Induction Motors: Construction, Principle of Operation, Power and Torque Calculations, Characteristics and Speed Control

Research · June 2020

DOI: 10.13140/RG.2.2.15490.71360

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Induction Motors: Construction, Principle of Operation, Power and Torque Calculations, Characteristics and Speed Control

Contents

Keywords: Induction Motor; 3-Phase Motors; Construction of Induction Motor; Rotor; Stator; Principle of Operation; Torque-Speed Characteristics; Speed Control.

Abstract Presently, about more than 90% of the mechanical power used in industry is provided by three phase induction motors since its robust and simple construction and its quite efficient energy conversion. Moreover, Three-phase induction have low cost, reasonably good power factor, self-starting and low maintenance cost. In this research, we start from the construction of the induction motor and its main parts Function. Then, the principle of operating of an induction machine is explained. Moreover, a detailed power and torque calculations considering the equivalent circuit of the induction machine. However, a power flow diagram of the induction motor is shown, and then the power calculations starting with the input electrical power down to the output mechanical power. And yet, developed torque of the induction motor is obtained using the developed mechanical power expression. Then, induction motor circuit is solved to get the rotor current, torque and power in terms of stator terminal voltage, slip of operation and machine parameters. Furthermore, main performance characteristics such as torque-speed characteristic, power factor, current and efficiency of induction motors are included in the fifth section. In the subsequent section, different methods of speed control are mentioned. Finally, there is a conclusion for this research.

1. Introduction

Induction machines are also called asynchronous machines are the most used electrical machines in the industry. In fact, induction motors are so common in industry that in many plants no other type of electric machine can be found. Three-phase. Induction motors are available as single-phase or three-phase. The single-phase induction motors are usually built in small sizes (up to 3 H.P). Therefore, it is important to study induction motor for better understanding since its essential role in the industry.[1]

2. Construction

An induction motor consists of many parts shown in Fig. 1, and an exploded view of squirrel cage and wound rotor induction motors is shown in Fig. 2.

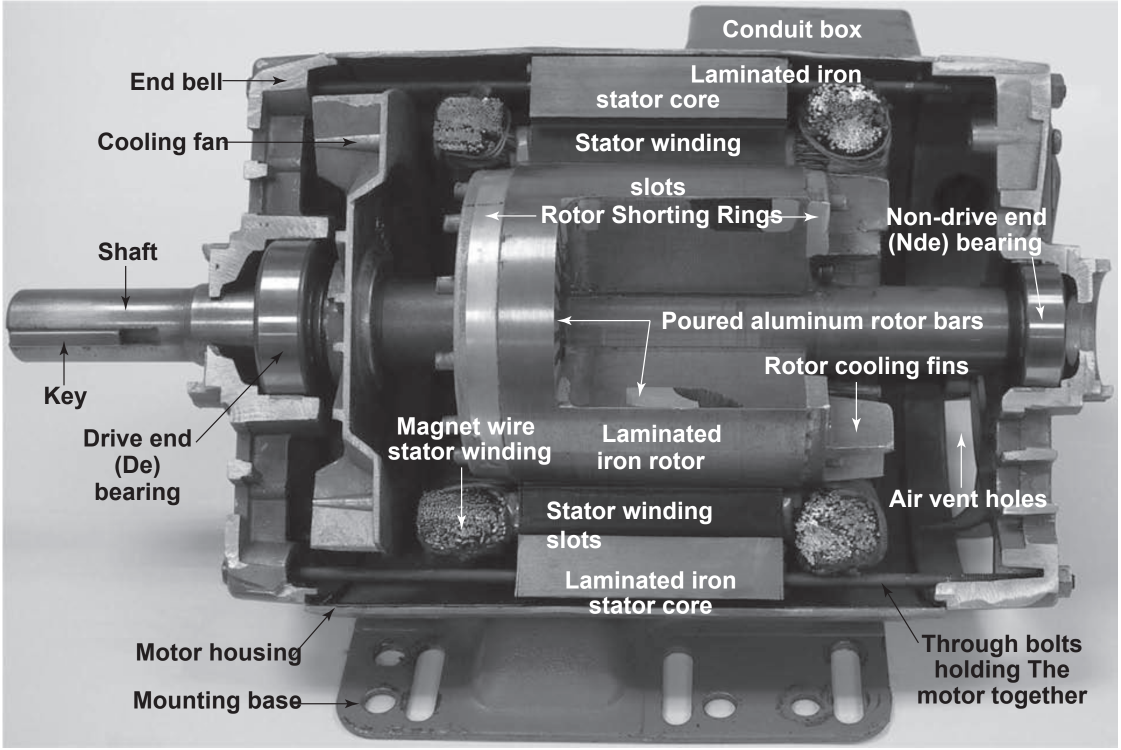
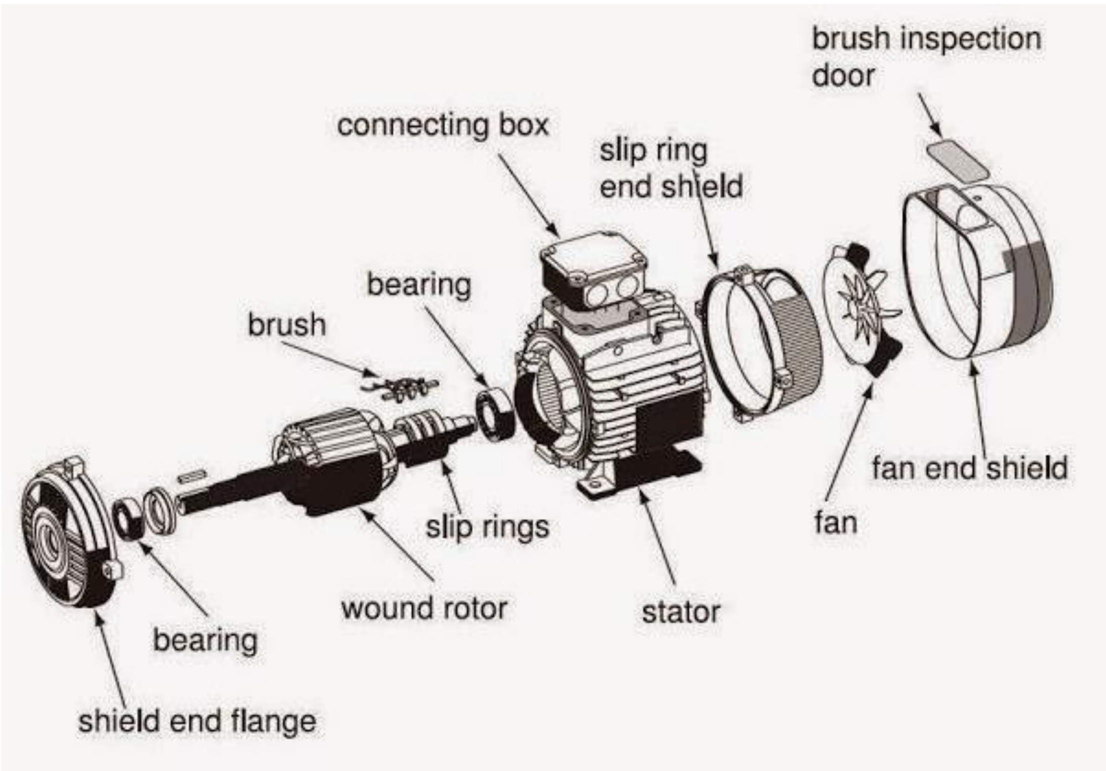
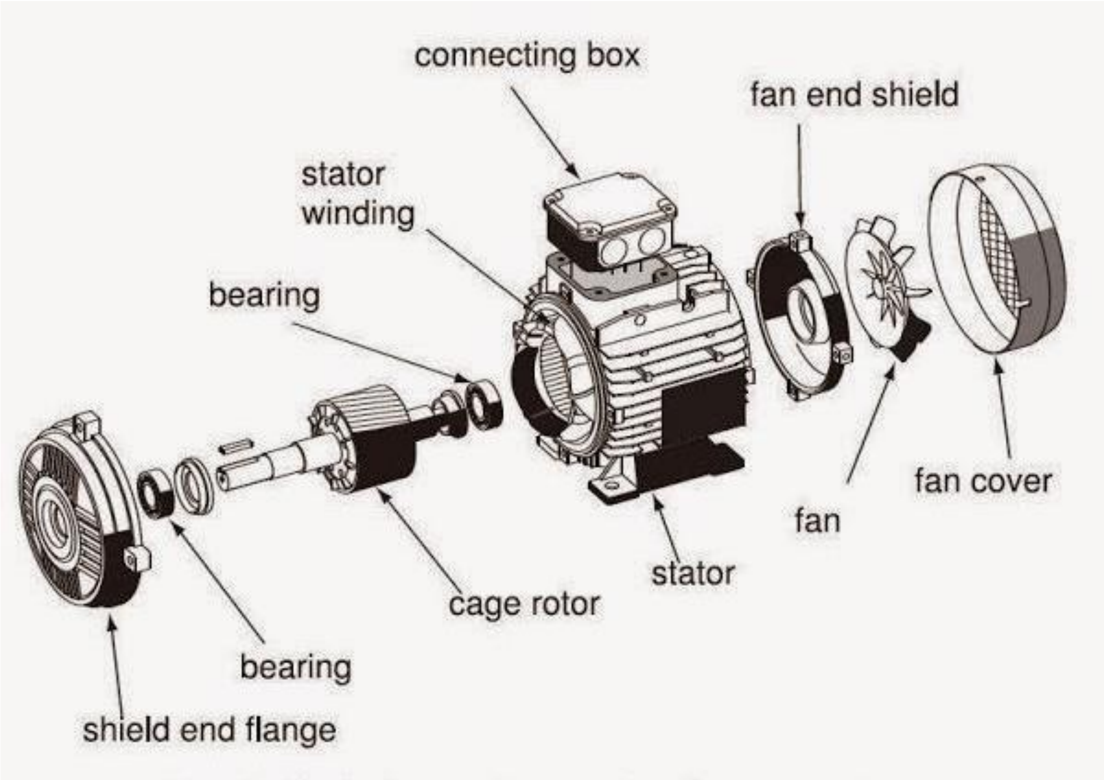


