Unit UEENEEG006A

SOLVE PROBLEMS IN SINGLE & THREE PHASE LOW VOLTAGE MACHINES

KS02-EG006A

BOOK 2 of 2

ROTATING MACHINES

Stage 1: *This list does not contain all equations in the course and transposition may be required.*

	A	B	C	D	E
1	$Q = It$	$F = ma$	$W = Pt$	$W = Fs$	$W = mgh$
2	$\mathbf{V = IR}$	$\mathbf{I = \frac{V}{R}}$	$\mathbf{R = \frac{V}{I}}$		$\mathbf{P = \frac{2\pi nT}{60}}$
3	$P = VI$	$P = I^2R$	$P = \frac{V^2}{R}$		$\eta\,\% = \frac{output}{input} \times \frac{100}{1}$
4	$R = \frac{\rho l}{A}$	$R_2 = \frac{R_1 A_1 l_2}{A_2 l_1}$	$R_h = R_c(1 + \alpha\Delta t)$		
5	$V_T = V_1 + V_2 + V_3$	$R_T = R_1 + R_2 + R_3$	$I_T = I_1 = I_2 = I_3$	$V_1 = V_T \frac{R_1}{R_1 + R_2}$	
6	$V_T = V_1 = V_2 = V_3$	$\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$	$I_T = I_1 + I_2 + I_3$	$I_2 = I_T \frac{R_1}{R_1 + R_2}$	$R_T = \frac{R_1 R_2}{R_1 + R_2}$
7	$C = \frac{Q}{V}$	$C = \frac{A \in_o \in_r}{d}$	$r = RC$	$C_T = C_1 + C_2 + C_3$	$\frac{1}{C_T} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3}$
8	$L = N\frac{\Delta\emptyset}{\Delta I}$	$L = \frac{N^2}{S}$	$r = \frac{L}{R}$	$V = N\frac{\Delta\emptyset}{\Delta t}$	$V = L\frac{\Delta I}{\Delta t}$
9	$e = Blv$	$F = Bil$	$F_m = IN$	$B = \frac{\emptyset}{A}$	$S = \frac{l}{\mu_o \mu_r A}$
10	$E_g = k\emptyset n$	$T = k\emptyset I_a$	$T = Fr$	$H = \frac{F_m}{l}$	$\emptyset = \frac{F_m}{S}$

Equation Sheet - Symbols obtained from AS1046

Stage 2: *This list does not contain all equations in the course and transposition may be required.*

Stage 1: *equations are also used during stage 2*

	A	B	C	D	E
11	$V_{ave} = 0.637V_{max}$	$V_{RMS} = 0.707V_{max}$	$v = V_{max} \sin\theta$	$V_L = \sqrt{3}V_P$	$f = \frac{nP}{120}$
12	$I_{ave} = 0.637I_{max}$	$I_{RMS} = 0.707I_{max}$	$i = I_{max} \sin\theta$	$I_L = \sqrt{3}I_P$	$t = \frac{1}{f}$
13	$I = \frac{V}{Z}$	$V = IZ$	$Z = \frac{V}{I}$		
14	$Z = \sqrt{R^2 + X^2}$	$Z = \sqrt{R^2 + (X_L - X_C)^2}$	$X_L = 2\pi fL$	$X_C = \frac{1}{2\pi fC}$	$\cos\theta = \frac{R}{Z}$
15	$P = VI\cos\theta$	$S = VI$	$Q = VI\sin\theta$	$P = \sqrt{S^2 - Q^2}$	$\cos\theta = \frac{P}{S}$
16	$P = \sqrt{3}V_L I_L \cos\theta$	$S = \sqrt{3}V_L I_L$	$Q = \sqrt{3}V_L I_L \sin\theta$	$\tan\theta = \sqrt{3}\left(\frac{W_1 - W_2}{W_1 + W_2}\right)$	$\theta = cos^{-1}\lambda$
17	$V' = 4.44\emptyset fN$	$\frac{V_1}{V_2} = \frac{N_1}{N_2}$	$\frac{I_2}{I_1} = \frac{N_1}{N_2}$	$V_{reg}\% = \frac{(V_{NL} - V_{FL})}{V_{FL}} \times \frac{100}{1}$	
18	$N_{syn} = \frac{120f}{P}$	$f_r = \frac{S\% \times f}{100}$	$S\% = \frac{\lvert n_{syn} - n \rvert}{n_{syn}} \times \frac{100}{1}$	$V_{reg}\% = \frac{(V_{NL} - V_{FL})}{V_{NL}} \times \frac{100}{1}$	$T = k\emptyset Ia$
19					
20			$P = \frac{2\pi nT}{60}$	$\eta\ \% = \frac{output}{input} \times \frac{100}{1}$	

Stage 2a: *This list does not contain all equations in the course and transposition may be required.*

Stage 1: *equations are also used during stage 2*

	A	B	C	D	E
21					
22	$V_T = E_G - (I\,R_i)$	$E = \frac{F}{A}$	$E = \frac{I}{d^2}$	$E = \frac{I}{d^2} \times \cos\theta$	$\eta = \frac{F}{P}$
23			$Q_c = P(\tan\theta_1 - \tan\theta_2)$	$X_c = R(\tan\theta_1 - \tan\theta_2)$	
24					

Stage 3: *This list does not contain all equations in the course and transposition may be required.*

	A	B	C	D	E
25	$V_P\text{Y} = 57.7\% V_P\Delta$	$I_P\text{Y} = 57.7\% I_P\Delta$	$I_{motor\ st} = \left(\frac{\%TAP}{100}\right) \times I_{DOL}$	$I_{line\ st} = \left(\frac{\%TAP}{100}\right)^2 \times I_{DOL}$	
26	$I_{ST} = \frac{1}{3} \times I_{DOL}$	$T_{ST} = \frac{1}{3} \times T_{DOL}$	$V_{st} = \left(\frac{\%TAP}{100}\right) \times V_{DOL}$		
27	$I_{ST} = \left(\frac{V_{st}}{V}\right) \times I_{DOL}$	$T_{ST} = \left(\frac{V_{st}}{V}\right)^2 \times T_{DOL}$	$\text{Constant} = \frac{V}{f}$		
28					

Unit Guide – Summary

FULL unit guides can be accessed online at www.training.gov.au

The following information is summarised and is intended to provide a broad overview only.

Unit:

UEENEEG006A Solve problems in single and three phase low voltage machines

Unit Descriptor

This unit covers ascertaining correct operation of single and three phase machines and solving machine problems as they apply to servicing, fault finding, installation and compliance work functions. It encompasses safe working practices, machine connections circuit arrangements, issues related to machine operation, characteristics and protection and solutions to machine problems derived from calculated and measured parameters

Pre-Requisites

Pre-requisites are units of study that must be completed prior to commencing a new unit of study. That is, you must pass subject 'X' before you are allowed to commence subject 'Y'. In some instances, pre-requisite units may be studied concurrently with new units of study.

Pre-requisites for this unit of study are:

- UEENEEE101A Apply Occupational Health and Safety regulations, codes and practices in the workplace
- UEENEEE102A Fabricate, dismantle, assemble of electrotechnology components
- UEENEEE104A Solve problems in d.c circuits
- UEENEEE105A Fix and secure electrotechnology equipment
- UEENEEE107A Use drawings, diagrams, schedules, standards, codes and specifications
- UEENEEG101A Solve problems in electromagnetic devices and related circuits
- UEENEEG102A Solve problems in low voltage a.c. circuit

  UEENEEG106A Terminate cables, cords and accessories for low voltage circuits

Literacy and numeracy skills indicators for this unit – NRS Level 5:

Participants are best equipped to achieve competency in this unit if they have reading, writing and numeracy skills at a level indicated by the following NRS levels.

The National Reporting System (NRS) is a nationally recognised mechanism for determining adult English language, literacy and numeracy levels.

In context for this unit of study these Indicators of Competence (IoC) are not an assessment system, but merely a guide to the specific reading writing and numeracy levels for this unit.

Further information pertaining to the description of each scale is given in Volume 2, Part 3 *'Literacy and Numeracy'*, of the UEE11 training package, available at http://training.gov.au

Skill	IoC	Indicator of Competence
Reading: Level 5	5.1	Reads and interprets structurally intricate texts in chosen fields of knowledge and across a number of genres, which involve complex relationship between pieces of information and/or propositions.
	5.2	Interprets subtle nuances, infers purpose of author and makes judgements about the quality of an argument.
	5.3	Reads and critically evaluates texts containing data which includes some abstraction, symbolism, and technicality presented in graphic, diagrammatic, formatted or visual form.
Writing: Level 5	5.4	Demonstrates well-developed writing skills by selecting stylistic devices to express complex relationships between ideas and purposes.
	5.5	Generates complex written texts with control over generic structure.
Numeracy: Level 5	5.10	Interprets, selects and investigates appropriate mathematical information and relationships highly embedded in an activity, item or text.
	5.11	Selects and applies a wide range of mathematical strategies flexibly to generate solutions to problems across a broad range of contexts.
	5.12	Analyses and evaluates the appropriateness, interpretations and wider implications of all aspects of a mathematical activity.
	5.13	Uses a wide range of oral and written informal and formal language and representation including symbols, diagrams and charts to communicate mathematically.

Unit Guide – Assessment

Unit Guide – Assessment

Required skills and knowledge

This describes the essential skills and knowledge and their level, required for this unit.

Evidence shall show that knowledge has been acquired of safe working practices, rationale and solving problems in the relevant unit. The knowledge and skills shall be contextualised to current industry standards, technologies and practices.

View the section title page in your class workbook or the complete unit guide for a full list of the fundamentals covered by each topic within this unit.

Below is a list indicating the content areas to be covered by the required skills and knowledge specification for this unit:

Note: Topics may not be delivered in the order indicated by the full unit guide.

Additional information pertinent to your learning may also be included during unit delivery.

KS01-EG006A - Single and three-phase transformers - Class workbook 1

WORKBOOK SECTION NUMBER	CONTENT	TOPIC NUMBER AS LISTED IN THE FULL UNIT GUIDE
Section 1	Transformer construction	T1
Section 2	Transformer operation	T2
Section 3	Transformer losses, efficiency and cooling	T3
Section 4	Transformer voltage regulation and percent impedance	T4
Section 5	Parallel operation of transformers and transformer auxiliary equipment	T5
Section 6	Auto-transformers and instrument transformers	T6

KS02-EG006A - Alternating current rotating machines - Class workbook 2

Section 1	Operating Principles of three phase induction motors	T1
Section 2	Three phase induction motor construction	T2
Section 3	Three phase induction motor characteristics	T3
Section 4	Single phase motors – split phase	T4
Section 5	Single phase motors – capacitor and shaded pole types	T5
Section 6	Single phase motors – universal	T6
Section 7	Motor protection	T7
Section 8	Three phase synchronous machines: operation principles and construction	T8
Section 9	Alternators and generators	T9

Unit Guide – Assessment

Student Assessment Guide for this unit:

Evidence for competence in this unit shall be considered holistically. The required skills and knowledge relating to this unit will be assessed in following manner:

Unit Number	**UEENEEG006A**
KS Number(s)	**KS01-EG006A (TRANSFORMERS) and KS02-EG006A (Rotation AC Machines)**
Unit Title	**Solve problems in single and three phase low voltage machines**
Superceded	**UEENEEG008B, UEENEEG004B, Electrical Machines - 9080V**

Notes

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SQUIRREL CAGE INDUCTION MOTORS

PURPOSE:

This section introduces the purpose, construction and operation of the squirrel cage three phase induction motor.

TO ACHIEVE THE PURPOSE OF THIS SECTION:

- At the end of this section the student will be able to:
- Describe the basic function of the squirrel cage induction motor.
- Identify the component parts of a squirrel cage induction motor.
- Calculate the speed of rotation of the rotating magnetic field of an induction motor.
- State the direction of rotation of the rotor of an induction motor given the direction of rotation of the rotating magnetic field.
- Describe how torque is developed within an induction motor.
- Describe the meaning of the term slip and calculate the percentage slip of an induction motor.
- Reverse the direction of rotation of an induction motor.
- Identify induction motor details from a motor nameplate.

REFERENCES:

- Hampson, J. & Hanssen, S. *Electrical Trade Principles,* 2nd Edition, Section 6
- Jenneson, J.R. *Electrical Principles for the Electrical Trade,* 3rd Edition, Pages 223 - 228

1. INTRODUCTION

A typical squirrel cage, three phase induction motor is shown in figure 1. The basic function of a motor of this type is to carry out energy conversion, that is -

the conversion of____________________energy to____________________energy.

