator voltage ($P_K=f(P_m)$).

5. SLIP CHARACTERISTIC:

It is the variation between slip, s and P_m mechanical power at nominal stator voltage ($s=f(P_m)$).

Characteristics of 10 HP, 4 poles, 380 V line voltage, star-connected three-phase squirrel cage induction motor. n=1430 rpm at full-load. At no-load: $\cos\varphi_{so} = 0.083$, $I_{so} = 5.9$ A, Total loss; $P_{so} = 320$ W. $\cos\varphi_s = 0.55$ when the rotor is not moving.



- A squirrel cage induction motor fed from a supply with constant voltage and frequency is basically a constant speed motor. This kind of motors is robust and cheap and has very simple structure.

  Until the advent of modern solid-state drives, induction motors in general were not good machines for applications requiring considerable speed control. The normal operating range of a typical induction motor (design classes A, B, and C) is confined to less than 5% slip, and the speed variation over that range is more or less directly proportional to the load on the shaft of the motor. Even if the slip could be made larger, the efficiency of the motor would become very poor, since the rotor copper losses are directly proportional to the slip on the motor.

There are really only two techniques by which the speed of an induction motor can be controlled. One is to vary the synchronous speed, which is the speed of the stator and rotor magnetic fields, since the rotor speed always remains near n_s. *The other technique is to vary the slip of the motor for a given load. Each of* these approaches will be taken up in more detail.
The synchronous speed of an induction motor is given by

$$n_s = \frac{120 * f}{p}$$

so the only ways in which the synchronous speed of the machine can be varied are (1) by changing the electrical frequency and (2) by changing the number of poles on the machine. Slip control may be accomplished by varying either the rotor resistance or the terminal voltage of the motor.

Induction Motor Speed Control by Pole Changing

The stator windings of an induction motor can be designed in such a way that when connection of the windings is changed the number of poles also changes. Since the squirrel cage induction motor does not have a certain pole number on the rotor, the motor can be operated with any number of poles on the stator.

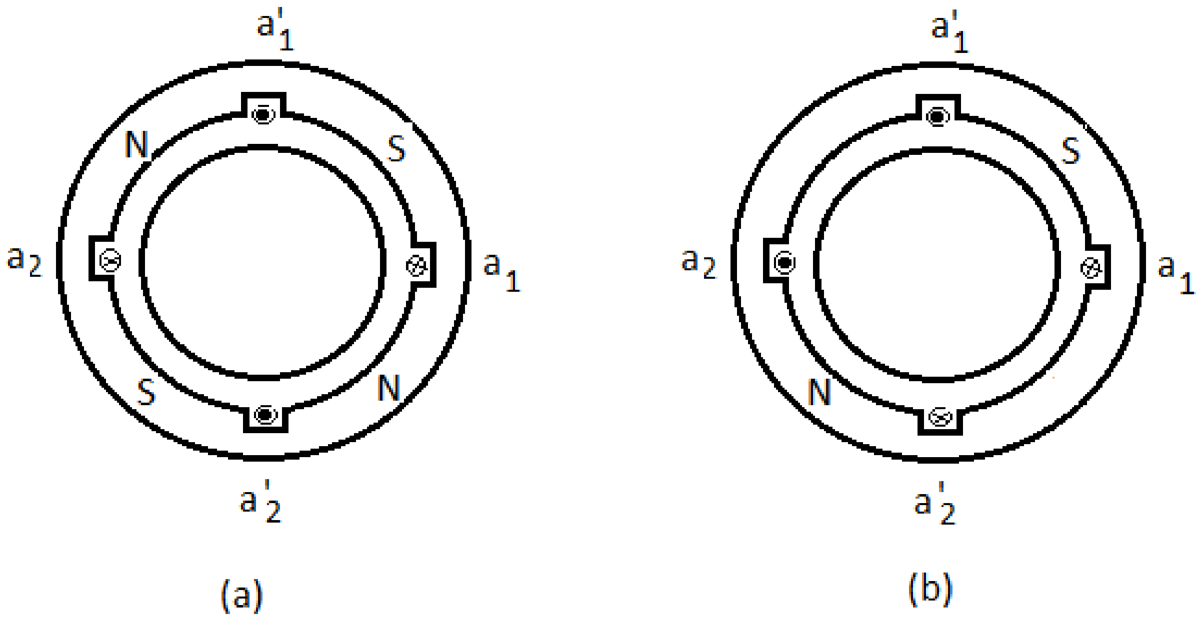


Fig. Speed control by pole changing

- The induction motor with a single winding can be operated with two different synchronous speed. The basic principle changing the pole number of the winding is shown in the figure (a) and (b). In the figure, one phase winding is only shown for simplicity. The coils in Fig.(a) have been connected to form 4 poles. In Fig.(b), 2 pole forming is shown by changing the current direction in one coil using switches. It is possible to obtain 4 synchronous speed by two independent stator windings. As can be seen it is possible to control the speed of induction motors by changing the number of poles. However, this technique increases cost of the motor since the stator windings are complicated.

