and white segments. The number of segments (both black and white) is equal to the number of poles of the motor. For a 6-pole motor, there will be six segments, three black and three white, as shown in Fig 2a.

Fig 1

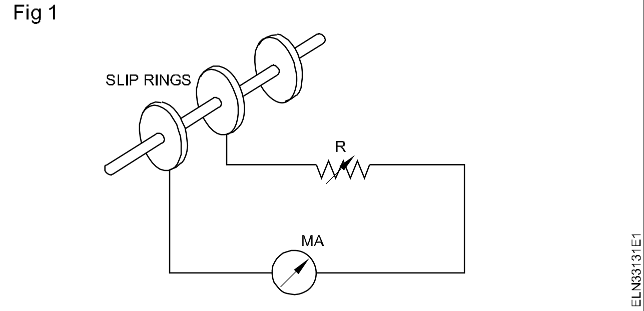
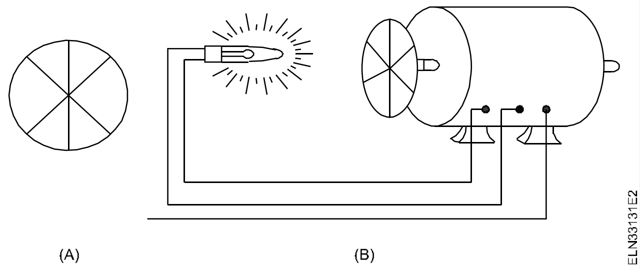


Fig 2

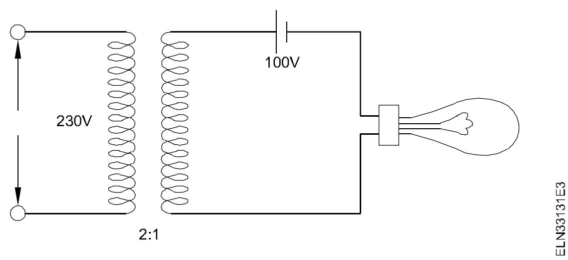


The painted disc is mounted on the end of the shaft and illuminated by means of a neon-filled stroboscopic lamp, which may be supplied preferably with a combined d.c. and a.c. supply although only a.c. supply will do (When combined d.c. and a.c. supply is used, the lamp should be tried both ways in its socket to see which way it gives better light.). The connections for combined supply are shown in Fig 3 whereas Fig 2b shows the connections for single supply only. It must be noted that with combined d.c. and a.c. supply, the lamp will flash once per cycle (It will flash only when the two voltages add and remain extinguished when they oppose). But with a.c. supply, it will flash twice per cycle.

Consider the case when the revolving disc is seen in the flash light of the bulb which is fed by the combined d.c. and a.c. supply.

If the disc were to rotate at synchronous speed, it would appear to be stationary, Since in actual practice, its speed is slightly less than the synchronous speed, it appears to rotate slowly backwards.

Fig 3



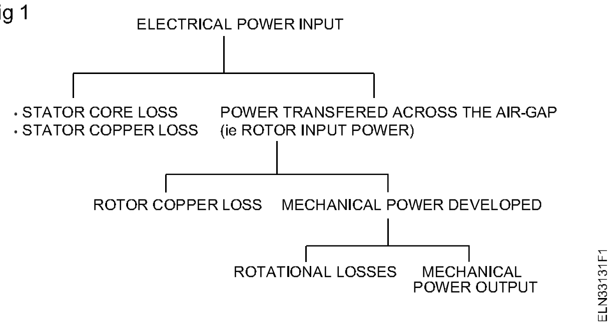
Efficiency - characteristics of induction motor- no load test - blocked rotor test

Objectives: At the end of this lesson you shall be able to
- **state the power flow diagram of an induction motor indicating the losses**
- **calculate the efficiency from the given data.**

When the three-phase induction motor is running at no-load, the slip has a value very close to zero. The torque developed in the rotor is to overcome the rotational losses consisting of friction and windage. The input power to the motor is to overcome stator iron loss and stator copper loss. The stator iron loss (consisting of eddy current and hysteresis) depends on the supply frequency and the flux density in the iron core. It is practically constant. The iron loss of the rotor is, however, negligible because the frequency of the rotor currents under normal condition is always small.