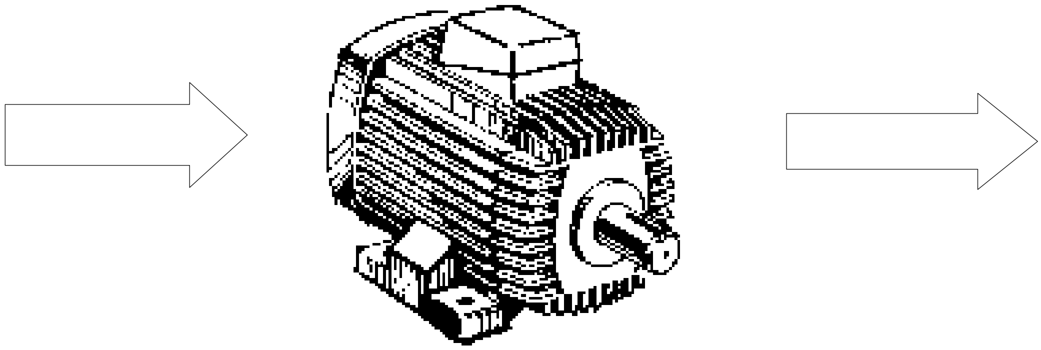

Figure 1

The squirrel cage induction motor is the most commonly used AC motor. Overall, it consists of two main parts -

- A stationary part called the ____________________

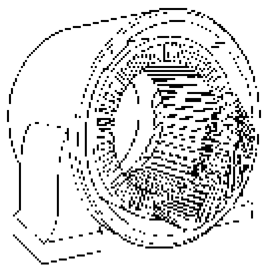

Figure 2

- A revolving part called the ____________________

Figure 3

The induction motor derives its name from the fact that the rotor is not connected electrically to the source of supply but acts like the secondary winding of a transformer. The currents in the rotor conductors are set up as a result of the voltages induced in the rotor by the magnetic field of the stator.

That is the process called____.

The induction motor depends, for its operation, upon the production of a -

____.

The method of producing such a field will now be considered.

STATOR CONSTRUCTION

The stator consists of three main parts, as shown in figure 4, -

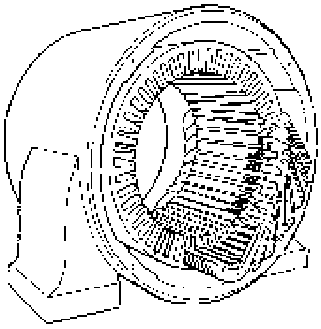

Figure 4

Frame - is of cast or fabricated steel.
- are manufactured in various forms.

The type of frame used is governed by the environmental conditions the motor is to operate under, for example -

- open type - which allows free ventilation to take place.
- drip proof - which has a closed upper half, while allowing ventilation through the lower half.
- totally enclosed - which prevents the exchange of air between the inside and outside of the frame.

- two end shields that house bearings to support the rotor are bolted to the frame.

Stator core - slotted on the inside circumference to carry the stator winding.
- made of low loss silicon steel to reduce hysteresis loss.
- laminated to reduce eddy current loss, see figure 5
- laminations are insulated from one another to further reduce eddy current loss
- is pressed directly into the frame.

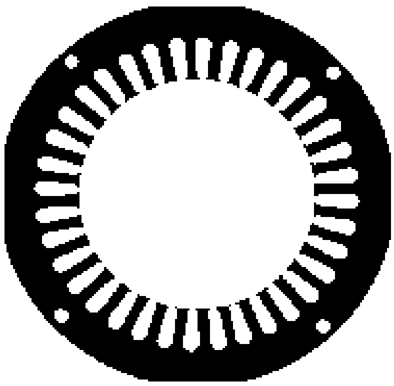

Figure 5

Winding - consists of three identical phase windings which are displaced by 120 electrical degrees around the stator.

- each phase winding consists of a number of series connected coils which produce the required number of stator poles.

- the windings are generally connected in delta, but may be connected in star. In either case the phase conductors must be of sufficient csa area to carry the line current when star connected and $\frac{1}{\sqrt{3}}$ of the line current when delta connected.

2. ROTOR CONSTRUCTION

The squirrel cage motor uses a rotor known as the squirrel cage rotor, or cage motor. The name is derived from the arrangement of the rotor conductors. See figure 6.

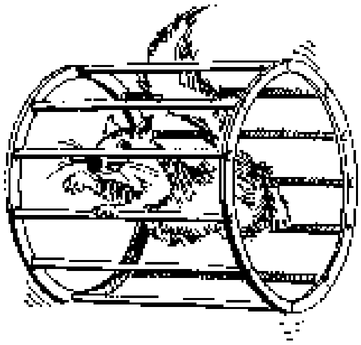

Figure 6

The squirrel cage rotor consists of -

- a shaft
- a laminated silicon steel core having partly closed slots, see figure 7.

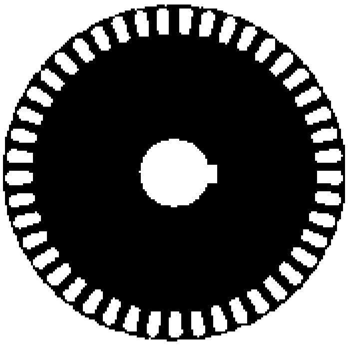

Figure 7

- a squirrel cage winding - which consists of solid copper alloy or aluminium bars embedded in the rotor slots. Each bar is short circuited by end rings, see figures 8 and 9.

Figure 8

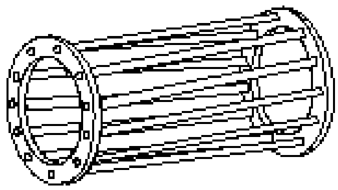

Figure 9

In smaller motors the complete rotor winding, including bars, end rings and fan, is a one piece casting. In larger motors the conductors are formed bars, generally copper, inserted in slots in the rotor laminations, which are then welded to the short circuiting end rings.

Rotor slots are generally "________________" to reduce any magnetic locking between the stator and the rotor and to reduce magnetic noise when the motor is running.

The rotor is supported on bearings so that it can rotate freely.

The air gap clearance between the rotor and the stator is typically about "**0.5mm**", but varies depending upon the rating of the motor.

3. OVERALL CONSTRUCTION

Figure 10 shows and exploded view of a general purpose squirrel cage induction motor.

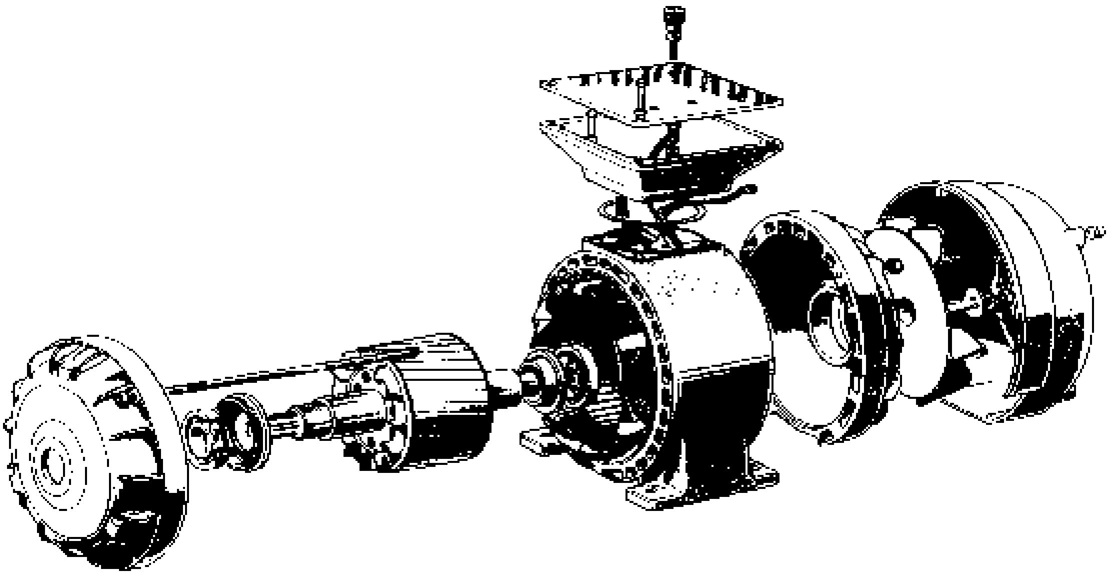

Figure 10

The circuit diagram for the squirrel cage motor would be as shown in figure 11.

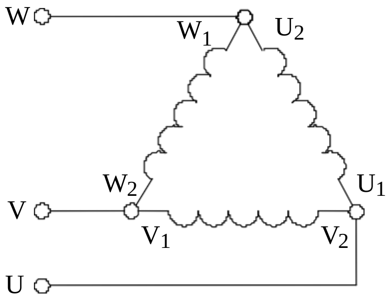

Figure 11

4. ROTATING MAGNETIC FIELD PRODUCED BY THREE PHASE CURRENTS

The rotating magnetic field of a three phase induction motor is produced by supplying current to three single phase windings on the stator. The three windings must be so arranged and connected that -

- there is a phase difference of 120 electrical degrees, irrespective of the number of poles
- the currents supplied to them must also differ by a phase angle of 120° between any two of the three.

Figure 12 shows a simplified diagram of the winding arrangements for a three phase induction motor.

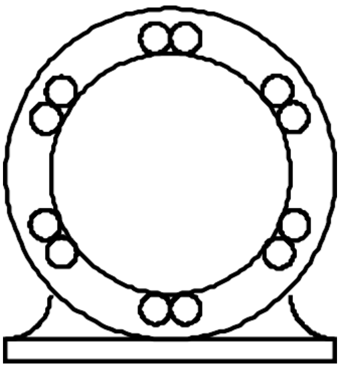

Figure 12

Figure 13 illustrates the phase relationship between the currents in a three phase system, in which the current in B phase lags the current in A phase by an angle of 120° and the current in C phase lags that in B phase by 120°.

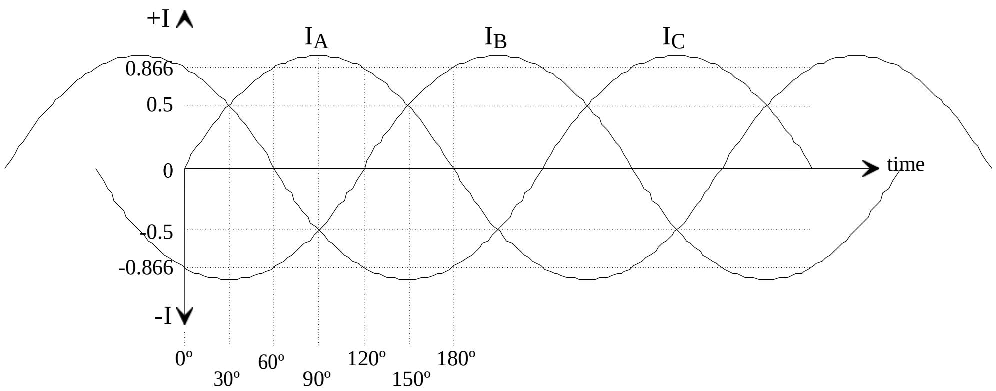

Figure 13

By application of the right hand conductor rule, the direction of the magnetic field developed by the stator can be determined. The following assumptions will apply -

- positive current flows into the start of a phase winding
- negative current flows into the finish of a phase winding.

A stator fitted with a two pole, three phase winding is shown in figure 14. The magnetic field produced by this stator will be considered at three phase angles, namely 0°, 30° and 60°. The directions of the phase currents are identified by the dots and crosses.