Speed Control by Changing the Line Frequency

If the electrical frequency applied to the stator of an induction motor is changed, the rate of rotation of its magnetic fields n_s *will change in direct proportion to the* change in electrical frequency, and the no-load point on the torque–speed characteristic curve will change with it (see Figures given below). The synchronous speed of the motor at rated conditions is known as the *base speed. By using variable frequency control, it is* possible to adjust the speed of the motor either above or below base speed. A properly designed variable-frequency induction motor drive can be *very flexible. It can control* the speed of an induction motor over a range from as little as 5 percent of base speed up to about twice base speed. However, it is important to maintain certain voltage and torque limits on the motor as the frequency is varied, to ensure safe operation.

When running at speeds below the base speed of the motor, it is necessary to reduce the terminal voltage applied to the stator for proper operation. The terminal voltage applied to the stator should be decreased linearly with decreasing stator frequency. This process is called *derating. If it is not done, the steel in the* core of the induction motor will saturate and excessive magnetization currents will flow in the machine.

To understand the necessity for derating, recall that an induction motor is basically a rotating transformer. As with any transformer, the flux in the core of an induction motor can be found from Faraday's law:

$$v(t) = -N\frac{d\emptyset}{dt}$$

If a voltage $v(t) = V_M \sin\omega t$ is applied to the core, the reulting flux ϕ is;

$$\emptyset(t) = \frac{1}{N_p}\int v(t)dt$$

$$= \frac{1}{N_p}\int V_M.sin\omega t.dt$$

$$\emptyset(t) = -\frac{V_M}{\omega N_p} cos\omega t$$

- Note that the electrical frequency appears in the *denominator of this expression.* Therefore, if the electrical frequency applied to the stator *decreases by 10 percent* while the magnitude of the voltage applied to the stator remains constant, the flux in the core of the motor will increase by about 10 percent and the magnetization current of the motor will increase. In the unsaturated region of the motor's magnetization curve, the increase in magnetization current will also be about 10 percent. However, in the saturated region of the motor's magnetization curve, a 10 percent increase in flux requires a much larger increase in magnetization current. Induction motors are normally designed to operate near the saturation point on their magnetization curves, so the increase in flux due to a decrease in frequency will cause excessive magnetization currents to flow in the motor.

To avoid excessive magnetization currents, it is customary to decrease the applied stator voltage in direct proportion to the decrease in frequency whenever the frequency falls below the rated frequency of the motor. Since the applied voltage, *v appears in the numerator and the frequency,* ω *appears in* the denominator of Equation given above (the last equation), the two effects counteract (neutralize) each other, and the magnetization current is unaffected.

When the voltage applied to an induction motor is varied linearly with frequency below the base speed, the flux in the motor will remain approximately constant. Therefore, the maximum torque which the motor can supply remains fairly high. However, the maximum power rating of the motor must be decreased linearly with decreases in frequency to protect the stator circuit from overheating. The power supplied to a three-phase induction motor is given by

$$P = \sqrt{3} V_L I_L cos\emptyset$$

If the voltage V_L *is decreased, then the maximum power P must also be decreased,* or else the current flowing in the motor will become excessive, and the motor will overheat.

Fig.a given in the next slide shows a family of induction motor torque–speed characteristic curves for speeds below base speed, assuming that the magnitude of the stator voltage varies linearly with frequency.