Fig. 1 Induction motor cutaway view with labels.



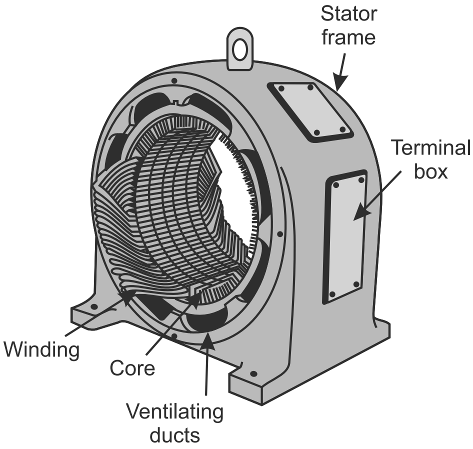
(a)



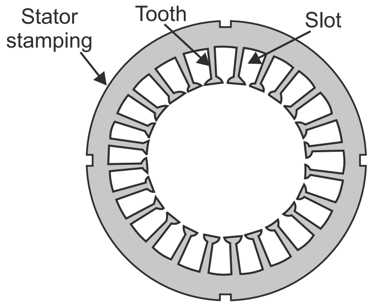
(b)

Fig. 2 (a) An exploded view of wound rotor induction motor. (b) An exploded view of squirrel cage induction motor.

However, stator and rotor are the main parts of the induction machine. Stator has three main parts: Outer frame, Stator core and Stator winding. Outer frame or motor housing is the outer body of the motor. Its function is to support the stator core and to protect the inner parts of the machine against mechanical impacts. Stator core is made of thin soft-iron laminations varies from 0.3 to 0.5 mm in thickness stacked and screwed together to minimize hysteresis and eddy current losses. Furthermore, each lamination is insulated from the other with a thin varnish layer on both sides for better insulating. Slots are punched on the inner periphery of the stampings, as shown in Fig. 3.b. Stator winding are three phase winding carried on the stator core where the six terminals of the winding are connected in the terminal box of the machine. Therefore, the three-phase winding could be connected in star or delta.[2],[3]



(a)



(b)

Fig. 3 (a) Stator. (b) Stator stamping.

Rotor is the rotating part of the motor. It have cooling fins. At the back, there is another bearing and a cooling fan affixed to the rotor. The fan is enclosed by a fan cover. There are two types of rotors, Squirrel cage rotor and Phase wound rotor. Most of the induction motors employed in the industry have squirrel cage rotor Due to its simple and robust construction. It consists of a laminated cylindrical core having semi-closed circular slots at the outer periphery. Copper or aluminum bar conductors are placed in these slots and short circuited at each end by copper or aluminum rings as shown in Fig. 4. Thus, the rotor winding is permanently short-circuited and no external resistance can be added in the rotor circuit. The slots are skewed compared to the shaft to obtain smooth and sufficient torque, and reduces the magnetic locking of the stator and rotor, and increases the rotor resistance since the length of the rotor bar conductors is increased.[2],[3]

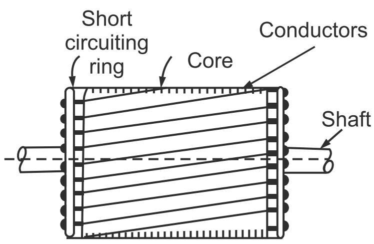


Fig. 4 Squirrel cage rotor.

On the other hand, Phase wound rotor consists of stampings as in stator core. A number of semi-closed slots are punched at its outer periphery. A 3-phase insulated winding is placed in these slots. The rotor is wound for the same number of poles as that of stator. The rotor winding is connected in star and its remaining three terminals are connected to the slip rings. In this case, any external resistance can be added in the rotor circuit. The rotor is also skewed as in squirrel cage rotor. Finally, a shaft is fixed to the rotor to transfer mechanical power.[2],[3]

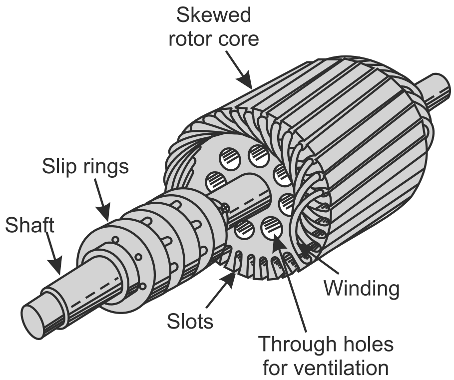


Fig. 5 Phase wound rotor.