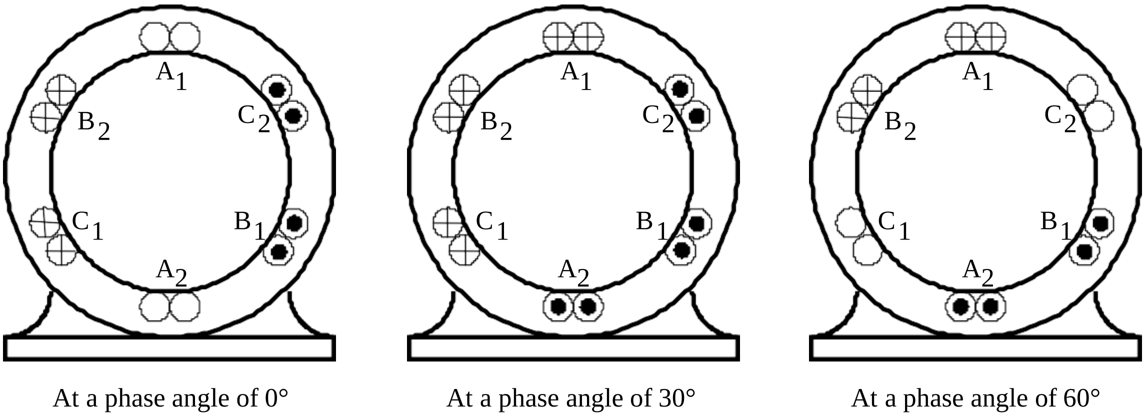

Figure 14

It should be observed that a phase change of 30 electrical degrees produces a corresponding rotation of the magnetic field. Also, if a closer inspection was carried out it would be found that the strength of the field -

- ____

  and
- is equal to__________times the maximum flux produced by one phase.

If the resultant flux was determined for further values of phase angles throughout the cycle, it would be found that in one cycle the magnetic field rotates through 360 electrical degrees.

5. SPEED OF ROTATING MAGNETIC FIELD

The speed of rotation of the rotating magnetic field is given a specific name, that is, the

- ______________________________________.

The speed of rotation of the rotating magnetic field depends on the -

- ____

  and the
- ____.

The speed of rotation of the rotating magnetic field is known as the synchronous speed and is given by -

where:

n_S = synchronous speed in rpm

f = supply frequency in hertz

P = number of stator poles

Example: 1

Determine the synchronous speed of a 2 pole stator which is supplied from a 50Hz supply.

Example: 2

A 4 pole induction motor is supplied from a 50Hz supply, determine the synchronous speed.

Example: 3

Determine the number of stator poles required for a three phase induction motor to operate with a synchronous speed of 1000 rpm when supplied from a 50Hz supply.

6. INDUCTION MOTOR ACTION

The effort required to rotate a shaft about its centre is called "____________________" or "________________________________".

In an induction motor, torque is developed by the interaction of the -

- rotating magnetic field established by the stator windings

  and the

- magnetic field set up by the rotor currents.

The development of torque in an induction motor can be explained by considering the interaction of the fluxes set up by the stator and rotor windings, as illustrated in figure 15. This diagram shows a section of the stator, air gap and rotor of a squirrel cage induction motor.

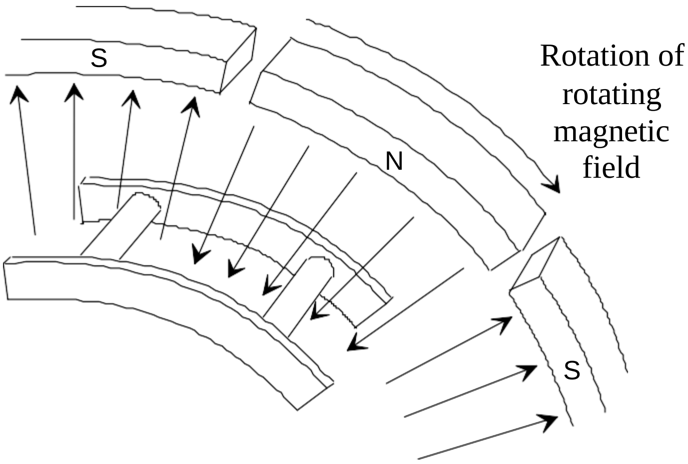

Figure 15

Due to the interaction of the stator and rotor magnetic fields, forces are exerted on the rotor conductors. As the rotor is mounted on bearings and free to rotate, a torque or turning effort is developed which causes the rotor to spin -

"__________________________________" direction as the rotating magnetic field.

To maintain an induced rotor field, the rotor must spin at a speed that is "______________________" than that of the rotating magnetic field.

This difference in speed is known as the "______________" of the motor

The previous operation may be summarised as follows. When the stator winding of a three phase motor is energised the following events occur -

- the stator sets up a rotating magnetic field that rotates at __________________ speed
- the rotating stator flux crosses the air gap and_____________an emf in the rotor conductors
- as a result of the induced rotor emf, rotor_________________________flows
- these high rotor currents establish a rotor _________________________
- rotor flux interacts with the stator flux which causes the rotor to _______________
- the rotating force exerted on the rotor is known as the________________of the motor
- the rotor will accelerate until it approaches_______________________speed.
- acceleration of the rotor______________when the induced rotor current is of sufficient value to develop the necessary load torque.

If the load torque increases, the rotor has to slow down to induce a greater rotor emf and hence a greater rotor current to accommodate the extra load.

The torque developed by the induction motor is proportional to the product of the -

- air gap flux

  and
- component of rotor current in phase with it.

7. LOAD VARIATION

If the torque required by the load increases -

- the rotor speed _______________________
- a____________________emf is induced in the rotor
- the rotor currents ______________________
- the forces exerted on the rotor conductors_______________________, that is, additional torque to accommodate the extra load
- the current taken by the stator____________________to provide the additional energy required to drive the additional load.

8. SLIP

To produce torque, there must be a rotor flux caused by current flowing in the rotor conductors. If the rotor could run at synchronous speed, there would be -

- no relative motion between the____________________and ____________________.

Consequently, there would be no -

- ______________________________
- ______________________________
- ______________________________
- ______________________________

and so the rotor would slow down. Therefore, an induction motor cannot run at synchronous speed.

With the rotor running just below synchronous speed, sufficient torque is developed to keep the rotor turning. The difference between the synchronous speed of the rotating field and the actual speed of the rotor is called the - "________________________".

Slip speed can be determined from the expression -

where: n_S = synchronous speed in rpm

n = rotor speed in rpm

n_{slip} = slip speed in rpm

Slip is generally expressed as a percentage of the synchronous speed and is known as the - "___________________________________".

Percentage slip can be calculated using the equation -

where: s% = percentage slip

ns = synchronous speed in rpm

n = rotor speed in rpm

Practical values of slip are -

- large motors, rated at or greater than 1,000kW, rarely exceeds 0.5%
- small motors, rated at 10kW or less, seldom exceeds 3%.

Example: 4

A 4 pole 50Hz induction motor operates with a rotor speed of 1440 rpm. Determine the -

a) synchronous speed

b) slip speed

c) percentage slip

Example: 5

An induction motor operates with a 2% slip. If the synchronous speed of the motor is 1500 rpm, determine the actual rotor speed.

9. TERMINAL BLOCK MARKINGS

The overall winding of the basic three phase induction motor consists of three individual windings, one per phase. These windings -

- are identical in every respect they -
  - are wound using the same size and type of winding wire
  - have the same number of turns.
- should be thought of as three individual, highly inductive, iron cored coils. See figure 16.

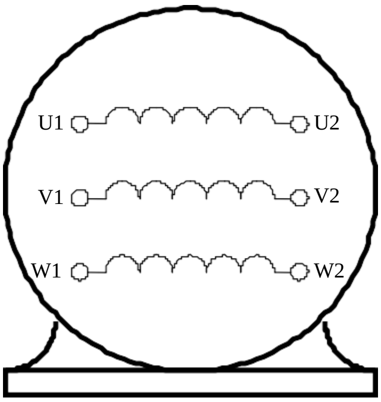

Figure 16

The international standard for labelling each phase winding is U, V and W -

- with the starts of the windings labelled U1, V1 and W1
- and the finishes U2, V2 and W2.

The purpose of marking the windings in this fashion is to assist in their correct connection.

The windings may be connected internally in either star or delta.

Motors that are internally connected in star or delta are fitted with a terminal block having three connection studs.

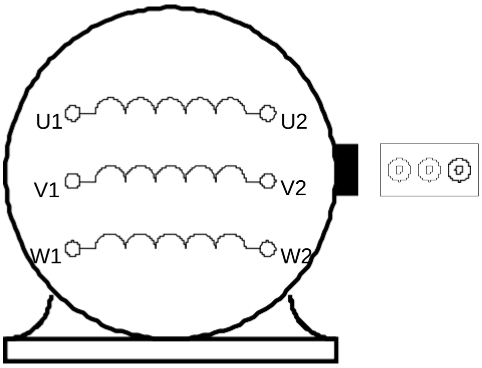

Figure 17

Many three phase motors the windings are not internally connected in either star or delta. Instead, a connection is taken from each end of the phase windings to an individual connection stud on the terminal block. As a result, the terminal block on a motor using this arrangement would be as shown in figure 18. The connection studs in the terminal box would be labelled as shown in figure 19.

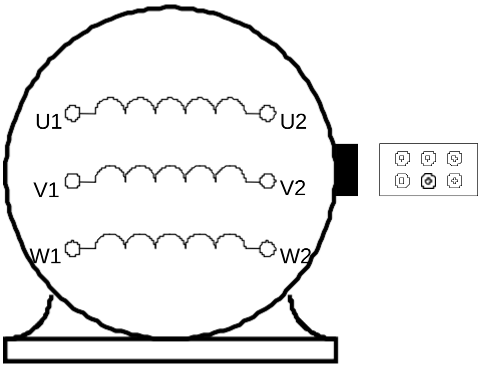

Figure 18

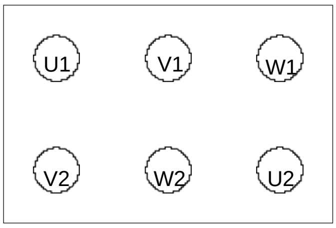

Figure 19

The provision of a terminal block fitted with six connection studs allows the motor to be -

- __________________ connected; or
- __________________ connected; or
- started via a___________________________starter.

Within the six stud terminal block, the terminals are arranged for easy connection in either star or delta by the connection of terminal block links. The type of connection, that is, star or delta can be identified by the placement of these links. Figure 20 shows the placement of links for a star connected motor and figure 21 the placement of links for a delta connected motor.

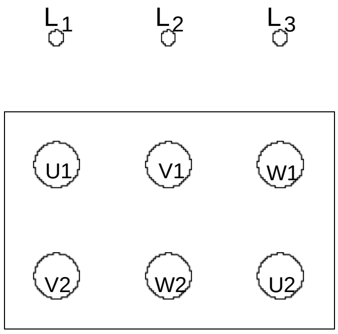

Figure 20

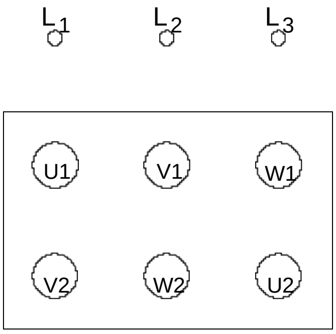

Figure 21

When a motor is started via a star-delta starter there will no links used in the terminal block. The reason being that six leads have to be connected from the motor to the starter to achieve the required operation. In this case the connections at the terminal block would be as shown in figure 22.

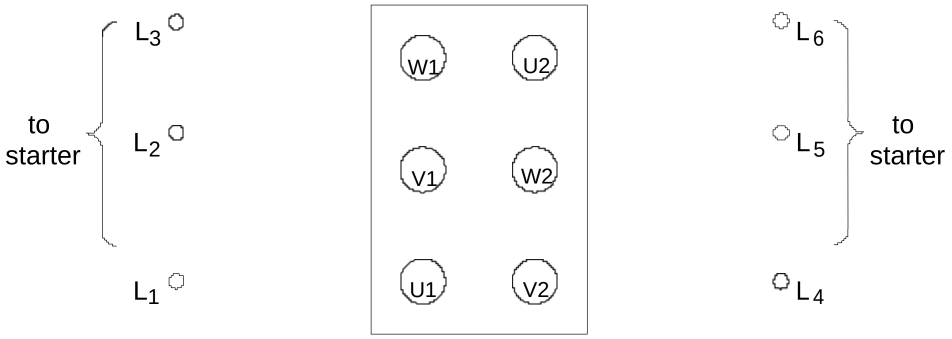

Figure 22

10. REVERSAL OF ROTATION

The direction of rotation of the rotating magnetic field depends upon the order in which the successive phase currents reach their maximum positive values, that is, the-

________________________________.

Since the rotor follows the rotating magnetic field set by the stator, the direction of rotation of the motor may be reversed by reversing the phase sequence of the supply to the motor. This is achieved by reversing any two incoming supply leads.

Figure 23 shows the connections to the terminal block of a squirrel cage motor. Figure 24 shows the connections required to reverse the direction of rotation of the motor.