If a mechanical load is then applied to the motor shaft, the initial reaction is for the shaft load to drop the motor speed slightly, thereby increasing the slip. The increased slip subsequently causes I_2 to increase to that value which, when inserted into the equation for torque calculation (i.e $T = K\phi_s I_2 \cos \phi_s$), yields sufficient torque to provide a balance of power to the load. Thus an equilibrium is established and the operation proceeds at a particular value of slip. In fact, for each value of load horsepower requirement, there is a unique value of slip. Once slip is specified then the power input, the rotor current, the developed torque, the power output and the efficiency are all determined. The power flow diagram in a statement form is shown in Fig 1. Note that the loss quantities are placed on the left side of the flow point. Fig 2 is the same power flow diagram but now expressed in terms of all the appropriate relationships needed to compute the performance.

Fig 1



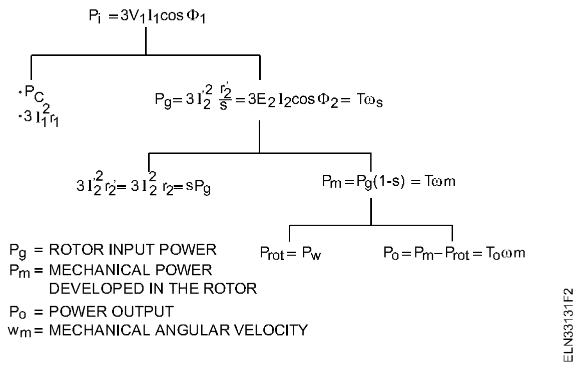
Torque, Mechanical power and Rotor output : Stator input P_i = stator output + stator losses.

The stator output is transferred fully inductively to the rotor circuit.

Obviously, rotor input P_g = stator output.

Rotor gross output, P_m = rotor input P_g - rotor cu. losses.

Fig 2



This rotor output is converted into mechanical energy and gives rise to the gross torque T. Out of this gross torque developed, some is lost due to windage and friction losses in the rotor, and the rest appear are useful torque T_o.

Let n r.p.s be the actual speed of the rotor and if it is in Nm, then

T x $2\pi n$ = rotor gross output in watts, P_m.

$$\text{Therefore, } T = \frac{\text{rotor gross output in watts, } P_m}{2\pi\ n}\ \text{N.m}$$

The value of gross torque in kg.m is given by

$$T = \frac{\text{rotor gross output in watts}}{9.81 \times 2\pi\ n}\ \text{Kg m}$$

$$= \frac{P_m}{9.81 \times 2\pi\ n}\ \text{Kg m}$$

If there were no copper losses in the rotor, the rotor output will equal the rotor input and the rotor will run at synchronous speed.

$$\text{Therefore, } T = \frac{\text{rotor input } P_g}{2\,\pi\ n_s}$$

From the above two equation we get,

Rotor gross output = P_m = Tw = T x $2\pi n$

Rotor input = P_g = TW_s = T x $2\pi n_s$

The difference between the two equals the rotor copper loss.

Therefore, rotor copper loss = s x rotor input

= s x power across air gap

= sP_g.

$$\text{Also rotor input, } P_g = \frac{\text{rotor copper loss}}{s}$$

Rotor gross output P_m = Input P_g - rotor cu.loss

= (1 - s) P_g

$$\text{or } \frac{\text{rotor gross output, } p_m}{\text{rotor input, } p_g} = 1 - s$$

rotor gross output. Pm = (1 - s)P_g

$$\text{Therefore rotor efficiency} = \frac{n}{n_s}$$

Example

The power input to a 4-pole, 3-phase, 50 Hz. induction motor is 50kW, the slip is 5%. The stator losses are 1.2 kW and the windage and friction losses are 0.2 kW. Find (i) the rotor speed, (ii) the rotor copper loss, (iii) the efficiency.

Data given

No. of poles	P = 4
Frequency	f = 50 Hz
Phases	= 3
Input power	= 50kW
% Slip	s = 5%
Stator losses	= 1.2 kW
Friction & Windage losses	= 0.2 kW

Find:

Rotor speed	= N
Rotor copper loss	= s x input power to rotor
efficiency	= η

SOLUTION

$$\text{Synchronous speed} = N_s = \frac{120f}{p} = \frac{6000}{4} = 1500\ \text{rpm}$$

$$\text{Fractional slip} = s = \frac{N_s - N_r}{N_s}$$

$$\frac{5}{100} = \frac{1500 - N_r}{1500}$$

$$75 = 1500 - N_r$$

Therefore, rotor speed, Nr = 1500 - 75 = 1425 rpm.