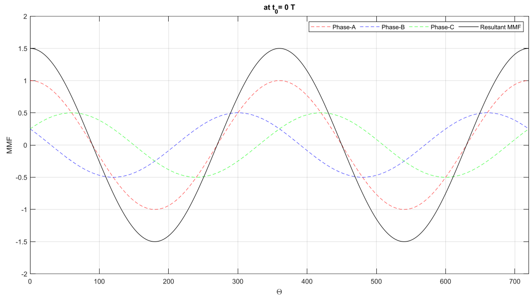
3. Principle of Operation

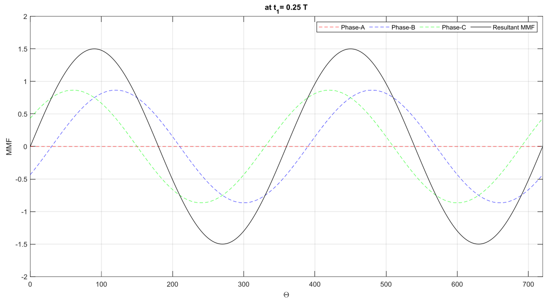
When 3-phase supply is fed to the stator winding of a 3-phase wound induction motor, a resultant rotating magnetic field at constant angular velocity is produced in the stator core. Fig. 6 shows the stator resultant MMF at four different instances along the air-gap. Let this field is revolting in an anti-clockwise direction at synchronous speed n_s. Where,

$$n_s = \frac{120f}{P} \ (rpm) \qquad \mathbf{1}$$

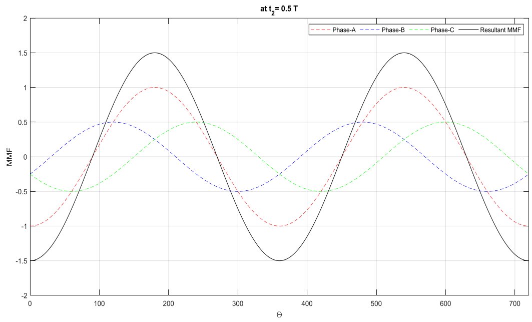
Where f is the frequency of the input electrical power, And P is the number of poles of the induction machine.

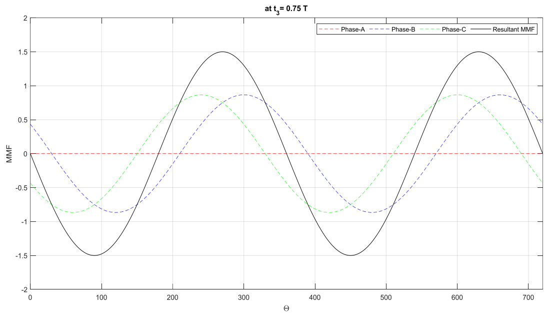
The rotating magnetic field is cut by the stationary rotor conductors and an emf is induced in the rotor conductors. As the rotor conductors are short circuited, current flows through them, Furthermore, a resultant field is produced by the rotor current carrying conductors. This field tries to come in line with the stator rotating field, As a result, an electromagnetic torque is developed and rotor starts rotating in same direction as that of stator rotating field. The rotor then run at a mechanical speed close to and less than the synchronous speed as it tries to attain synchronous speed but never reach. It is because if the rotor revolve at the synchronous speed then the relative speed between rotating stator field and rotor will be zero, therefore, neither emf will be induced in rotor conductors or current nor rotor field and hence no torque will be produced. Thus, an induction motor can never run at synchronous speed.[4],[5]





(a) **(b)**





(c) **(d)**

Fig. 6 (a) Resultant MMF at $\boldsymbol{t_0 = 0}$. (b) Resultant MMF at $\boldsymbol{t_1 = T/4}$. (c) Resultant MMF at $\boldsymbol{t_2 = T/2}$. (d) Resultant MMF at $\boldsymbol{t_3 = 3T/4}$.

4. Power and Torque Calculations

Consider the induction machine equivalent circuit shown in Fig. 7.

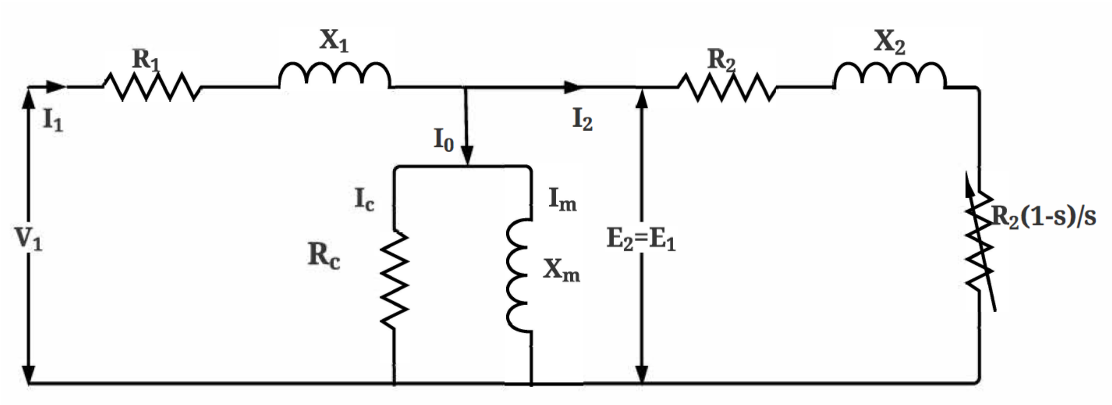


Fig. 7 Induction machine equivalent circuit.

Where,

V_1: Per-phase terminal voltage on the stator winding

R_1: Per-phase stator winding resistance

X_1: Per-phase stator leakage reactance

E_1: Per-phase induced voltage in the stator winding

X_m: Per-phase stator magnetizing reactance

R_c: Per-phase stator core loss resistance

E_2: Per-phase induced voltage in rotor at standstill referred to the primary (i.e. Stator)

R_2: Per-phase rotor circuit resistance referred to the primary

X_2: Per-phase rotor leakage reactance referred to the primary

s: Slip of the induction motor

Electrical input power is given to the stator. There are stator copper and core losses and the remaining power cross the air gap all the way to the rotor. In the rotor there are rotor copper and iron loss that is normally small compared to stator iron loss, therefor, they sometimes lumped together with mechanical losses and called rotational losses. However, the remaining power is converted into mechanical power. Then there are mechanical losses and the remaining power is available as mechanical output power. The power flow diagram is shown in Fig. 8.[6]

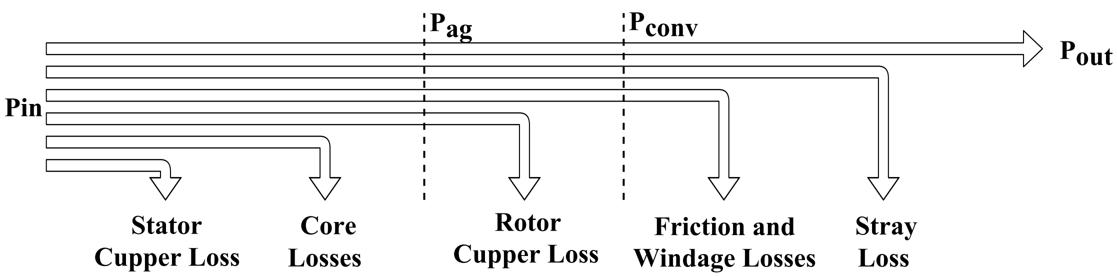


Fig. 8 The power flow diagram of the induction motor.