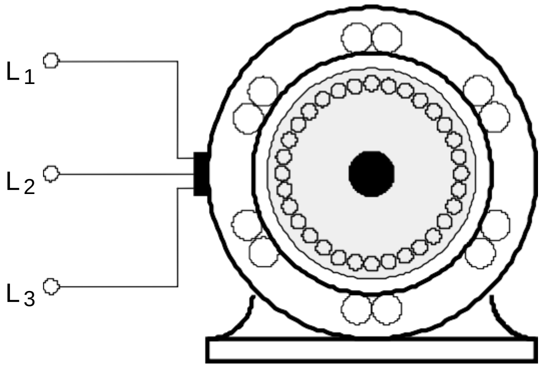

Figure 23

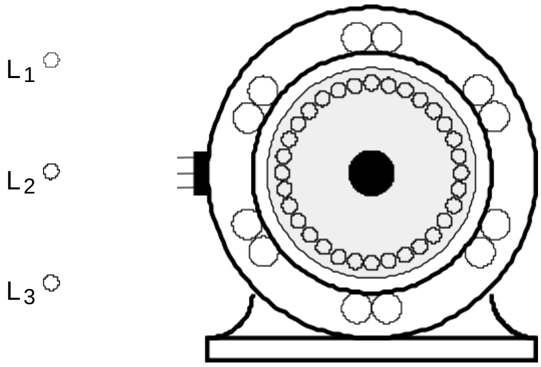

Figure 24

11. NAMEPLATE DETAILS

Motor nameplates provide information from which you can -

- determine wiring requirements
- obtain performance data
- obtain the information required to achieve appropriate motor replacement.

The type of information found on motor nameplates may include –

- ☐ manufacturer
- ☐ type of motor
- ☐ serial and model number
- ☐ frame size
- ☐ output rating
- ☐ full load current rating
- ☐ voltage rating
- ☐ frequency rating
- ☐ number of phases
- ☐ full load speed
- ☐ winding connection method
- ☐ duty
- ☐ ambient temperature

Figure 13 shows the layout of a typical induction motor nameplate.

Motor 3~ 50Hz		IEC 34-1
		No.
15kW	1440 rpm	
	Cl. F	cos ϕ = 0.85
415V	29A	Δ
Cat. No. 0410E	IP55	kg

Figure 13

NAME: **Practical 7**

SQUIRREL CAGE MOTOR CHARCTERISTICS

PURPOSE:

To investigate the operating characteristics of the squirrel cage induction motor.

TO ACHIEVE THE PURPOSE OF THIS SECTION:

At the end of this practical assignment the student will be able to determine by test and measurement the effect of increasing the load on an induction motor on:

- line current.
- rotor speed.
- motor slip.
- motor output power.

EQUIPMENT:

- 1 x 41.5/24V three-phase, 50Hz, AC supply
- 1 x 41.5V three-phase induction motor + double machine bed
- 1 x eddy current load
- 1 x variable DC power supply
- 1 x digital multimeter
- 1 x AC current clamp
- 1 x optical tachometer
- 4mm connection leads

– REMEMBER –
– WORK SAFELY AT ALL TIMES –
Observe correct isolation procedures

PROCEDURE

1. MOTOR OPERATION

1. Connect the motor in delta as shown in figure 1 with the dynamometer attached.

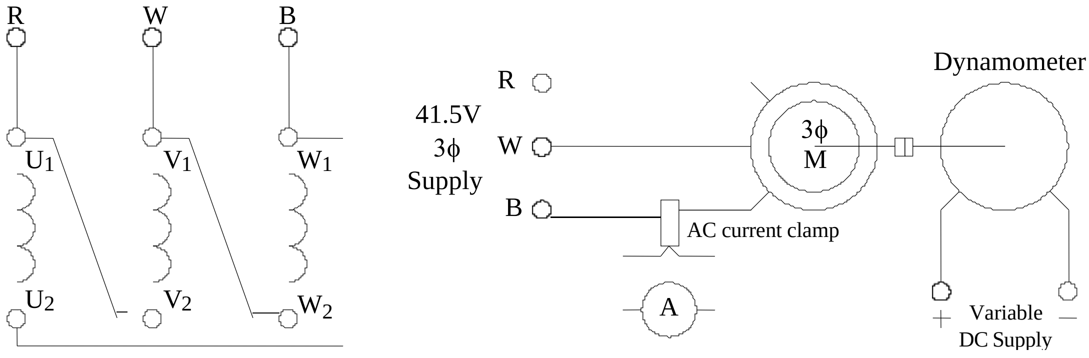

Figure 1

2. **<u>Do not proceed</u>** until the teacher checks your circuit and completes the progress table.

Progress Table 1

attempt 1	attempt 2	attempt 3
5	2	0

3. Switch on the supply and adjust the DC power supply to the dynamometer for a motor torque of 0.1Nm.

4. Using the optical tachometer measure the rotor speed. Also measure the line current. Record both values in table 1.

Table 1

Torque Nm	Rotor Speed rpm	Line Current amperes	Slip %	Power Output watts
0.1				
0.15				
0.2				
0.25				
0.3				
0.35				
0.4				
0.45				

5. Increase to DC supply to the dynamometer for a motor torque of 0.15Nm.

6. Measure motor speed and line current. Record in table 1.
7. Repeat the procedure for each of the torque values shown in table 1.
8. **<u>Do not proceed</u>** until the teacher checks your results and completes the progress table.

Progress Table 2

attempt 1	attempt 2	attempt 3
5	2	0

9. Switch off the supply, then disconnect the circuit.
10. Please return all equipment to its proper place, safely and carefully.
11. The nameplate details for the motor tested are shown in figure 2.

Motor 3~ 50Hz	IEC 34-1	
Poles 4	No. FF42	
50W	1420 rpm	
	Cl. F cos ϕ = 0.7	
41.5V	2A Δ	
Cat. No. 0410E	IP55	kg

Figure 2

2. OBSERVATIONS:

1. What is the effect of increased load on the line current taken by an induction motor?

2. If the load on an induction motor is increased, is the motor required to deliver more or less torque?

3. On the axes shown in figure 3 draw the speed-torque curve for the motor tested.

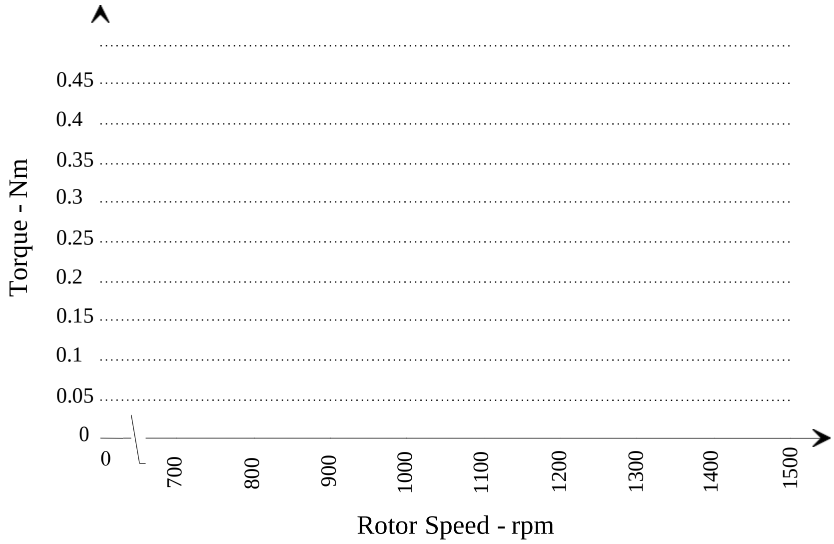

Figure 3

4. Based on your observations and the graph in figure 3, what effect does increased load have on the speed of an induction motor?

____

____

____

5. For each value of torque determine the percentage slip of the motor and record the values in the appropriate column of table 1. Show the complete calculation for the first value in the space below.

Use the equation $S\% = \frac{\gamma S - \gamma}{\gamma S} \text{ x } 100$

____

____

____

6. Based on your observations, what effect does increased load have on the slip of an induction motor?

____

____

____

7. For each value of torque determine the power output of the motor and record the values in the appropriate column of table 1. Show the complete calculation for the first value in the space below.

   Use the equation $P_{OUT} = \frac{2\pi nT}{60}$

   ____

   ____

   ____

8. On the axes shown in figure 4 draw the graph of power output versus torque for the motor tested.

   ____

   ____

   ____

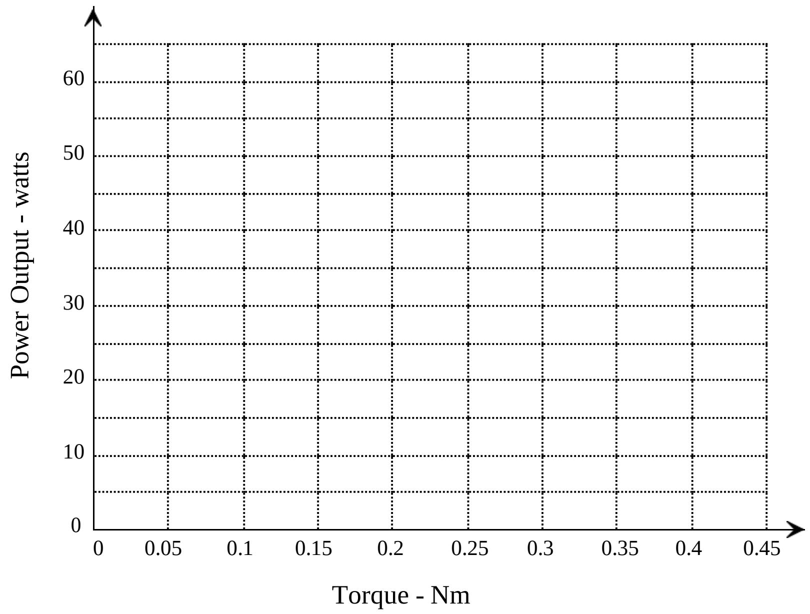

Figure 4

9. Based on your observations and the graph in figure 4, what effect does increased load have on the output power of an induction motor?

   ____

   ____

   ____

NOTES

****

SQUIRREL CAGE INDUCTION MOTORS

SECTION A

In the following statements one of the suggested answers is best. Place the identifying letter on your answer sheet.

1. The rotor current in a three phase induction motor is:-
   a) zero, since no supply is connected to the rotor circuit;
   b) supplied by the d.c. connected to the rotor terminals;
   c) supplied by the a.c. connected to the rotor terminals;
   d) induced by the stator field cutting the rotor conductors.

2. A three phase winding will produce an electromagnetic field which:-
   a) rotates at a constant speed;
   b) reverses direction each cycle;
   c) reverses direction each half cycle;
   d) is stationary and constant in strength.

3. Increasing the frequency of supply to a three phase stator winding will:-
   a) cause the magnetic field to rotate faster;
   b) cause the magnetic field to rotate slower;
   c) increase the strength of the magnetic field;
   d) increase the number of poles in the stator winding.

4. To reverse the direction of rotation of a rotating magnetic field you must:-
   a) reverse the connections to alternate pole windings;
   b) reverse the phase sequence of the supply;
   c) reverse the connections to the rotor winding;
   d) reverse the connections to all pole windings.

5. The rotor current in an induction motor is:-
   a) supplied from the separate rotor supply;
   b) induced by the rotating magnetic field;
   c) supplied from the stator supply terminals;
   d) always the same frequency as the stator supply.

6. The rotor speed of an induction motor is:-
   a) always slightly higher than the speed of the rotating magnetic field;
   b) always slightly lower than the speed of the rotating magnetic field;
   c) always the same as the speed of the rotating magnetic field;
   d) dependant only on the size of the load the motor is driving.

7. A six pole three phase motor on a 50 hertz supply will have a rated speed of about:-
   a) 2,800 r.p.m.;
   b) 1440 r.p.m.;
   c) 960 r.p.m.;
   d) 720 r.p.m.

8. The motor in question 7 will have a slip speed of:-
   a) 200 r.p.m.;
   b) 60 r.p.m.;
   c) 40 r.p.m.;
   d) 30 r.p.m.

9. When a three phase motor is running on no load and one supply conductor is open circuited:-
   a) the motor will stop and then start in the opposite direction;
   b) the motor will continue to run in the same direction;
   c) the motor will overload and burn out;
   d) the motor will stop due to loss of the RMF.

10. When a three phase motor is started with one supply conductor open circuited it will:-
    a) start and run normally;
    b) not start and may burn out;
    c) not start, but not burn out;
    d) start, but the direction of rotation will be random.