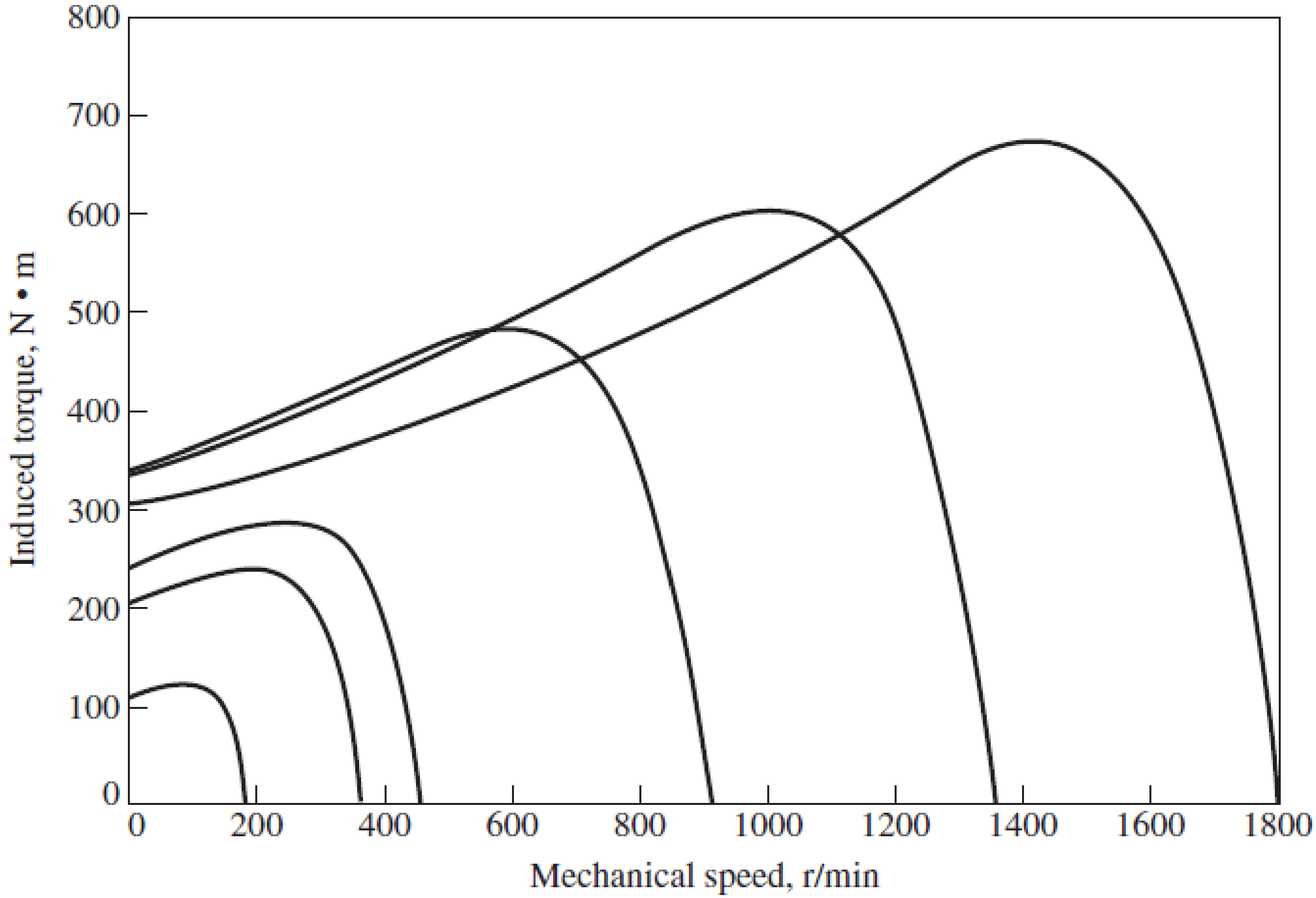


Figure a: The family of torque–speed characteristic curves for speeds below base speed, assuming that the line voltage is derated linearly with frequency.

When the electrical frequency applied to the motor exceeds the rated frequency of the motor, the stator voltage is held constant at the rated value. Although saturation considerations would permit the voltage to be raised above the rated value under these circumstances, it is limited to the rated voltage to protect the winding insulation of the motor. The higher the electrical frequency above base speed, the larger the denominator of Equation (last equation given above) becomes. Since the numerator term is held constant above rated frequency, the resulting flux in the machine decreases and the maximum torque decreases with it. Fig.b given below shows a family of induction motor torque–speed characteristic curves for speeds above base speed, assuming that the stator voltage is held constant.