Thus, for a balanced 3-phase induction motor, the power input is

$$P_{in} = 3V_1 I_1 \cos(\emptyset) \qquad \mathbf{2}$$

Where $\emptyset$ is the input power factor.

And,

$$I_1 = \frac{V_1}{Z_{eq}} \qquad \textbf{3}$$

Where,

$$\begin{aligned} Z_{eq} &= R_1 + jX_1 + \left[\left(\frac{R_2}{s} + jX_2\right)//R_c//jX_m\right] \\ &= R_1 + jX_1 + \frac{1}{G_C - jB_M + \frac{1}{\frac{R_2}{s} + jX_2}} \end{aligned} \qquad \textbf{4}$$

And,

$$I_2 = \frac{E_2}{\frac{R_2}{s} + jX_2} \qquad \textbf{5}$$

Where,

$$E_2 = \frac{jX_m}{R_1 + j(X_1 + X_m)} V_1 \qquad \textbf{6}$$

Thus, the stator copper losses, the core losses, and the rotor copper losses can be obtained.

Stator Copper Loss $= P_{Cu1} = 3{I_1}^2 R_1$ **7**

Core Losses $= P_C = 3{E_1}^2 G_C$ **8**

Therefore, air-gap power can be obtained as

$$P_{ag} = P_{in} - P_{Cu1} - P_C \qquad \textbf{9}$$

If we examined the equivalent circuit of the rotor closely, we find the resistance R_2/s is the only element that can consume the air-gap power, Therefore,

$$P_{ag} = \frac{3{I_2}^2 R_2}{s} \qquad \textbf{10}$$

But the actual resistive losses in the rotor winding is

$$P_{Cu2} = 3{I_2}^2 R_2 = sP_{ag} \qquad \textbf{11}$$

Thus, converted mechanical power is given by

$$P_{conv} = P_{ag} - P_{Cu2} = \frac{3{I_2}^2R_2}{s} - 3{I_2}^2R_2 = 3{I_2}^2R_2\left(\frac{1}{s} - 1\right)$$
$$= 3{I_2}^2R_2\left(\frac{1-s}{s}\right) = (1-s)P_{ag} \qquad \textbf{12}$$

Substituting from Eq. 5 into Eq. 12 yield

$$P_{conv} = \frac{3R_2{E_2}^2(1-s)}{s\left(\frac{R_2}{s} + jX_2\right)^2} \qquad \textbf{13}$$

Finally, mechanical power output can be obtained as

$$P_{out} = P_{conv} - P_{rot} \qquad \textbf{14}$$

Where P_{rot} is the mechanical rotational losses in the machine.

Developed torque τ_d can be obtained using the relations

$$\tau_d = \frac{P_{conv}}{\omega_m} = 3{I_2}^2R_2\left(\frac{1-s}{s\omega_m}\right) \qquad \textbf{15}$$

$$\omega_m = (1-s)\omega_s \qquad \textbf{16}$$

Where ω_m is the mechanical speed of the machine, And ω_s is the mechanical synchronous speed of the machine.

$$\omega_s = \frac{4\pi f}{P} \qquad \textbf{17}$$

Substituting from Eq. 16 into Eq. 15.we get

$$\tau_d = \frac{P_{conv}}{(1-s)\omega_s} = \frac{3{I_2}^2R_2}{s\omega_s} = \frac{P_{ag}}{\omega_s} \qquad \textbf{18}$$

Similarly, the output torque τ_l can be obtained as

$$\tau_l = \frac{P_{out}}{\omega_m} \qquad \textbf{19}$$

Now, in order to simplify computations, V_1, R_1, X_1 and can be replaced by the Thevenin equivalent circuit values V_{th}, R_{th}, X_{th}, as shown in Fig. 9.[2],[7]

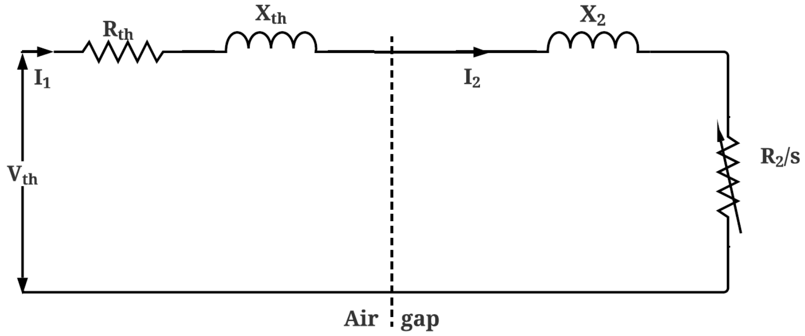


Fig. 9 Thevenin equivalent circuit.

Where,

$$V_{th} = \frac{jX_m}{R_1 + jX_1 + jX_m} V_1 \qquad \textbf{20}$$

The magnitude of the thevenin voltage V_{th} is

$$V_{th} = \frac{X_m}{\sqrt{{R_1}^2 + (X_1 + X_m)^2}} V_1 \qquad \textbf{21}$$

Since, normally, ${R_1}^2 \ll (X_1 + X_m)^2$ then then V_{th} is approximately,

$$V_{th} \approx \frac{X_m}{X_1 + X_m} V_1 \qquad \textbf{22}$$

The thevenin impedance is

$$Z_{th} = \frac{jX_m(R_1 + jX_1)}{R_1 + j(X_1 + X_m)} = R_{th} + jX_{th} \qquad \textbf{23}$$

As if ${R_1}^2 \ll (X_1 + X_m)^2$ then,

$$R_{th} \approx \left(\frac{X_m}{X_1 + X_m}\right)^2 R_1 \qquad \textbf{24}$$

Also as $X_1 \ll X_m$. Then,

$$X_{th} \approx X_1 \qquad \textbf{25}$$

Here, the current I_2 is given by

$$I_2 = \frac{V_{th}}{Z_{th} + Z_2} = \frac{V_{th}}{R_{th} + \frac{R_2}{s} + j(X_{th} + X_2)} \qquad \textbf{26}$$

The magnitude of the Thevenin voltage I_2 is

$$I_2 = \frac{V_{th}}{\sqrt{\left(R_{th} + \frac{R_2}{s}\right)^2 + (X_{th} + X_2)^2}} \qquad \textbf{27}$$

Retrieving Eq. 10. Thus, the air-gap is given by

$$P_{ag} = \frac{3{V_{th}}^2 R_2}{\left(\left(R_{th} + \frac{R_2}{s}\right)^2 + (X_{th} + X_2)^2\right) s} \qquad \textbf{28}$$