SECTION B

Blank spaces in the following statements represent omissions. Write the appropriate information on your answer sheet.

As load on an induction motor increases the speed of the motor will______(1)_____ and the slip speed of the motor will______(2)_____.

The speed of the rotating magnetic field in a three phase induction motor depends on the number of poles in the winding and the______(3)_____.

The strength of the rotating magnetic field in a three phase induction motor is equal to _____(4)_____times the______(5)_____flux produce in one of the phase windings.

The direction that a three phase induction motor rotates depends on the______(6)_____ of the supply currents.

When an induction motor is driving a load the speed of the motor cannot reach_____(7)_____.

If the windings in a three phase induction motor are connected in delta the current in the conductors supplying the motor would be______(8)_____the current in the motor windings.

The stator core of a three phase induction motor is laminated to reduce______(9)_____ loss and the laminations are made from silicon steel to reduce______(10)_____loss.

The stator winding of a three phase induction motor consists of______(11)_____ identical winding displaced by_____(12)_____degrees from each other.

The______(13)_____induction motor has a short circuited rotor winding.

To change the direction of a three phase induction motor the connections to any two of the______(14)_____must be changed.

Either the rotor slots or the stator slots are______(15)_____to reduce the noise from a three phase induction motor.

When running on no load the speed of a three phase induction motor is _____(16)_____synchronous speed.

SECTION C

1. A six pole three phase induction motor is connected to a 60Hz supply and runs at full load at 1050r.p.m. Determine:-

a) the synchronous speed of the motor; (1 200 r.p.m.)

b) the slip speed of the motor. (150 r.p.m.)

SECTION D

1. Figure 1 represents the stator windings of a three phase induction motor and it's terminal block:-
   a) Connect the windings to the terminal block using the international standard;
   b) Connect the terminals of the terminal block so that the motor windings are connected in delta;
   c) Connect the terminal block to the supply terminals.
   d) Connect the terminal block of Figure 2 to the supply terminals so that the direction of rotation of the motor in Figure 1 is reversed.

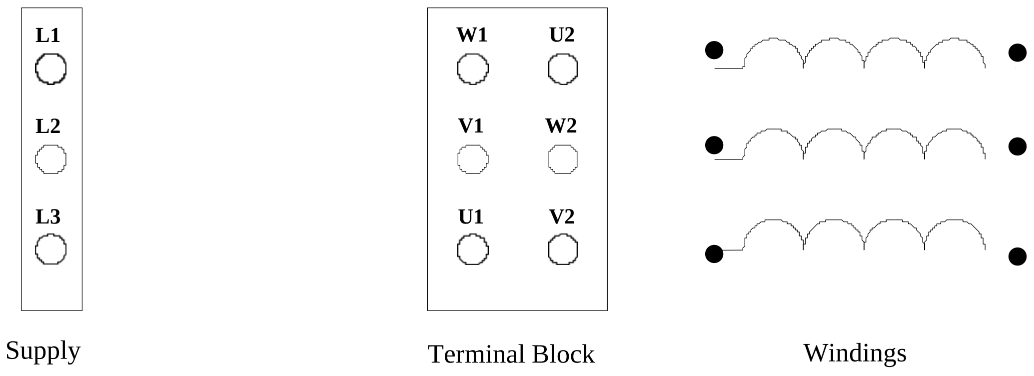

Figure 1.

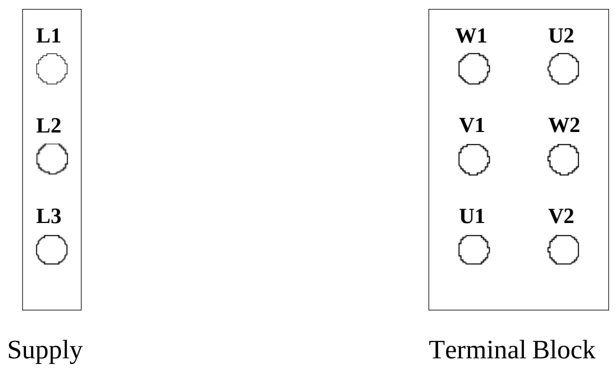

Figure 2.

Section 8

SLIP-RING INDUCTION MOTORS

PURPOSE:

This section introduces the behaviour and characteristics of three phase slip-ring induction motors. In addition, the torque-speed characteristics of the squirrel cage motor are considered.

TO ACHIEVE THE PURPOSE OF THIS SECTION:

At the end of this section the student will be able to:

- Identify the components parts of a slip-ring induction motor.
- Interpret information from the torque-slip curves of the slip-ring induction motor.
- Reverse the direction of rotation of a slip-ring induction motor.
- List the operating characteristics of slip-ring induction motors.
- List the advantages and disadvantages of both squirrel cage and slip-ring induction motors.
- Calculate the output power of induction motors given the shaft speed and torque.

REFERENCES:

- Hampson, J. & Hanssen, S. *Electrical Trade Principles*, 2nd Edition, Section 6
- Jenneson, J.R. *Electrical Principles for the Electrical Trade*, 5th Edition, Pages 223 - 232

1. SLIP-RING MOTOR CONSTRUCTION

The basic squirrel cage induction motor is a relatively constant speed motor.

Many industrial applications require three phase motors with variable speed control. Thus, another type of induction motor is required for variable speed applications. The slip-ring induction motor, also called the wound rotor induction motor, meets these needs.

An exploded view of the construction of the slip-ring motor is shown in figure 1.

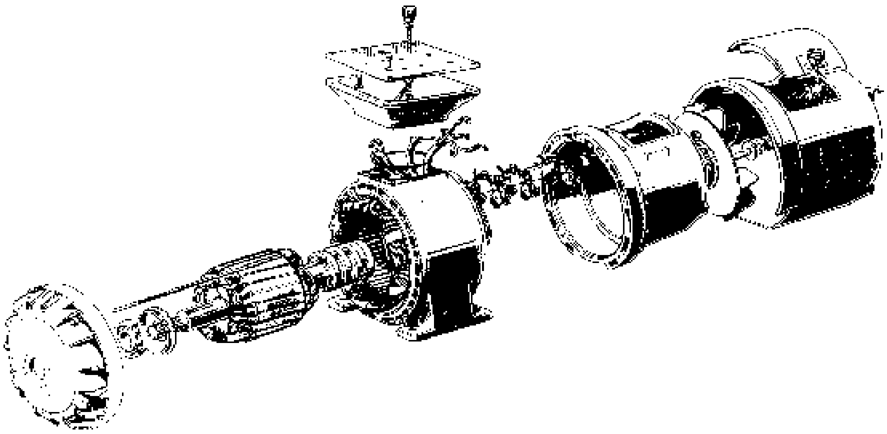

Figure 1

The slip-ring motor is arranged in the following way -

- Stator - the same stator construction and winding arrangement as the squirrel-cage induction motor.
- rotor - the cylindrical core of the rotor is made up of steel laminations
  - slots are cut into the cylindrical core to hold the formed coils for three single-phase windings
  - the windings are placed 120 electrical degrees apart
  - the insulated coils of the rotor winding are grouped to form the same number of poles as in the stator windings
  - the rotor windings are star connected
- slip-rings and brush gear - three leads from the rotor windings terminate at three slip rings mounted on the rotor shaft
  - carbon brushes ride on these slip rings and are held securely by adjustable springs mounted in the brush holders
  - the brush holders are fixed rigidly, since it is not necessary to vary their position
  - leads from the carbon brushes are connected to an external speed controller.

2. TERMINAL MARKINGS

The terminal markings used in conjunction with slip-ring motors are as follows -

- the stator leads are labelled U, V and W.

  This is the same marking system used with squirrel-cage induction motors.

- the rotor leads are marked K , L and M.

  Usually, the K lead connects to the rotor ring nearest the bearing housing. The L lead connects to the middle slip ring and the M lead connects to the slip ring nearest the rotor windings.

The circuit diagram of the slip-ring motor is shown in figure 2.

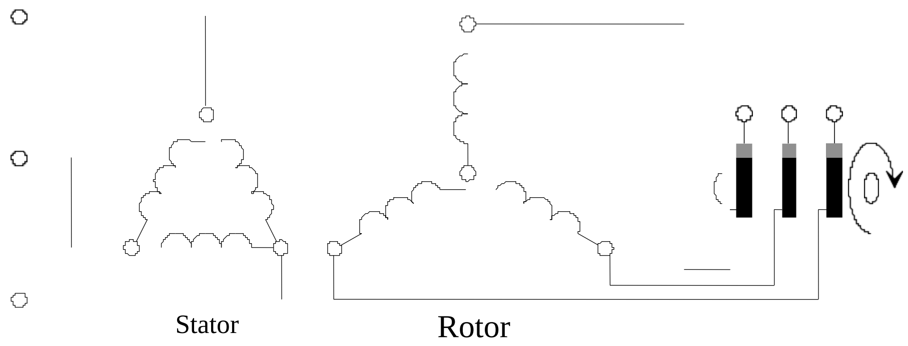

Figure 2

Because of the access to the rotor winding provided via the slip-rings and brushes, the operating characteristics of the motor may be changed by the insertion of resistance into each phase of the rotor circuit.

The Australian Standard drawing symbol for the slip-ring motor is shown in figure 3.

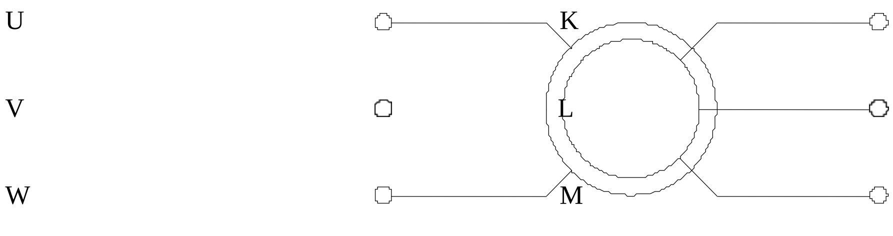

Figure 3

3. OPERATION

When the stator windings of a slip-ring motor are energised from a three-phase supply, the rotating magnetic field formed travels around the inside of the stator core, just as in a squirrel-cage induction motor. The speed of the rotating magnetic field depends upon the -

- number of stator poles

  and

- frequency of the supply.

The equation used to find the synchronous speed for squirrel-cage induction motors can also be used for this type of motor -

Having established the stator develops a rotating magnetic field, now consider the effect of this field on the rotor under three different operating conditions -

- slip-rings open circuit
- slip-rings short circuited
- resistance added to the rotor circuit via slip-rings and brushes.

Slip-rings Open Circuit:

The motor circuit is arranged as shown in figure 4.

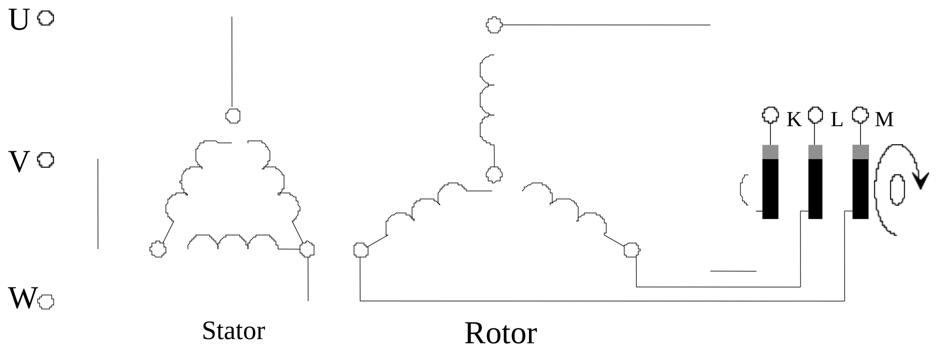

Figure 4

As the rotating field travels at the synchronous speed, it cuts the wound-rotor windings and -

- _______________ voltages in the rotor windings
- as the rotor winding is open circuit_____________rotor currents flow
- with no rotor current_____________torque is developed.

Therefore, with the slip-rings open circuit, the stator draws current from the supply but the motor does not________________________.

Slip-Rings Short Circuited:

The circuit diagram for the motor with the slip-rings short circuited is as shown in figure 5.