Input power to rotor = (50 - 1.2)kW

Rotor copper loss = s x input power to rotor

= 0.05 x 48.8

= 2.44 kW.

Rotor output = Rotor input - (Friction and windage loss + rotor cu.loss)

= 48.8 - (0.2 + 2.44)

= 46.16 kW

$$\text{Efficiency} = \frac{\text{Output}}{\text{Input}} = \frac{44.56 \times 100}{50} = 92.32\%.$$

Characteristics of squirrel cage induction motor

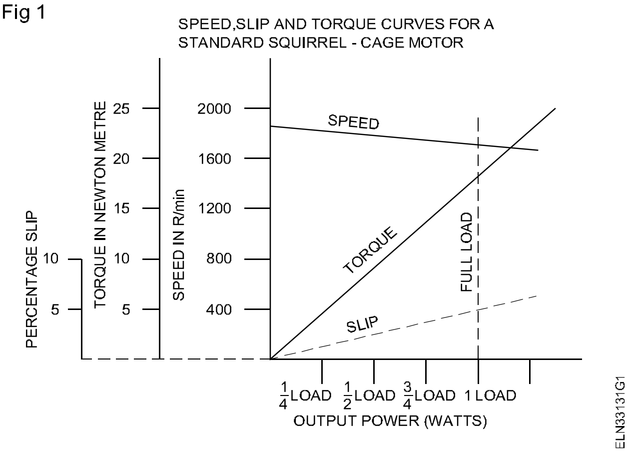
Objective: At the end of this lesson you shall be able to
- **describe the characteristics and application of a 3-phase squirrel cage induction motor.**

The most important characteristic of the induction motor is the speed torque characteristic which is also called the mechanical characteristic. A study of this characteristic will give an idea about the behaviour of the motor in load conditions. As the torque of the motor is also dependent on the slip, it will be interesting to study the characteristic of the squirrel cage induction motor to find the relationship between load, speed, torque and slip.

Speed, torque and slip characteristics : It has already been made clear that the rotor speed of a squirrel cage motor will always lag behind the synchronous speed of the stator field. The rotor slip is necessary in order to induce the rotor currents required for the motor torque. At no load, only a small torque is required to overcome the motor's mechanical losses, and the rotor slip will be very small, say about two percent. As the mechanical load is increased, however, the rotor speed will decrease, and hence, the slip will increase. This increase in slip inturn increases the induced rotor currents, and the increased rotor current in turn, will produce a higher torque to meet the increased load.

Fig 1 shows the typical speed torque and slip characteristic curves for a standard squirrel cage motor. The speed curve shows that a standard squirrel cage motor will operate at a relatively constant speed from no load to full load.

Fig 1



Since the squirrel cage rotor is constructed basically of heavy copper/aluminium bars, shorted by two end rings, the rotor impedance will be relatively, low and hence, a small increase in the rotor induced voltage will produce a relatively large increase in the rotor current. Therefore, as the squirrel cage motor is loaded, from no-load to full load, a small decrease in speed is required to cause a relative increase in the rotor current. For this reason, regulation of a squirrel cage motor is very good. But the motor is often classified as a constant speed device.

The slip curve shows that the percentage slip is less than 5% load, and is a straight line.

Since the torque will increase in almost direct proportion to the rotor slip, the torque graph is similar to the slip graph which also has a straight line characteristic as shown in Fig 1.

Relationship between torque, slip rotor resistance and rotor inductive reactance : It was stated earlier that torque is produced in an induction motor by the interaction of the stator and the rotor fluxes. The amount of torque produced is dependent on the strength of these two fields and the phase relation between them. This may be expressed mathematically as