Also, Retrieving Eq. 18. Thus, the rotor developed torque is given by

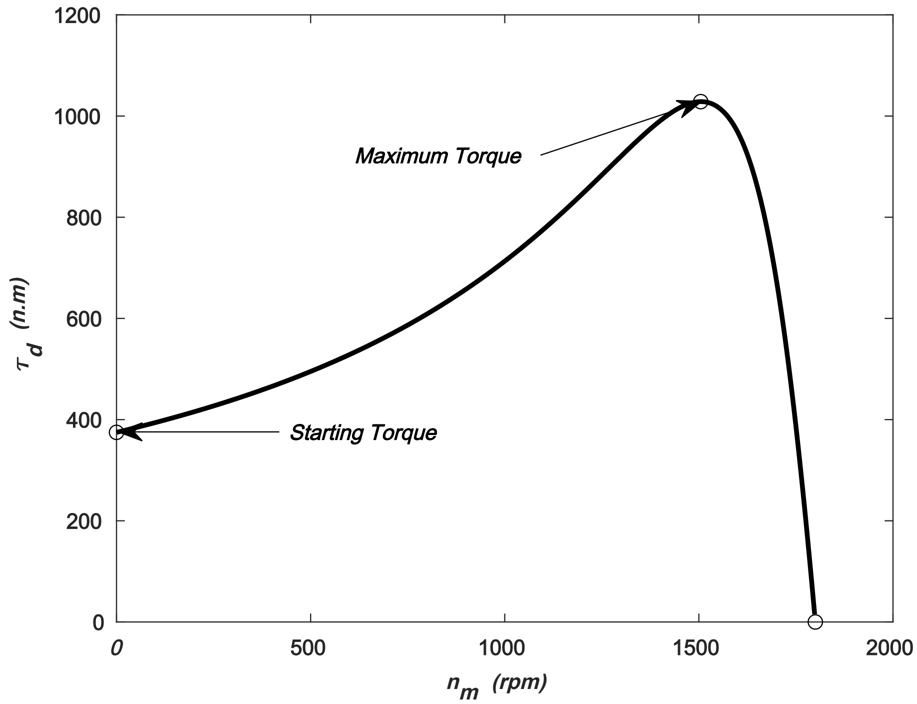
$$\tau_d = \frac{3{V_{th}}^2 R_2}{\left(\left(R_{th} + \frac{R_2}{s}\right)^2 + (X_{th} + X_2)^2\right) \omega_s s} \qquad \textbf{29}$$

5. Performance Characteristics

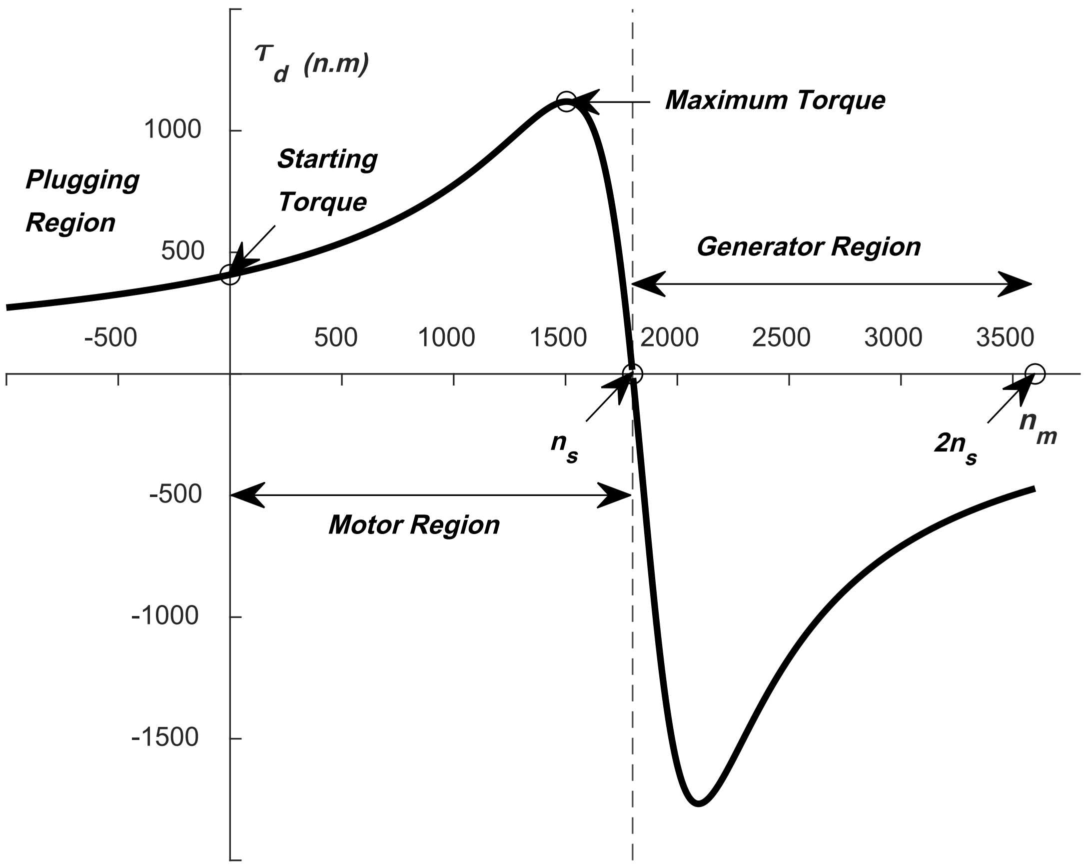
It is so significant to study the machine performance characteristics such as torque-speed characteristic, efficiency, power factor, current, starting torque, maximum torque of the machine since it help to decide the proper machine for an critical application.[7]

5.1. Torque-Speed Characteristic

Torque-speed characteristic shows the dependence of developed torque on mechanical speed and several important information such as pullout torque and starting torque of the machine. Moreover, it is useful in speed control, which will be discussed in the next section, however, consider Eq. 29, torque-speed curve can be plotted for speeds both above and below the normal motor range showing maximum and starting torque and different modes of operation as shown in Fig. 10.[5],[8]



(a)



(b)

Fig. 10 (a) Torque-speed characteristic curve. (b) Torque-speed characteristic curve at different modes of operation.

An expression for maximum developed torque can be obtained by Differentiating Eq. 29 with respect to slip s and equating the result to zero. And so on the condition for maximum torque is obtained and it is given by

$$\frac{R_2}{s_{\tau_{max}}} = \sqrt{{R_{th}}^2 + (X_{th} + X_2)^2} \qquad \textbf{30}$$

Thus, slip at maximum torque is

$$s_{\tau_{max}} = \frac{R_2}{\sqrt{{R_{th}}^2 + (X_{th} + X_2)^2}} \qquad \textbf{31}$$

And from Eq. 29 and 31, maximum torque is given by

$$\tau_{d_{max}} = \frac{3{V_{th}}^2}{\left(R_{th} + \sqrt{{R_{th}}^2 + (X_{th} + X_2)^2}\right) 2\omega_s} \qquad \textbf{32}$$

Since s = 1 at starting, An expression for starting torque can be obtained by putting s = 1 at Eq. 29.

$$\tau_{d_{start}} = \frac{3{V_{th}}^2 R_2}{\left(\left(R_{th} + \frac{R_2}{s}\right)^2 + (X_{th} + X_2)^2\right) \omega_s} \qquad \textbf{33}$$

Furthermore, it is possible in the case of wound rotor induction motors to obtain maximum torque at starting. Retrieving Eq. 31, the condition for maximum torque at starting can be expressed as

$$R_2 = \sqrt{{R_{th}}^2 + (X_{th} + X_2)^2} \qquad \textbf{34}$$

Therefore, at starting some external resistance could be added in the rotor circuit to fulfill this condition.[8],[9]