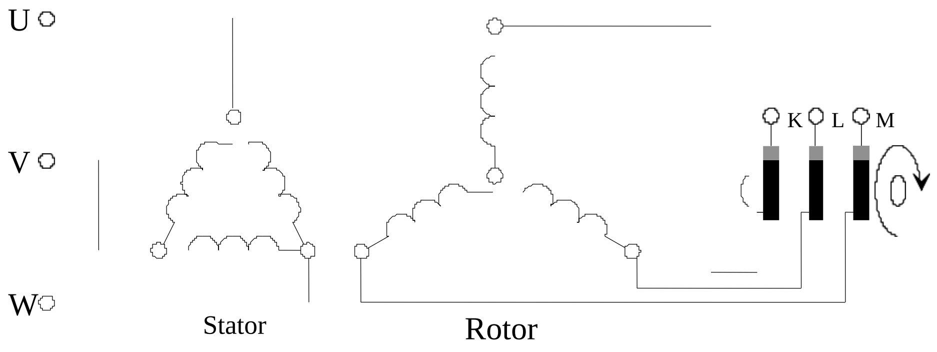

Figure 5

Under these operating conditions -

- the stator establishes a___________________magnetic field
- the rotating field______________voltages into the rotor windings
- induced rotor voltages cause rotor________________to flow
- the interaction between the rotating field and the rotor field results in the development of _________________
- the rotor______________and accelerates up to final operating speed.

With the slip-rings short circuited the motor operates exactly the same as the squirrel cage motor.

Added Rotor Resistance:

Resistance may be added to the rotor circuit via the slip-rings and brushes. It is normal practice to use three resistors, one per rotor phase. The three resistors are star connected and connected to the brushes as shown in figure 6.

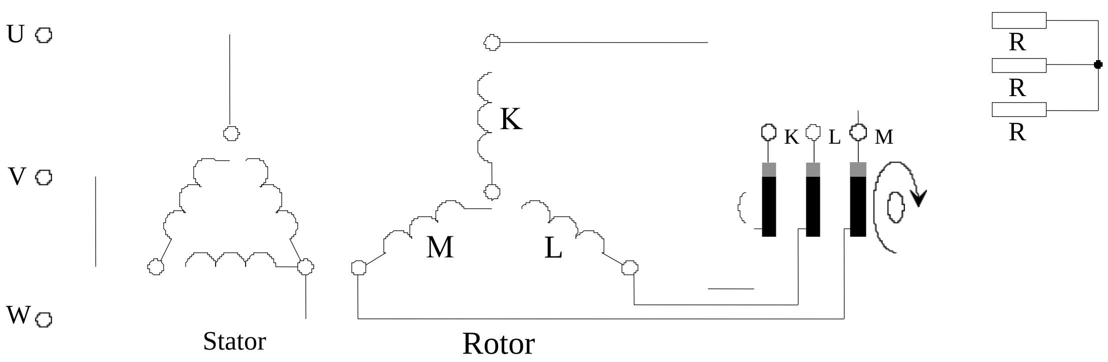

Figure 6

To examine the effect of the additional resistance, consider the motor is running at a particular speed and the resistance is then added -

- added resistance causes rotor current to ___________________
- for an instant decreased current causes a________________in torque
- reduced torque causes the rotor speed to __________________
- decreased rotor speed causes________________rotor emf
- increased rotor emf causes________________rotor current
- motor torque returns to the value required to drive the load but at ___________ speed.

Overall, the effect of added rotor resistance is to cause the motor to develop the required torque at a lower speed.

The greater the value of resistance added, the slower the rotor speed.

If variable resistors are added to the rotor circuit, as shown in figure 7, the speed of the motor may be controlled over a range from low speed to normal operating speed.

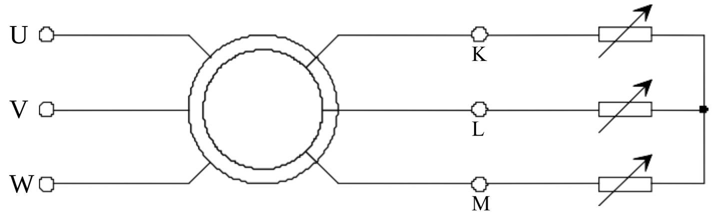

Figure 7

Slip-ring motors have the advantage that maximum torque can be made to occur at any speed by adding resistance to the rotor circuit to match the rotor reactance. The circuit used to achieve this operation is shown in figure 7.

4. MOTOR CURRENT

When power is first applied to a stationary motor, the stator windings act as the primary of a transformer and the rotor behaves as a shorted secondary winding. As a result of this action a high circulating current flows in the rotor and a high starting current is taken by the stator windings.

As the rotor accelerates in the direction of the rotating magnetic field -

- the difference between rotor speed and the rotating magnetic field _________________
- the generated rotor voltage _______________
- causing the rotor circulating currents to _______________
- which in turn________________stator current.

The typical relationship between the stator current and the rotor speed is shown in figure 8.

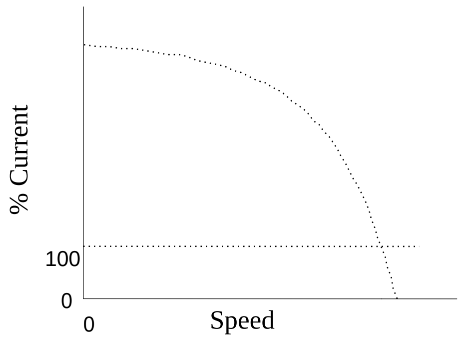

Figure 8

The initial circulating current in the rotor is affected by the -

- ______________________________________
- ______________________________________
- ______________________________________

That is, the rotor current is limited by the impedance of the rotor circuit.

5. TORQUE - SPEED CURVES

As discussed, the torque a motor develops depends upon its speed, but the relationship between the two cannot be expressed in the form of an equation. Consequently, the relationship is shown in the form of a curve, known as the "***torque-speed curve***".

Figure 9 shows the torque-speed curve of a conventional three phase induction motor.

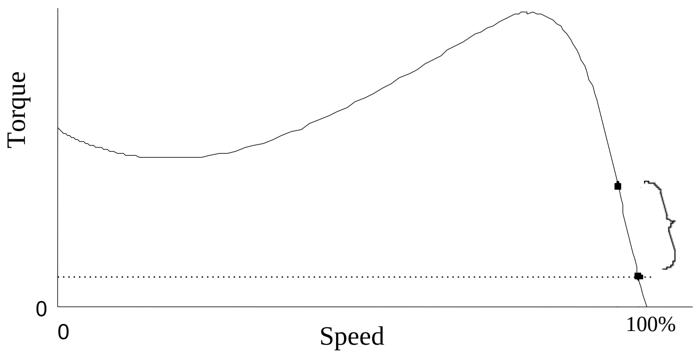

Figure 9

The torque - speed curve shown in figure 9 indicates that -

- for the motor to accelerate, the torque developed at starting must be greater than the standstill torque of the load.

- ***locked rotor torque*** or ***starting torque*** is developed at the instant of starting ($X_{LR} > R_R$)

Starting torque is typically =________________full load torque

- as the motor accelerates, rotor reactance decreases in value and approaches the value of rotor resistance.

- maximum torque will occur when rotor reactance is equal to rotor resistance ($X_{LR} = R_R$). The point on the curve where this occurs is known as the breakdown torque or the stalling torque. If the load exceeds this value the motor will stall.

Breakdown torque is typically =________________full load torque

- further acceleration decreases rotor reactance, causing torque to decrease ($X_{LR} < R_R$)

- the motor will accelerate to a speed that allows the motor to develop sufficient torque to meet the needs of the load.

SQUIRREL CAGE MOTOR CHARACTERISTICS

The performance characteristics of the squirrel cage motor are governed by -

- ____ and
- ____.

Standard squirrel cage induction motors are manufactured in three general types, designed to meet different operating characteristics. Although they are all considered to be constant speed motors, the speed regulation and starting torque of the several types are considerably different. The three types are -

- general purpose motor - curve 1;
  - normal starting torque
  - low starting current
  - normal slip.
- moderate starting torque - curve 2;
  - higher starting torque
  - lower starting current
  - slip slightly greater than type that of a general purpose motor
- high starting torque - curve 3;
  - highest starting torque
  - lowest starting current
  - highest slip.

Typical torque-speed performance curves for the three types of motor are shown in figure 10.

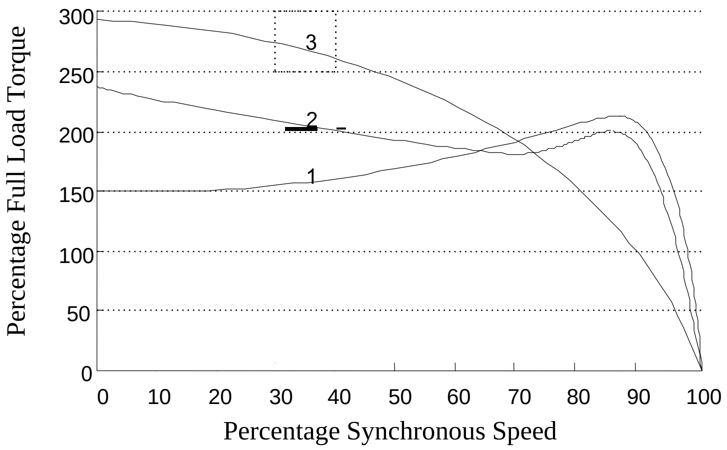

Figure 10

Table 1 details the characteristics of the three motors whose torque-speed curves are shown in figure 6.

Table 1

Curve	Starting Torque	Starting Current	Percentage Slip	Applications
1	Normal - approx. 1.5 x T_{FL}	Approx. 6 x I_{FL}	Normal - less that 5%	General purpose motor where load power requirements are not severe. For example, fans, blowers and machine tools.
2	High - approx. 2 to 2.5 x T_{FL}	Approx. 6 x I_{FL}	Increased - around 5%	Used where the motor is required to start at full load. Examples include, driving conveyors, reciprocating pumps and compressors.
3	High - approx. 3 x T_{FL}	Approx. 5 x I_{FL}	High - up to 10%	Flywheel mounted machinery such as presses and punches.

7. ROTOR RESISTANCE

It has already been shown that the maximum torque of an induction motor occurs when the rotor reactance is equal to the rotor resistance.

Since the resistance of the usual type of squirrel cage rotor is low, the maximum torque is obtained when the reactance is low, that is, when the slip and the frequency of the rotor currents are low.

This means that in order to have the rotor reactance equal its resistance at a higher slip, that is lower speed of rotation, the rotor resistance must be________________________.

The effect of increasing the resistance of the rotor circuit is to change the shape of the torque-speed curve. However, the magnitude of the breakdown torque is not affected, but it occurs at a higher slip, or lower rotor speed.

If the squirrel cage motor has a low resistance rotor, an increase of load causes only a small decrease in rotor speed. If a similar motor has a high resistance rotor, the same increase of load causes a much greater decrease in rotor speed.

The characteristics of the squirrel cage motor may be varied by changes to the rotor design -

- rotor resistance may be varied by changing the;
  - cross sectional area rotor conductors
  - rotor conductor material.
- rotor inductance may be varied by changing the;
  - depth of rotor bars in the iron core
  - shape of the rotor bars.

Figures 7, 8 and 9 illustrate variations of rotor design to achieve the operating characteristics of -

- general purpose motor - figure 11;
  - low resistance
  - low inductive reactance
- moderate starting torque motor - figure 12;
  - low resistance
  - high inductive reactance
- high starting torque motor - figure 13;
  - high resistance
  - low inductive reactance.

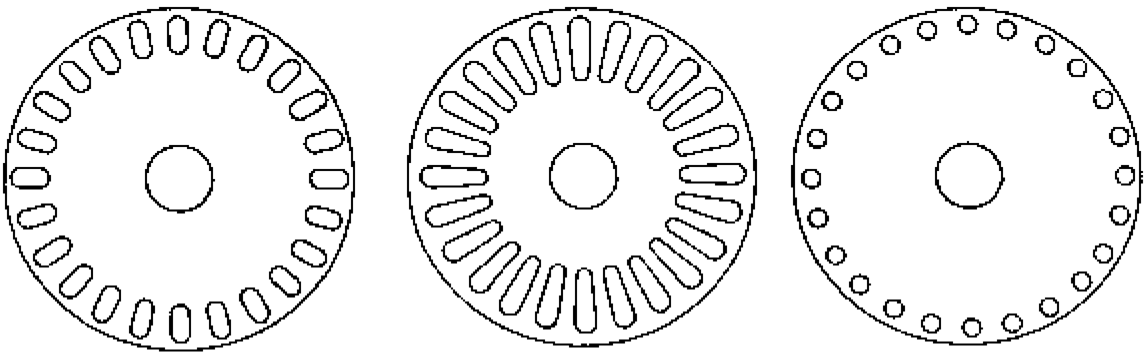

Figure 11 Figure 12 Figure 13

8. DUAL CAGE ROTORS

With the object of combining the features of -

- high efficiency
- small speed variation
- simple construction of the squirrel-cage motor with the high starting torque and low starting current of the slip-ring motor, the double-cage motor has been developed.