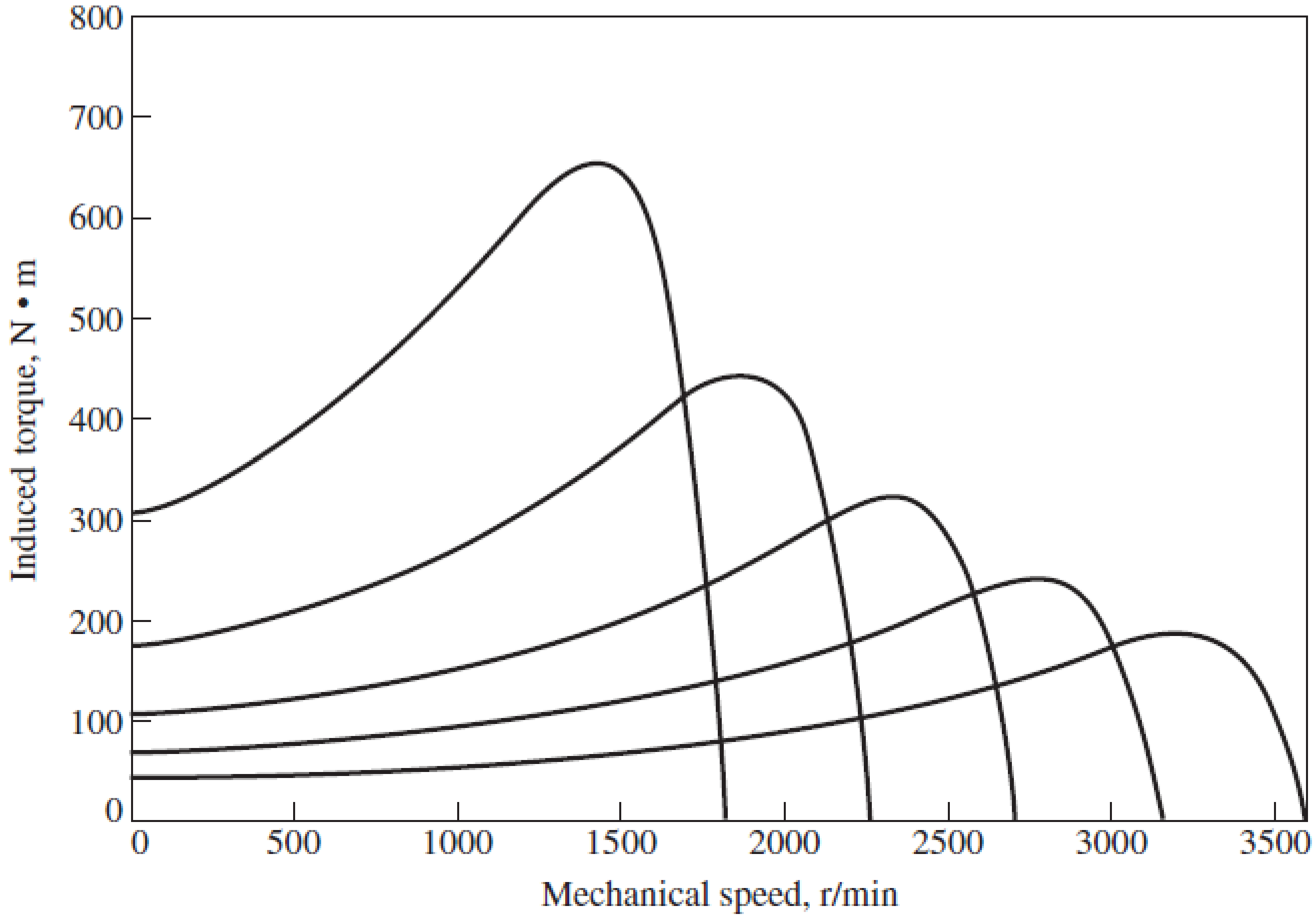


Figure b: The family of torque–speed characteristic curves for speeds above base speed, assuming that the line voltage is held constant.

If the stator voltage is varied linearly with frequency below base speed and is held constant at rated value above base speed, then the resulting family of torque–speed characteristics is as shown in Figure (c) given below. The rated speed for the motor shown in Figure (a-b-c) is 1800 r/min.

In the past, the principal disadvantage of electrical frequency control as a method of speed changing was that a dedicated generator or mechanical frequency changer was required to make it operate. This problem has disappeared with the development of modern solid-state variable-frequency motor drives. In fact, changing the line frequency with solid-state motor drives has become the method of choice for induction motor speed control. Note that this method can be used with *any induction motor, unlike the pole-changing technique, which requires* a motor with special stator windings.