5.2. Power Factor, Stator Current and Efficiency

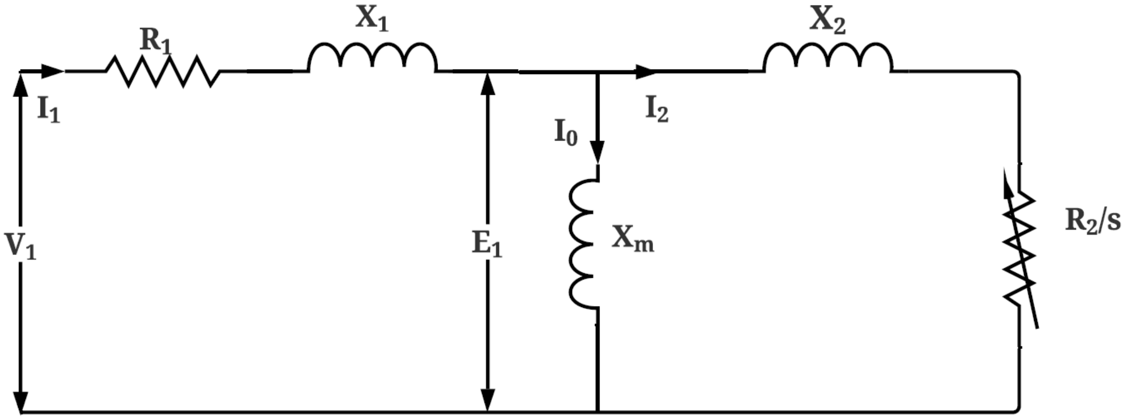


Fig. 11 IEEE-Recommended Equivalent Circuit.

Form Fig. 11, the input impedance is given by

$$Z_{eq} = R_1 + jX_1 + \left[\left(\frac{R_2}{s} + jX_2\right)//jX_m\right] = R_1 + jX_1 + \frac{jX_m\left(\frac{R_2}{s} + jX_2\right)}{\frac{R_2}{s} + j(X_m + X_2)} \quad \textbf{35}$$

$$= |Z_1|\angle\emptyset$$

Therefore, the stator current can be obtained using Eq. 3, and input power factor as

$$PF = \cos(\emptyset) \quad \textbf{36}$$

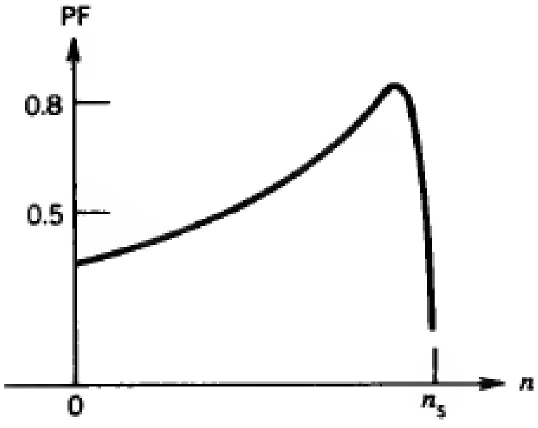
The efficiency of the induction motor is

$$\eta = \frac{P_{out}}{P_{in}} \quad \textbf{37}$$

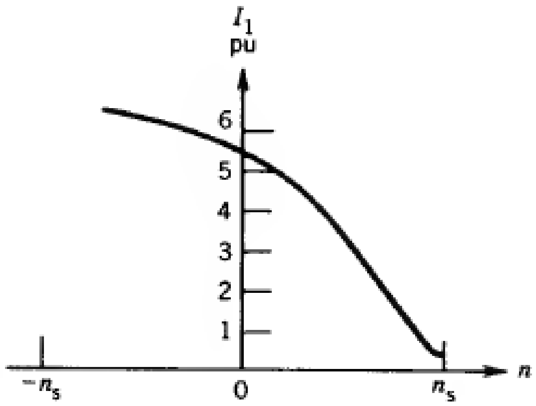
As discussed before, input electrical power and output mechanical power can be obtained, therefore substituting from Eq. 2 and 14 into 37. thus efficiency of the induction motor is calculated. Induction motors have another efficiency called internal or ideal efficiency of the machine ant it is given by

$$\eta_{internal} = \frac{P_{con}}{P_{ag}} = (1 - s) \quad \textbf{38}$$

The typical stator current, PF, and efficiency variation with speed are shown in Fig. 12.[7]



(a)



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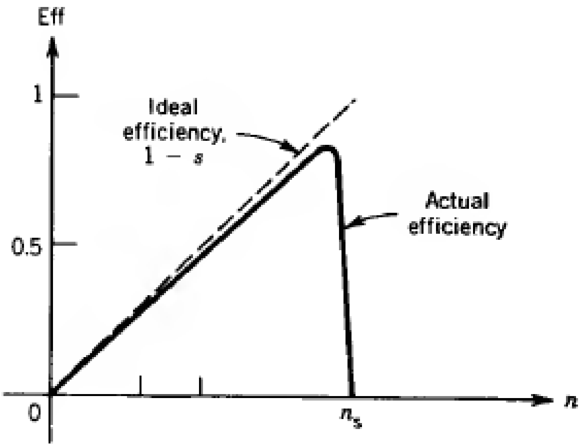


(c)

Fig. 12 (a) input PF as a function of speed. (b) Stator current as a function of speed. (c) Efficiency as a function of speed.

6. Speed Control

Many industrial applications require various speeds. Therefore, it have been a necessity to look at and evolve all Possible methods of speed control for satisfactory operation of the machine. Retrieving Eq. 16 and 29 ,the mechanical speed could by expressed as in Eq. 39. Thus, Eq. 39 And 40 showing the Possible methods of speed control of the induction motor.

$$\omega_m = \frac{3{V_{th}}^2 R_2 (1-s)}{\left(\left(R_{th} + \frac{R_2}{s}\right)^2 + (X_{th} + X_2)^2\right)\tau_d s} \qquad \mathbf{39}$$

$$n_m = \frac{120f}{P}(1-s) \qquad \mathbf{40}$$

However, there are two main approach by which the speed of an induction motor can be controlled. One is to adjust the synchronous speed of the stator and rotor magnetic fields. The other approach is to vary the slip of the motor for a given load.

6.1. Pole Changing

Consider Eq. 40, the speed of an induction motor can be changed by changing the number of poles of the machine as well as rotor speed since the rotor speed always remains near n_s. This can be done by the method of consequent poles or multiple stator windings. Changing the coil connections of the stator winding can the number of poles by the ratio 2:1. Thus, this method provides two synchronous speeds. If two independent sets of polyphase windings are used, each arranged for pole changing, four synchronous speeds could be obtained for the induction motor. However, pole changing method can change rotor speed only in discrete steps.[7],[8],[9]

6.2. Line Frequency Control

Similar to pole changing, the synchronous speed and hence the motor speed could be varied by changing the frequency of the supply as shown in Fig. 13 This method enables us to obtain a wide variation in the operating speed. However, frequency changer of the input power is required.