$T = K\, \phi_s I_R \, Cos\phi$

where T = torque in Newton metre

K = a constant

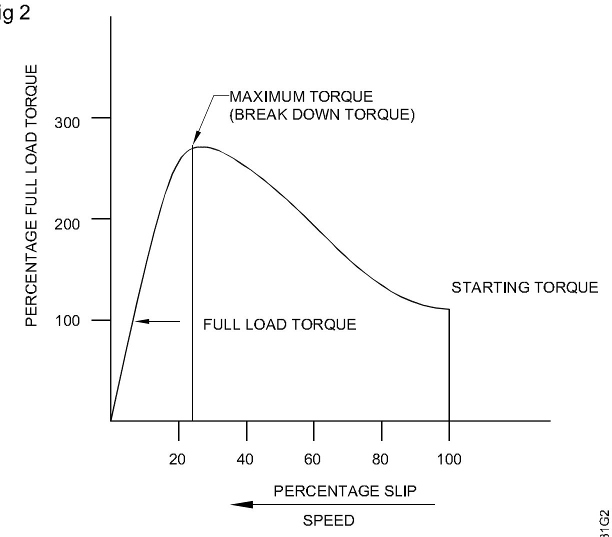
ϕ_s = stator flux in weber

I_R = rotor current in ampere

Cos ϕ = rotor power factor

From no load to full load, the torque constant (K), the stator flux (ϕ_s) and the rotor power factor (Cos ϕ) for a squirrel cage motor will be practically constant. Hence the motor's torque will vary almost directly with the induced rotor current (I_R) since the rotor current inturn will vary almost directly with its slip. Variation of the torque of a squirrel cage motor is often plotted against its rotor slip as shown in Fig 2.

Fig 2



TORQUE VARIATION VERSUS SLIP FOR A STANDARD SQUIRREL - CAGE MOTOR

The increase in the rotor current, and hence, the increase in the rotor torque for a given increase in the rotor slip is dependent on the rotor power factor. The rotor resistance for a squirrel cage motor will be constant. However, an increase in slip will increase the rotor frequency, and the resulting inductive reactance of the rotor from no load to full load and even upto 125 percent of rated load, the amount of rotor slip for a standard squirrel cage motor is relatively small and the rotor frequency will seldom exceed 2 to 5 Hz. Therefore, for the above range of load the effect of frequency change on impedance will be negligible, and as shown in Fig 2, the rotor torque will increase in almost a straight relationship with the slip.

Inbetween 10 to 25 percent slip the squirrel cage motor will attain its maximum possible torque. This torque is referred to as the maximum breakdown torque, and it may reach between 200 and 300 percent of the rated torque as shown in Fig 2. At the maximum torque, the rotor's inductive reactance will be equal to its resistance.

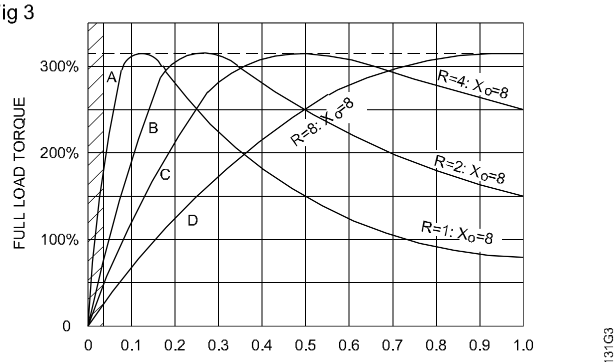
However, when the load and the resulting slip are increased much beyond the rated full load values, the increase in rotor frequency, and hence, the increase in rotor reactance and impedance become appreciable. This increase in rotor inductive reactance and the resulting decrease in rotor power factor will have two effects; first, the increase in impedance will cause a decrease in the rate at which the rotor current increases with an increase in slip, and second, the lagging rotor power factor will increase; that means, the rotor flux will reach its maximum sometime after the stator peak flux has been swept by it. The out-of-phase relationship between these two fields will reduce their interaction and their resulting torque. Hence, if the motor load is increased beyond the breakdown torque value, the torque falls rapidly due to the above two effects and the motor operation becomes unstable, and the motor will stall.

Effect of rotor resistance upon the torque/slip relationship: Fig 3 shows the relationship between torque and slip when the rotor resistance is changed. The shaded portion of the curve shows the actual operating area. Curve A for an induction motor with low rotor resistance, say 1 ohm, Curve B is for 2 ohm, Curve C is for 4 ohm and Curve D for 8 ohm.

Breakdown torque : In all these cases the standstill inductive reactance of the rotor is the same, say 8 ohm. From the curves it is clear that the maximum (breakdown) torque is the same for the four values of R. Further it is also clear that the maximum torque occurs at greater slip for higher resistance.

Starting torque : At the time of starting, the fractional slip is 1, and the starting torque is about 300% of the full load torque for the rotor having maximum resistance as shown by curve D of Fig 3, and at the same time the rotor having low resistance will produce a starting torque of 75% of the full load torque only, as shown by curve A of Fig 3. Hence, we can say that an induction motor having high rotor resistance will develop a high torque at the time of starting.