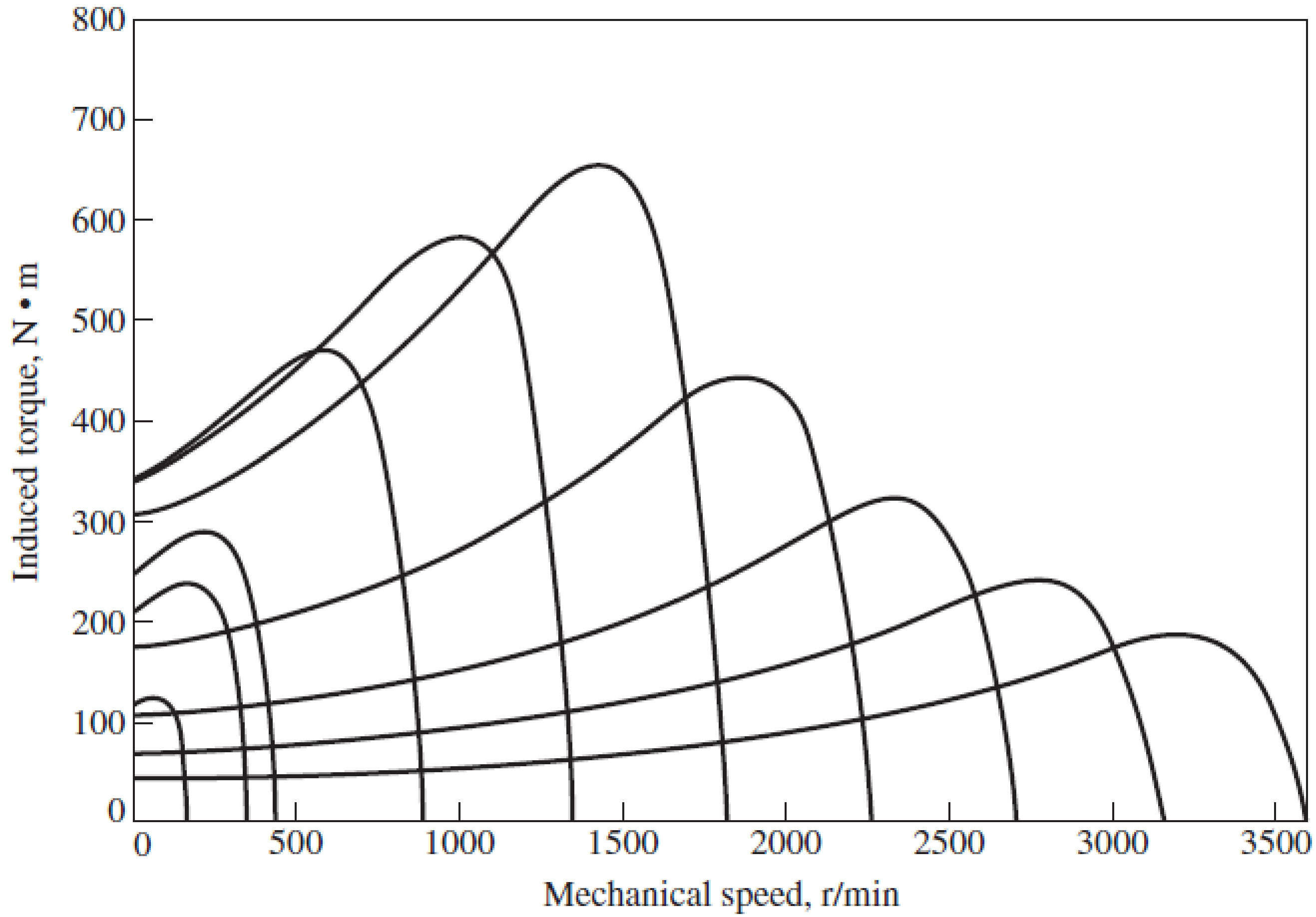


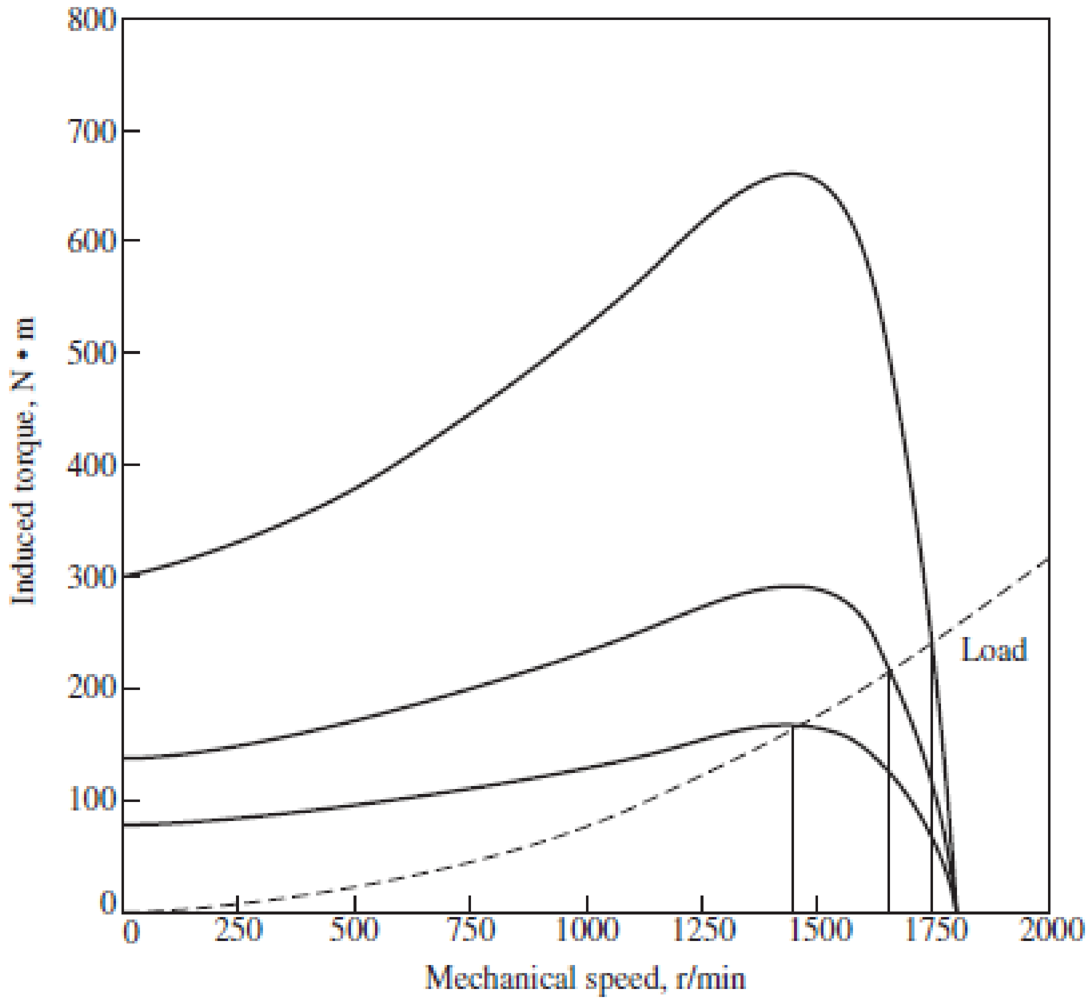
Fig.c: The torque–speed characteristic curves for all frequencies.

Induction Motor Speed Control by Changing The Line Voltage

$$T = 3.\frac{R'_R}{s\omega_s}\frac{V_s^2}{\left[(R_s + R'_R/s)^2 + X_s{}^2\right]}$$

From the above torque equation it can be seen that the torque developed by an induction motor is proportional to the square of the applied voltage. If a load has a torque–speed characteristic such as the one shown in Figure given below, then the speed of the motor may be controlled over a limited range by varying the line voltage. This method of speed control is sometimes used on small motors driving fans. For this reason, if the motor load is constant and the supply voltage (V_s) is changed then, the slip will change to sustain the motor torque constant. The simple way to change V_s voltage is to introduce impedance in series to the stator windings. But, this way has some disadvantages. If the impedance is resistive, the energy loss will be high. If the impedance is inductive, the power factor will be low. However, this technique can be used for short term operations.