As

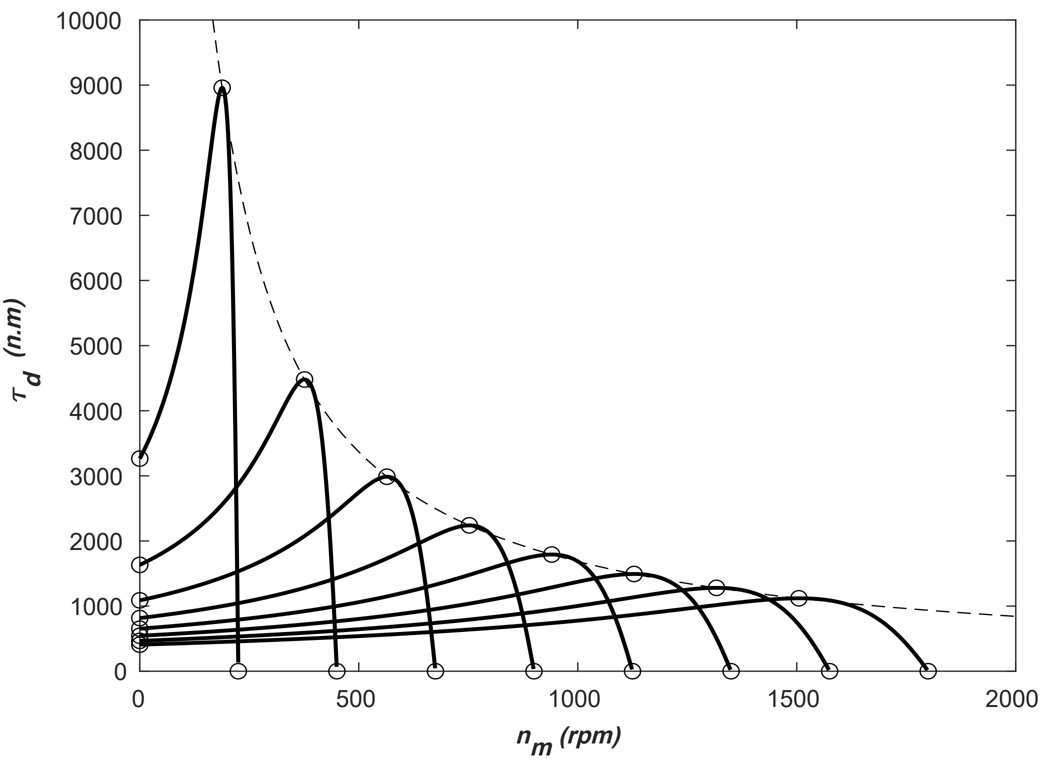
$$\phi_p \propto \frac{E_1}{f} \qquad \mathbf{41}$$

Where ϕ_p is the flux density of the air-gap.

If we neglect the voltage drop across R_1 and X_1 since it is normally small compared to terminal voltage, then

$$\phi_p \propto \frac{V_1}{f} \qquad \mathbf{42}$$

Thus, to maintain constant flux density and so the maximum torque developed, the applied voltage must be varied in direct proportion to the frequency.[7],[8],[9]



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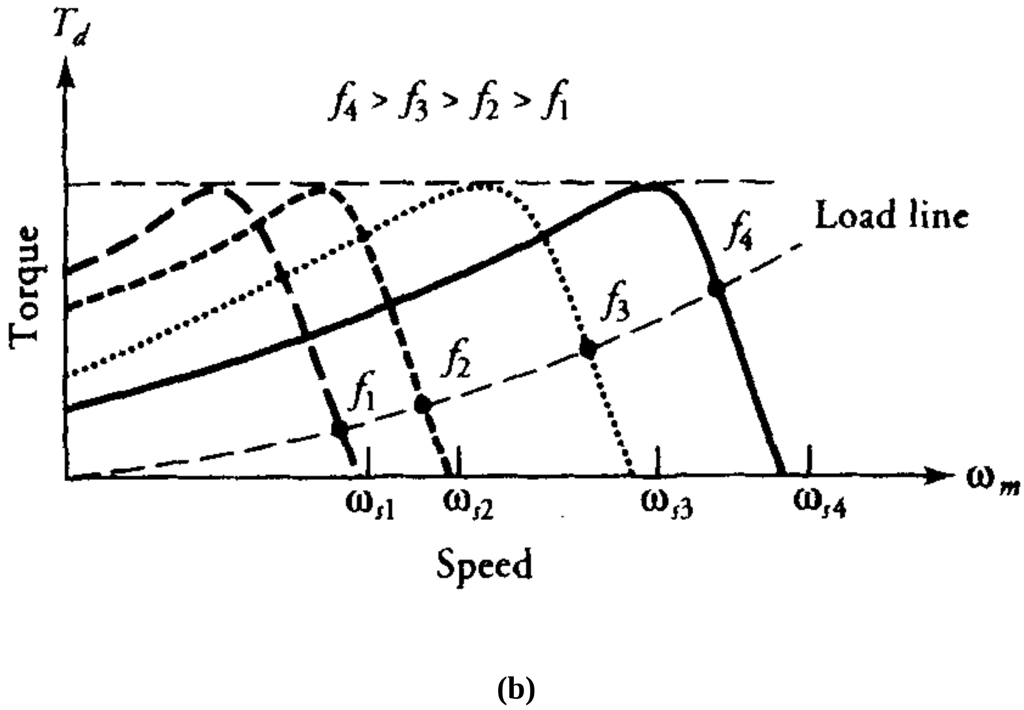


(b)

Fig. 13 Torque-speed characteristic at different supply frequencies: (a) assuming constant supply voltage. (b) assuming adjusted supply voltages.

6.3. Line Voltage Control

Since the torque developed by the motor is proportional to the square of the applied voltage, the adjusting in operating speed of an induction motor could be achieved by adjusting the applied voltage as shown in However, it reduce the maximum developed torque and thus the capability of the machine.[7],[8],[9]