Fig 3



FRACTIONAL SLIPS TORQUE/SLIP CURVES FOR AN INDUCTION MOTOR

Running torque : While looking at the normal operating region in the shaded portion of the graph, it will be found the torque at running is appreciably high for low resistance rotor motors and will be conspicuously less for high resistance rotor motors.

As squirrel cage induction motors will have less rotor resistance, their starting torque is low but running torque is quite satisfactory. This is partly compensated by the double squirrel cage motors which produce high starting and running torque. On the other hand, the slip ring induction motor, due to its wound rotor, has the possibility of inclusion of resistance at the time of starting and reducing the same while running.

Application of squirrel cage induction motor : Single squirrel cage motors are used widely in industries and in irrigation pump sets where fairly constant speed is required. This motor has fairly high efficiency, costs less and is found to be robust in construction.

Double squirrel cage induction motors are used in textile mills and metal cutting tool operations where high starting torque is essential.

No-load test of induction motor

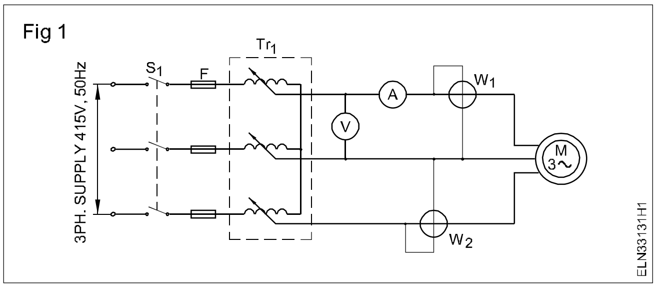
Objectives: At the end of this lesson you shall be able to
- **determine the constant (mechanical and iron losses of induction motor) by no-load test**
- **calculate the total equivalent resistance per phase.**

No-load test

The induction motor is connected to the supply through a 3-phase auto-transformer (Fig 1). The 3-phase auto-transformer is used to regulate the starting current by applying low voltage at the start, and then gradually increased to rated voltage. The ammeter and voltmeters are selected based upon the motor specification. The no-load current of the motor will be very low, up to 30% of full load.

As the power factor of the motor on no-load is very low, in the range of 0.1 to 0.2, the wattmeters selected are such as to give a current reading at low power factor. The wattmeter full scale reading will be approximate equal to the product of the ammeter and voltmeter full scale deflection values.

Fig 1



The calculation is done as follows to determine the constant losses of the induction motor.

At no-load, the output delivered by the motor is zero. All the mechanical power developed in the rotor is used to maintain the rotor running at its rated speed. Hence the input power is equal to the no-load copper loss plus iron losses and mechanical losses.

Calculation

V_{NL} is ® line stator voltage

I_{NL} is ® line current

P_{NL} is ® Three-phase power input.

The input power consists of the core loss P_c, friction and windage loss $P_{(rot)}$, and the stator copper loss.

$P_{NL} = P_c + P_{rot} + 3\, I^2_{NL}\, R_S$

This permits the sum of rotational loss to be evaluated.

$P_{rot + C} = P_{NL} - 3\, I^2_{NL}\, R_S$

where the stator resistance Rs per phase obtained from a resistance measurement at the stator terminal.

In star connection $R_S = R/2$.

Delta connection $R_S = 2/3\, R$.

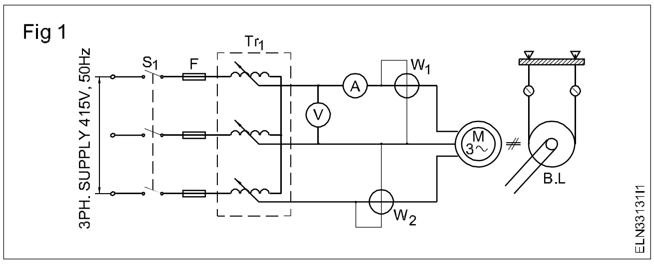
Blocked rotor test

Objectives: At the end of this lesson you shall be able to
- **determine the full load copper loss of a 3-phase induction motor by blocked rotor test**
- **calculate the total equivalent resistance per phase and efficiency.**

The connections are made similar to that of the no-load test. In this case the ammeter is selected to carry the full load current of the motor. Wattmeters will be of a suitable range and its power factor is 0.5 to unity.

An auto-transformer is used to give a much lower percentage of the rated voltage. The rotor is locked by a suitable arrangement such that it cannot rotate even if the supply is given to the motor. One such arrangement is shown in Fig 1. The belt is over-tightened on the pulley to prevent rotation.