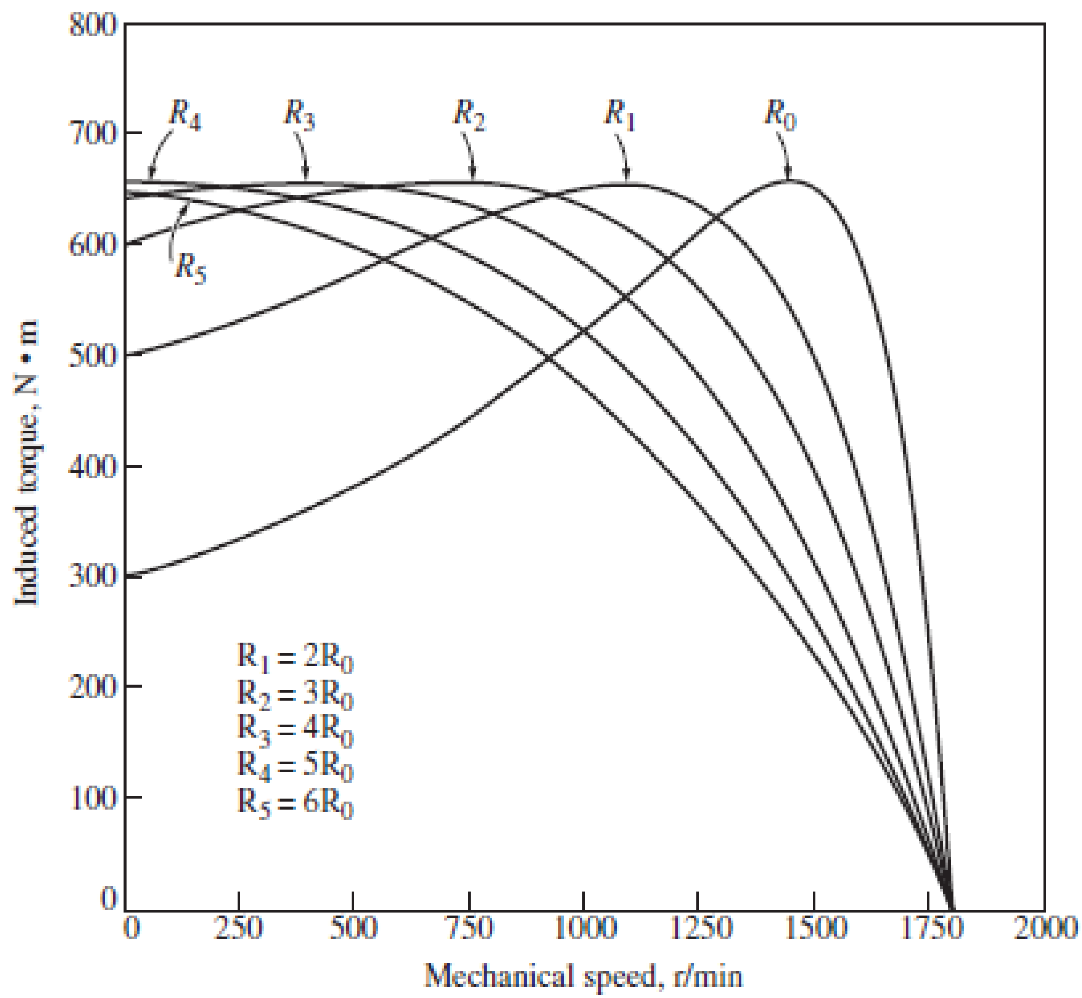
If there is a variable source like transformers, it is possible to operate the motor with various torque-speed characteristics.



Variable-line-voltage speed control in an induction motor.

Speed Control by Changing the Rotor Resistance

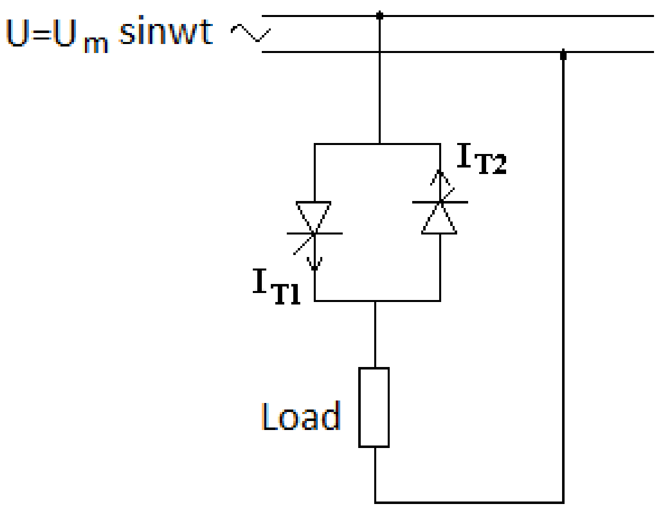
- In wound-rotor induction motors, it is possible to change the shape of the torque speed curve by inserting extra resistances into the rotor circuit of the machine. The resulting torque–speed characteristic curves are shown in Figure given below. If the torque–speed curve of the load is as shown in the figure, then changing the rotor resistance will change the operating speed of the motor. However, inserting extra resistances into the rotor circuit of an induction motor seriously reduces the efficiency of the machine.
- This method of speed control is mostly of historical interest, since very few wound-rotor induction motors are built anymore. When it is used, it is normally used only for short periods because of the efficiency problem mentioned in the previous paragraph.