The dual cage rotor is fitted with two squirrel-cages in specially shaped slots as shown in figure 14.

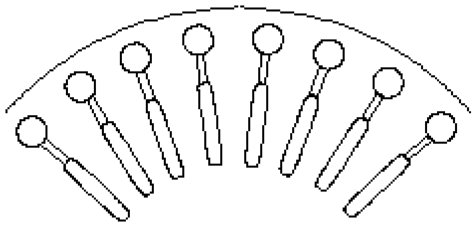

Figure 14

The conductors of the outer cage are of resistance material, but the conductors of the inner cage are of copper.

The reactance of the inner cage is much greater than that of the outer cage.

At the moment of starting -

- the rotor frequency is high
- the reactance (X_{LR}) of the inner cage is also high
- the greater current is in the outer cage which having a comparatively high resistance gives a high starting torque with a low starting current.

As the motor accelerates -

- the rotor frequency falls
- therefore the reactance's of both cages are reduced.

At normal operating speed -

- the rotor frequency is so low that the reactance's of both cages are negligible and the division of current is nearly inversely as their resistances. Thus, nearly all the rotor current is now in the low resistance inner cage, giving the motor the running characteristics of a low-resistance squirrel-cage motor.

The torque-speed characteristic for an induction motor fitted with a double cage rotor is shown in figure 15.

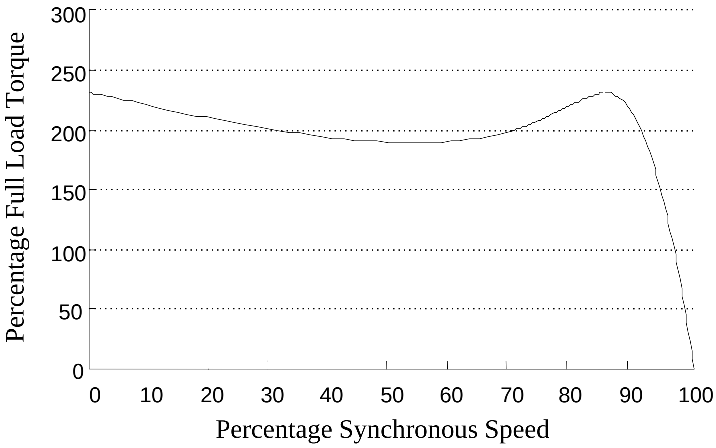

Figure 15

9. OUTPUT POWER

The output power delivered by an induction motor to a load depends on the -

- ___________________________________
- ___________________________________.

The effort required to rotate a shaft, flywheel, armature or any other device about its centre is called the torque or turning moment.

If a force (F) be applied to the shaft of a machine at some distance (r) from the centre as shown in figure 16, the tendency to turn the shaft is given by the product of the force (F) and the radius (r).

____

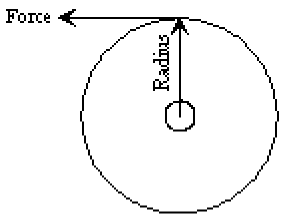

Figure 16

In the case of a motor the torque developed within it causes the motor shaft to rotate.

In an induction motor this torque is developed by the reaction of the rotor currents with the rotating magnetic field of the stator.

Consider a force of 'F' newtons acting tangentially on a rotor at a distance of 'r' metres from the centre of its shaft, as in figure 12.

The distance moved by the force in one revolution is the circumference of the rotor, that is -

Distance $= 2 \times \pi \times r$ metres

Work done per revolution = force x distance.

Work done per revolution $= F \times 2 \times \pi \times r$ as $T = F \times r$

$= 2 \times \pi \times T$

If the force is maintained throughout 'n' revolutions per minute, the work done per minute is given by -

Work done per revolution per minute $= 2 \times \pi \times n \times T$

Since the mechanical unit of power, the watt, is the rate of doing work, the power developed by the motor is -

where: P_{OUT} = motor output power in watts

n = motor speed in rpm

T = torque developed by motor in Newton metres

Example: 1

A three phase induction motor operates with a rotor speed of 1440 rpm and develops a torque of 66.32Nm at full load. Determine the full load power output.

Example: 2

A 3.75kW induction motor operates with a full load speed of 1465 rpm. Determine the torque developed by the motor.

In the slip-ring motor rotor circuit resistance is varied via the rotor rheostat to achieve a torque-speed characteristic which suits the requirements and nature of the load.

The torque-speed curves shown in figure 17 illustrate the variations that can be achieved with the slip-ring motor by variation of the rotor resistance.

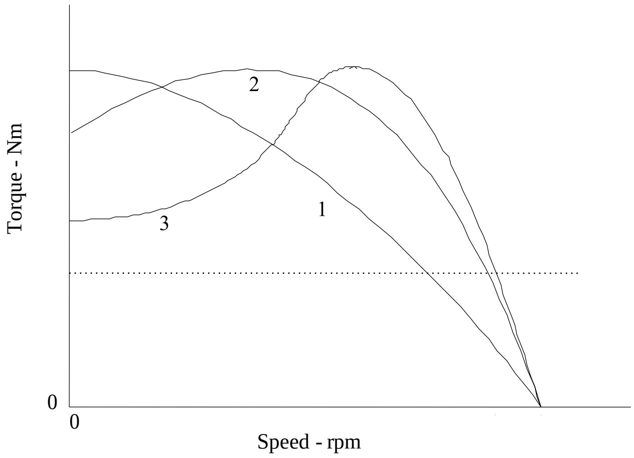

Figure 17

Curve 1 - rotor resistance equals rotor standstill reactance, develops_______starting torque.

Curve 2 - rotor resistance is lower than standstill reactance

Curve 3 - no added rotor resistance, operation is the same as the squirrel cage motor

Curve 4 - the starting characteristic that is achieved by varying the external resistance as the motor accelerates, maximum torque is developed throughout acceleration.

Since maximum torque can be maintained throughout the accelerating period, the slip-ring motor is used where high starting torque and a range of speed control is required.

Typical applications for this motor include -

- cranes
- large compressors
- elevators
- guillotines
- rock crushers
- pumps and presses.

This type of motor is also used in applications requiring adjustable speed.

10. REVERSAL OF ROTATION

The direction of rotation of a wound-rotor induction motor can be reversed. To do this, interchange the connections of any two of the three line leads feeding the stator windings.

Figure 18 shows the connection changes that are required to reverse the direction of rotation. **Note**, there is no reversal in the direction of rotation of the motor when any of the leads feeding from the slip-rings to the speed controller are interchanged.

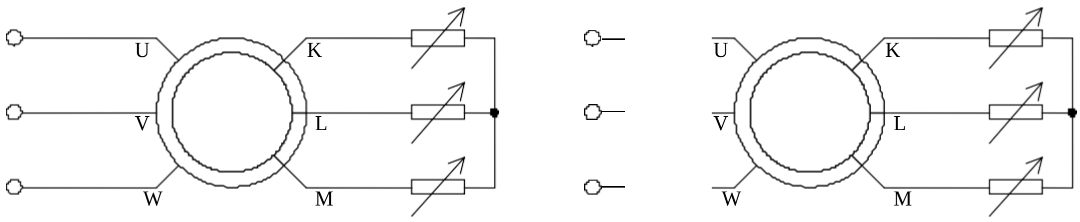

Figure 18

11. COMPARISON OF SQUIRREL CAGE AND SLIP RING MOTORS

Table 2 highlights the advantages and disadvantages of the squirrel cage and slip ring induction motors.

Table 2

Motor	Advantages	Disadvantages
Squirrel cage motor	• Simplicity and ruggedness of construction. • No sliding electrical contacts, hence no sparking and possible use in explosive atmospheres. • Wide range of speed control when used with electronic variable speed drives.	• Relatively poor starting torque. • Large starting current. • Fixed characteristics.
Slip-ring motor	• High Starting torque. • Relatively low starting current. • Smooth speed control over a wide range.	• High production cost compared to the squirrel cage motor. • Brushes and brush gear must be used causing the possibility of sparking and increased maintenance. • Inefficient speed control.

SLIP-RING INDUCTION MOTORS

PURPOSE:

To investigate the operation of the slip-ring induction motor.

TO ACHIEVE THE PURPOSE OF THIS SECTION:

At the end of this practical assignment the student will be able to :

- describe the effect of operating the slip-ring motor with the slip-rings open circuit.
- determine by test and measurement the effect on speed and line current of increasing the load on the slip-ring induction motor.
- state the effects on speed and line current of adding resistance to the rotor circuit of the slip-ring induction motor.

EQUIPMENT:

- 1 x 41.5/24V three-phase, 50Hz, AC supply
- 1 x 41.5V three-phase slip-ring induction motor + double machine bed
- 1 x inertia wheel
- 2 x digital multimeter
- 1 x AC current clamp
- 1 x optical tachometer
- 4 x sets of three 10 watt resistors - 1Ω, 2.2Ω, 4.7Ω and 6.8Ω
- 4mm connection leads

<u>NOTE</u>:

This practical segment is to be completed by students on an individual basis.

The time given per student is to be no longer than 40 minutes at the bench.

– REMEMBER –
– WORK SAFELY AT ALL TIMES –
Observe correct isolation procedures

PROCEDURE:

1. SLIP-RINGS OPEN CIRCUIT

1. Connect the motor in delta as shown in figure 1, with the slip-rings open circuit.

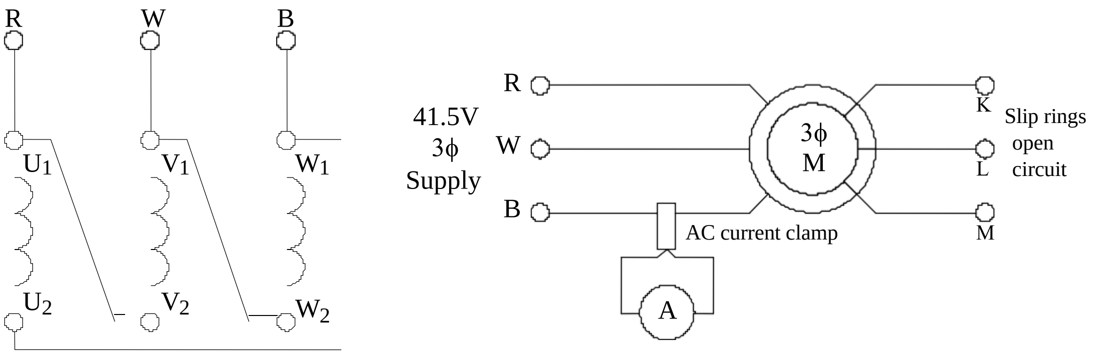

Figure 1

2. Switch on the supply and note any effects associated with the motor

The motor - ____

____

Does the motor run? ____________________

3. Using the AC current clamp measure the stator line current and record in table 1.

Table 1

Stator Line Current amperes	Stator Line Voltage volts	Rotor Line Voltage volts

4. Using a digital multimeter measure the stator line voltage and then the rotor line voltage. Record both values in table 1.

5. **Do not proceed** until the teacher checks your results and completes the progress table.

Progress Table 1

attempt 1	attempt 2	attempt 3
5	2	0

2. SLIP-RINGS SHORT CIRCUITED

1. Connect the motor as shown in figure 2, with the slip-rings short circuited.

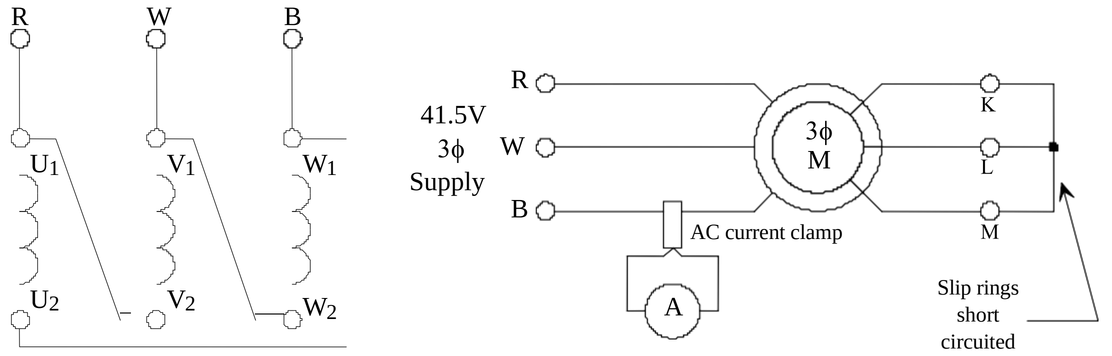

Figure 2

2. Switch on the supply and run the motor on no load and record in table 2 the line current taken by the motor and the speed of rotation of the motor.