Fig 1



As the rotor is in a locked condition it is equivalent to the short circuit secondary of a transformer. Therefore, a small induced voltage in the rotor cage winding will be sufficient to cause a large current to flow in the cage.

It is very essential to limit the supply voltage to a value less than 5% at start and then gradually increase until the starter current is equal to the full load current. The frequency of the starter supply voltage is maintained at normal rated supply frequency.

The method of calculating the copper losses from the result is illustrated through the example given below.

Example

A 5 HP 400V, 50 Hz, four-pole, three-phase induction motor was tested and the following data were obtained.

Blocked rotor test: $V_s = 54$. $P_s = 430$, $I_s = 7.5$ A.

The resistance of the stator winding gives a 4 V drop between the terminals' rated DC current flowing.

Find the power factor at short circuit and R_e and X_e and full load copper loss.

Given:

Output	= 5 HP
Voltage	= 400 V
Frequency	= 50 Hz.
Blocked rotor voltage, V_S	= 54 V
Power P_S,	= 430 W
Current, I_S	= 7.5 A

Find:

Power factor at short circuit = $\cos \theta_S$

Equivalent resistance, R_e/phase

Equivalent reactance X_e/phase

Full load copper loss = $3I^2 R_e$.

Known:

$W_S = \sqrt{3}\, V_S I_S \;\; \cos \varnothing_S$

Equivalent impedance $Z_e = \frac{V_s}{\sqrt{3}I_s} = \sqrt{R_e^2 + X_e^2}$

R_e = equivalent resistance $= \frac{P_s}{3I_s^2}$

X_e = equivalent reactance $= \sqrt{Z_e^2 - R_e^2}$

Solution:

$W_s = \sqrt{3}\, V_s I_s \quad \cos\varnothing_s$

$\cos\phi_s = \frac{W_s}{\sqrt{3}\, V_s I_s}$

$\cos\phi_S = \frac{430}{1.72 \times 54 \times 7.5}$

$= \frac{430}{696.6}$

$= 0.61$

Equivalent resistance R_e/phase $= \frac{P_s}{3 \times I_s^2}$

$= \frac{430}{3 \times (7.5)^2}$

$= \frac{430}{168.75} = 2.5\Omega$

X_e = equivalent reactance/phase $= \sqrt{Z_e^2 - R_e^2}$

$Z_e = \frac{54}{\sqrt{3} \times 7.5} = \frac{54}{12.90} = 4.1\Omega.$

$X_e = \sqrt{4.1^2 - 2.5^2} = \sqrt{16.81 - 6.25}$

$= \sqrt{10.56} = 3.24\Omega.$

Full load copper loss $= 3 I^2 R_e$

$= 3 \times 7.5^2 \times 2.5 = 421.875$ watts

Answer

i $\cos\phi_s = 0.61$

ii Equivalent resistance R_e /phase = 2.5 Ω

iii Equivalent reactance X_e/phase = 3.24 Ω

iv Full load copper loss = 421.875 watts

Efficiency from no-load and blocked rotor test

Objective: At the end of this lesson you shall be able to
- **determine the efficiency at full load.**

Example

A 5 HP 220V, 50 Hz four-pole, three-phase induction motor was tested and the following data were obtained.

No load test = V_{NL} = 220V, P_{NL} = 340 W, I_{NL} = 6.2 A

Blocked rotor test = V_{BR} = 54V, P_{BR} = 430W,

I_{BR} = 15.2 A

Application 4V DC across two stator terminals causes the rated current flow with stator (assume star connection). Determine the efficiency at full load.

Assuming star connection DC resistance/phase = R/2

SOLUTION:

$R_1 + R_2$ = 4/15.2 = 0.263 W

Resistance/phase = 0.263/2 = 0.1315 Ω

Effective AC resistance $R_s = 1.4 R_{ph}$

= 1.4 x 0.1315

= 0.1841 Ω

$R_{(rot + c)} = P_{NL} - 3I_{NL}^2 R_s$

$= 340 - 3 \times 6.2^2 \times 0.1841$

= 340 - 21.23

= 318.77 W(constant loss)

Copper loss $= 3I^2 R_e$ = 430 W

Output = 5 x 735.5 = 3677.5 W

Efficiency $= \frac{3677.5}{3677.5 + 318.77 + 430} = \frac{3677.5}{4426.2}$

= 0.830

% efficiency = 0.830 x 100

i.e. = 83%.