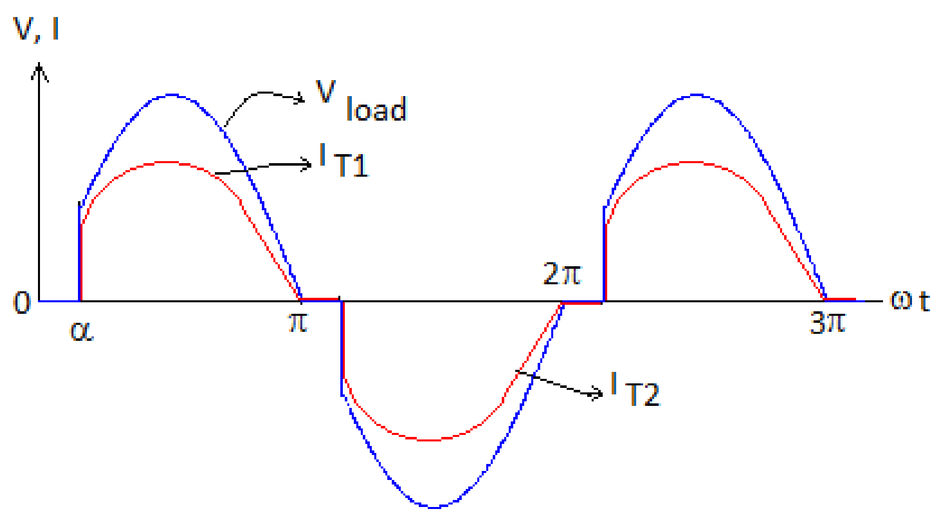


Speed control by varying the rotor resistance of a wound-rotor induction motor.

Squirrel Cage Induction Motor with Variable-Current Power Controller

- We mention before that the speed of a loaded squirrel cage induction motor is controlled by changing its stator voltage. The system providing this variable voltage consists of a constant source and AC power controller.





- In the figure given above a single-phase power controller (AC Chopper) and its output waveforms are shown. The power transferred to the load is controlled by the firing angle of the thyristors (α). In the figure the firing angle of the thyristors is about 30 degrees. The corresponding output voltage and current waveforms for a pure resistive load are also shown. If there was an inductance additional to the resistive load, the current would not jump at $\omega t=\alpha$. The current would start to rise exponentially from zero. In addition, the load current would reach to zero after $\omega t=\pi$ because of the inductive load.
- If the firing angle, α is made smaller or the load inductance becomes bigger, the current at one cycle will be zero at the next cycle where the current (flowing in the other thyristor) starts to increase. This means that both thyristos will be on during half period. The AC chopper circuit will act as there is no thyristors on the circuit since both thyristors will be always on.

- In this case, the firing angle is;

$$\alpha = \emptyset = \arctan\left(\frac{\omega L}{R}\right) rad$$

- In this condition ($\alpha<\phi$), current and voltage waveforms are completely sinusoidal. Effective control interval is $\phi < \alpha < \pi$. Even if α is much bigger than ϕ, the load current which has main harmonic much bigger than the other harmonics is drawn in case of highly inductive load.
- A three-phase power control circuit (AC chopper) for a squirrel cage induction motor is shown in Fig.a.