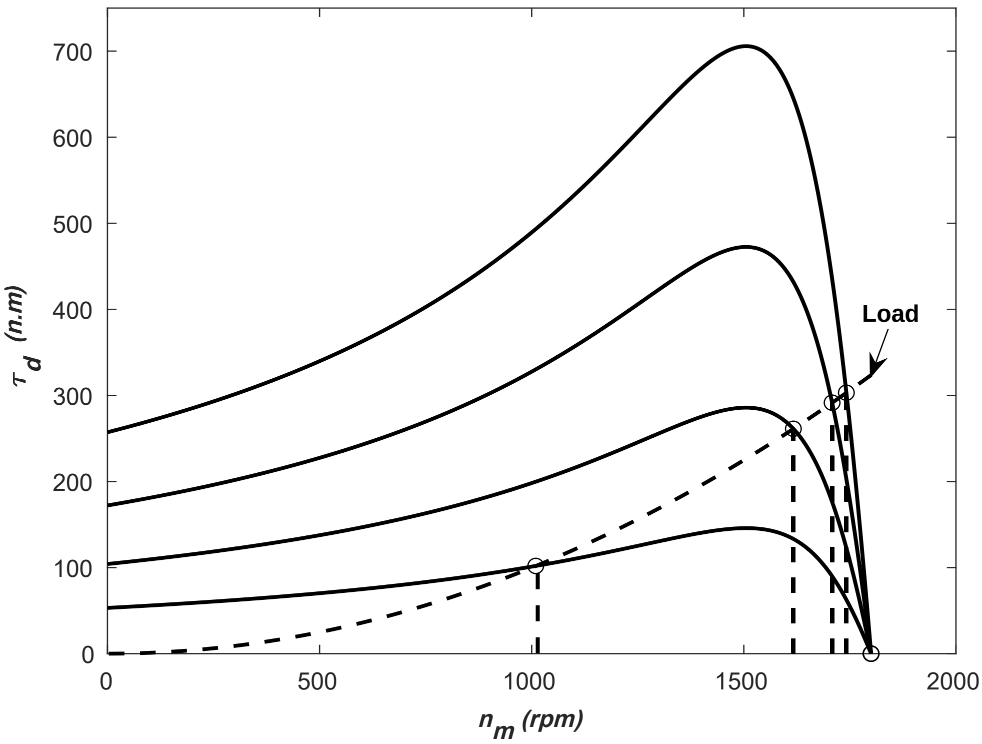
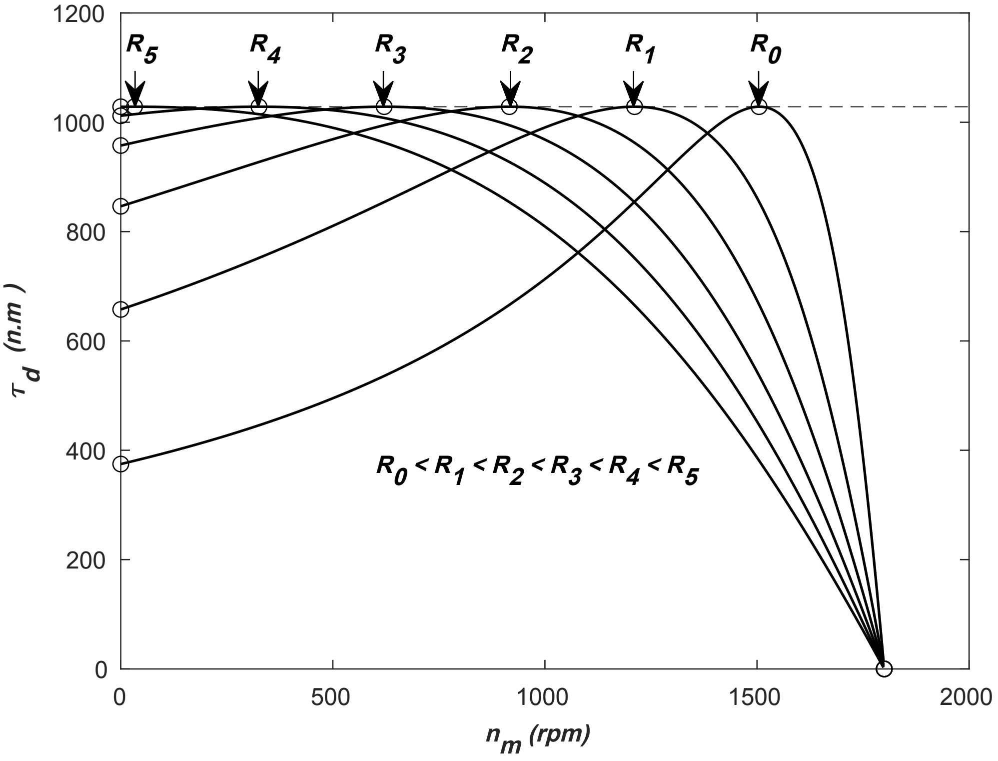


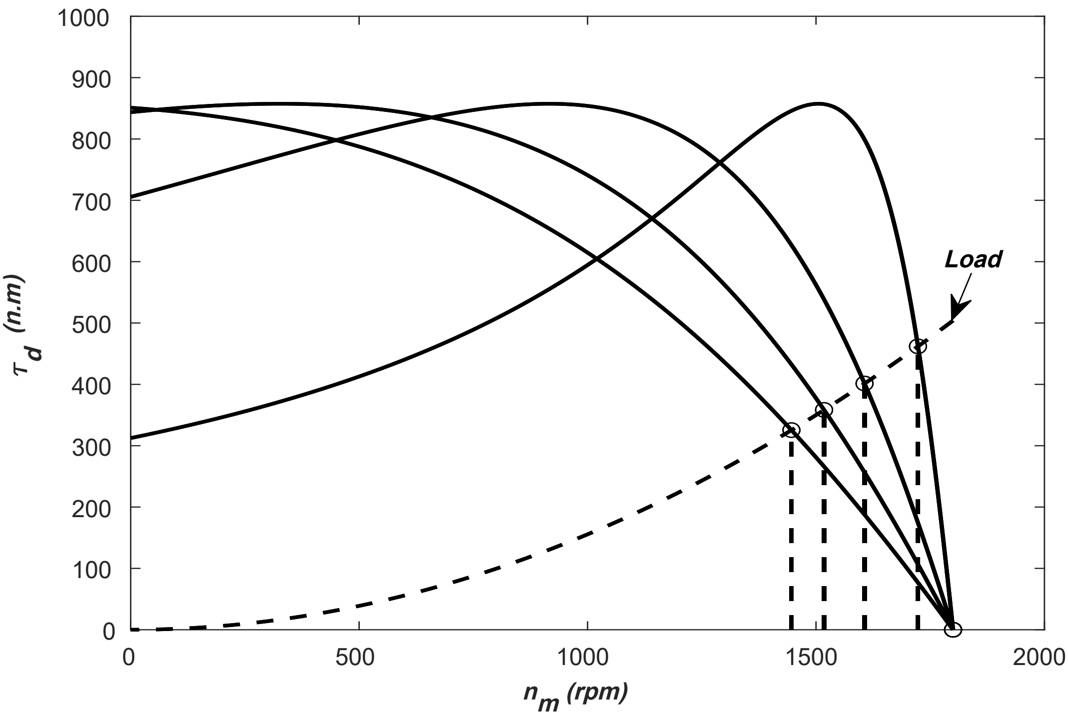
Fig. 14 Torque-speed characteristic at different line voltages.

6.4. Rotor Resistance Control

This method of speed control is suitable only for wound-rotor induction motors. The operating speed of the motor could be decreased by adding external resistance in the rotor circuit. However, an increase in the rotor resistance means an increase in the rotor copper loss and a reduction in the motor efficiency. Therefore, this method of speed control could be used only for short periods. Fig. 15 shows the effect of varying rotor circuit resistance on torque-speed characteristic and on the mechanical speed of the machine for critical load.[7],[8],[9]



(a)



(b)

Fig. 15 (a) Torque-speed characteristic at different rotor circuit resistance. (b) Rotor speed for critical load at different rotor circuit resistance.

7. Conclusion

The aim of the present research was to study and discuss some of induction machine fundamentals. However, this study has shown that induction machine have such a robust and straightforward construction. In addition, from stating its principle of operation, it have been clear why it called induction and asynchronous machine. Third Section has shown us different forms powers and torques in the induction motor and how to calculate them. However, there was some assumption to facilitate calculations. The results of this study indicate that the speed control methods of induction motors vary depending on the aimed rang of mechanical speed variation, cost, validity and the type of rotor. Therefore, the findings of this study showed that Great efforts are needed to overcome the drawbacks in these methods and improve it more.

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