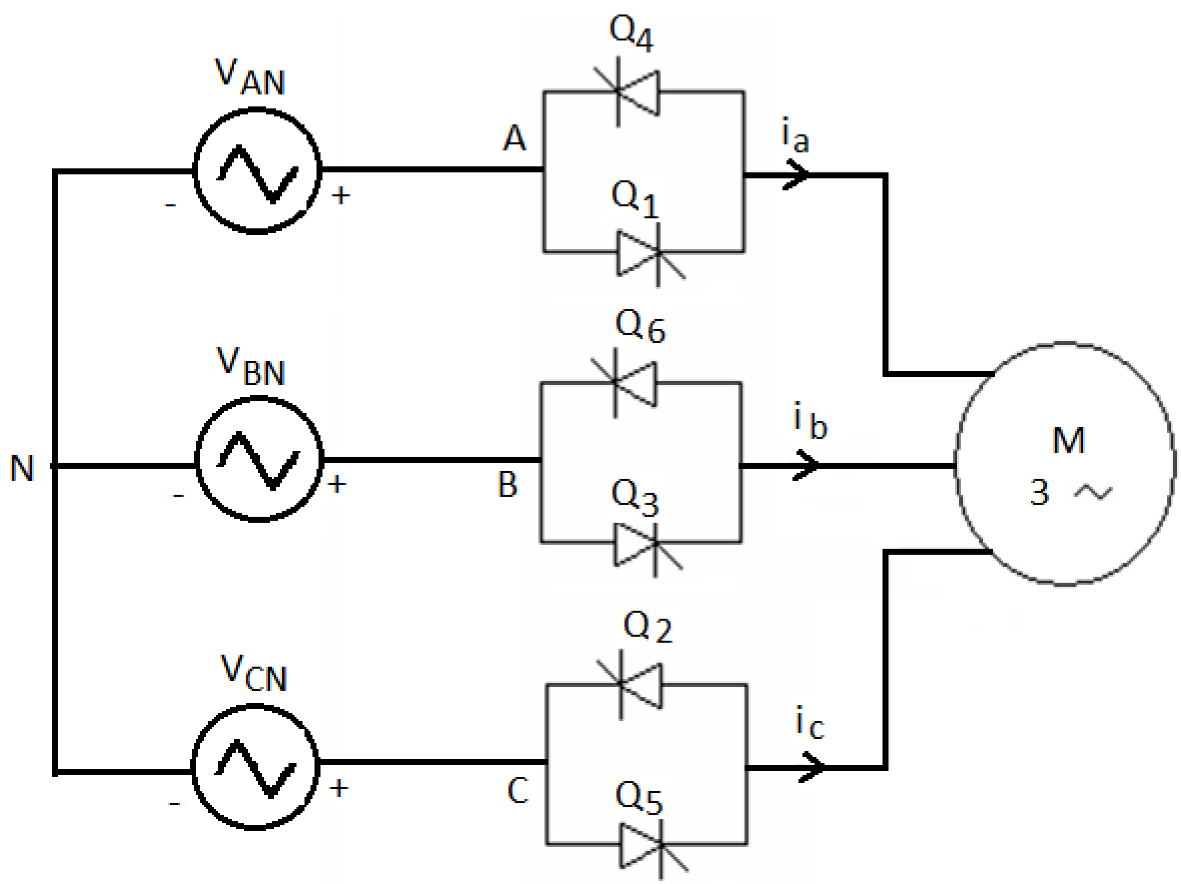


Figure a

The thyristors in Fig.a are fired in a certain order from Q_1 to Q_6. Three-phase currents will flow through the load. In this circuit, effective control interval is also $\phi < \alpha < \pi$. The motor speed can be controlled by controlling the main harmonic of the voltage waveform applied to the motor between zero and supply voltage. Voltage control is performed by controlling the firing angles of the thyristors. For a wide speed interval as the slip increases with the torque increase, D-class motors are normally used in these applications (Low starting current, high starting torque). A simple closed-loop control system is shown for this application in Fig.b.

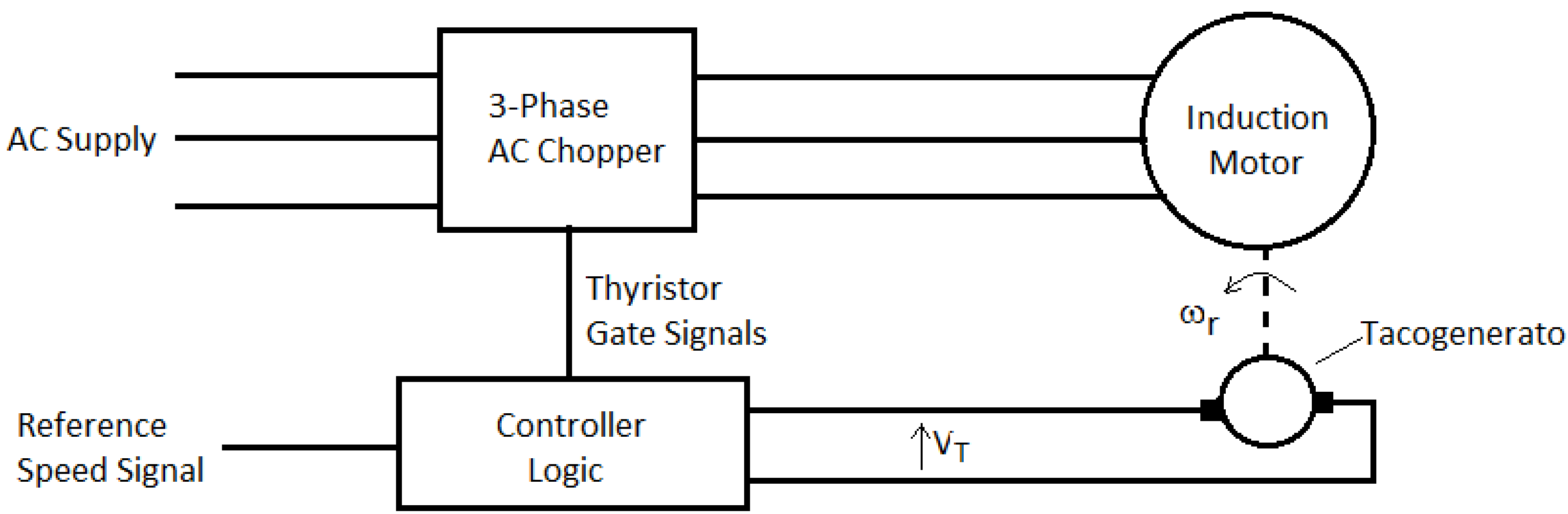


Figure b