Table 2

	Line Current amperes	Speed rpm
No Load		
Inertia Wheel		
Brake Band		

3. Switch off the motor and attach the inertia wheel.
4. Switch on the supply, run the motor, measure and record the motor line current and speed.
5. Switch off the motor and attach the brake band to the inertia wheel.
6. Switch on the supply, run the motor, measure and record the motor line current and speed.
7. **Do not proceed** until the teacher checks your results and completes the progress table.

Progress Table 2

attempt 1	attempt 2	attempt 3
5	2	0

3. ADDED ROTOR RESISTANCE

1. Connect the circuit as shown in figure 3, with a 1Ω, 10W resistor added to each phase of the rotor.

   Note: the motor is to be coupled to the inertia wheel.

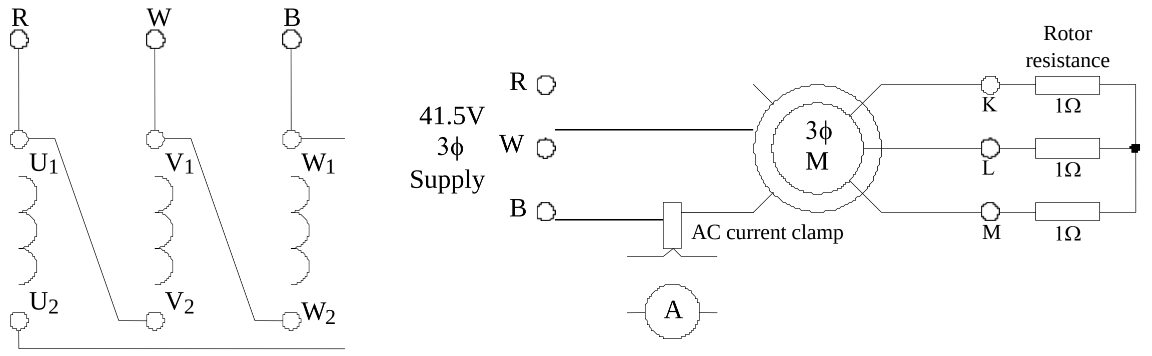

Figure 3

2. Switch on the supply, then measure the stator current and the rotor speed. Record the values in table 3.

Table 3

Added Rotor Resistance ohms	Stator Line Current amperes	Rotor Speed rpm
1Ω		
2.2Ω		
4.7Ω		
6.8Ω		

3. Replace the three 1Ω rotor resistors with three 2.2Ω resistors and repeat the procedure.
4. Repeat the procedure using rotor resistors of 4.7Ω and then 6.8Ω.
5. <u>**Do not proceed**</u> until the teacher checks your results and completes the progress table.

Progress Table 3

attempt 1	attempt 2	attempt 3
5	2	0

6. Switch off the supply, then disconnect the circuit.
7. Please return all equipment to its proper place, safely and carefully.

4. OBSERVATIONS:

1. Will a slip-ring induction motor operate with the slip-rings open circuit? If not, why not?

2. Why is rotor voltage present in the slip-ring motor when the slip-rings are open circuit?

3. Determine the phase turns ratio for the motor tested.

4. How does the operation of the slip-ring motor, with slip-rings short circuited, compare to that of the squirrel cage motor?

5. Based on your observations, what effect does increased load have on the slip of a slip-ring induction motor?

6. What effect does added rotor resistance have on the operating speed of the slip-ring induction motor?

7. If the resistance added to the rotor of a slip-ring induction motor is increased, what is the effect on stator current?

NOTES

****

SLIP-RING INDUCTION MOTORS

SECTION A

In the following statements one of the suggested answers is best. Place the identifying letter on your answer sheet.

1. An advantage of wound rotor induction motors is:-
   a) high starting current and torque;
   b) low starting torque with low current;
   c) low starting current and high starting torque;
   d) high starting current and low starting torque.

2. The rotor and stator windings of a slip ring induction motor must have the same:-
   a) number of phases;
   b) number of poles;
   c) number of poles and phases;
   d) connection method (star or delta).

3. The rotor windings of a slip ring induction motor are connected to an external:-
   a) source of a.c. supply;
   b) source of d.c. supply;
   c) variable resistance;
   d) star delta starter.

4. The rotor and stator windings of a slip ring induction motor are normally connected:-
   a) rotor in star and stator in delta;
   b) rotor in delta and stator in delta;
   c) rotor in star and stator in star;
   d) rotor in delta and stator in star.

5. The rotor current in a slip ring induction motor:-
   a) is constant at all loads;
   b) increases as load increases;
   c) decreases as load increases;
   d) varies independent of load.

6. Resistance is added to the rotor circuit of a slip induction motor to:-
    a) increase torque at lower speeds;
    b) reduce current during starting;
    c) reduce the speed of the motor;
    d) all of the above.
7. An eight pole, 50 hertz slip ring induction motor running at 720r.p.m. with the slip rings short circuited has a slip percent of:-
    a) 60%;
    b) 15%;
    c) 6%;
    d) 4%.
8. The motor in question 7 will have a slip speed of:-
    a) 780 r.p.m.;
    b) 280 r.p.m.;
    c) 60 r.p.m.;
    d) 30 r.p.m.
9. A squirrel cage induction motor with a high resistance rotor, compared to one with a lower resistance, would have:-
    a) a lower full load slip and greater starting torque;
    b) a higher full load slip and greater starting torque;
    c) a lower full load slip and smaller starting torque;
    d) a higher full load slip and smaller starting torque.
10. In a squirrel cage induction motor with dual cage rotor:-
    a) the inner cage has the higher resistance and carries the greater current at starting;
    b) the outer cage has the higher resistance and carries the greater current at starting;
    c) the inner cage has the higher resistance and carries the least current at starting;
    d) the outer cage has the higher resistance and carries the least current at starting.

SECTION B

Blank spaces in the following statements represent omissions. Write the appropriate information on your answer sheet.

The emf induced in the rotor winding of a slip ring induction motor is a maximum at _____(1)_____.

Adding resistance to the rotor circuit of the slip ring induction motor at starting _____(2)_____the starting current taken by the motor and_______(3)_____the available starting torque.

If two of the three leads connecting the slip rings of the slip ring induction motor to it's starting resistors are reversed the direction of rotation of the motor will be _____(4)_____.

The unit of torque is the______(5)_____.

The direction that a three phase induction motor rotates depends on the______(6)_____ of the supply currents.

When the torque required by the load on an induction motor is increased the speed of the motor______(7)_____, the slip speed______(8)_____the voltage induced in the rotor conductors______(9)_____, which causes the current in the rotor conductors to _____(10)_____. This causes the strength of the rotor magnetic field to _____(11)_____, which causes the motor output torque to_______(12)_____to meet the increased load demand on the motor.

The______(13)_____induction motor has a wound rotor winding which is always _____(14)_____connected to allow the connection of_______(15)_____during starting to______(16)_____starting current and_______(17)_____starting torque.

SECTION C

1. A 4 pole three phase induction motor is connected to a 50Hz supply and runs at a full load slip of 4%. If the motor is delivering 33.16 newton metres of torque to the load at this speed with an efficiency of 83.3 percent and a power factor of 0.86 determine:-
   a) the synchronous speed of the motor; (1 500 r.p.m.)
   b) the slip speed of the motor; (60 r.p.m.)
   c) the rotor speed of the motor; (1440 r.p.m.)
   d) the output power of the motor; (5kW)
   e) the input power of the motor; (6kW)
   f) the line current from the 415 volt supply. (9.71A)

SECTION D

1. Figure 1 represents the incomplete circuit diagram of a three phase slip ring induction motor and it's supply:-
   a) Connect the stator windings in delta;
   b) Connect the rotor windings in star;
   c) Complete the required connections, including the supply and starting resistors, for the motor to start and run.

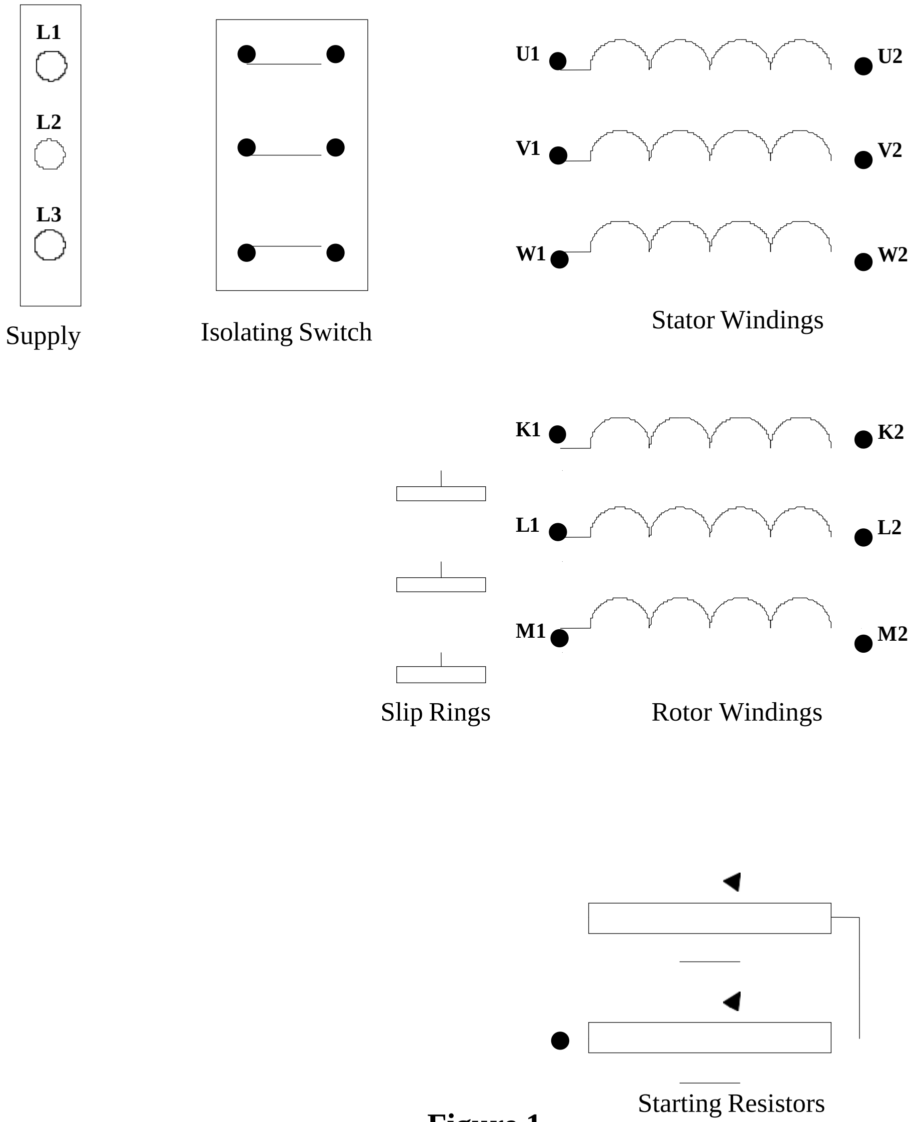

Figure 1.

Section 9

INDUCTION MOTOR LOAD CHARACTERISTICS

PURPOSE:

To examine the load characteristics of the three phase induction motor and the effect of supply voltage variation on torque developed.

TO ACHIEVE THE PURPOSE OF THIS SECTION:

At the end of this section the student will be able to:

- Interpret information from the load characteristic curves of an induction motor.
- Describe the flow of power through the induction motor.
- Calculate the percentage efficiency of an induction motor.
- State the losses associated with an induction motor.
- State the components of induction motor stator current.
- State the effects that a change of load has on the following quantities associated with an induction motor -
  - speed
  - rotor and stator current
  - power input and output
  - power factor
  - efficiency.
- Calculate the torque of an induction motor given the motor operating voltage, rated voltage and rated torque.

REFERENCES:

Electrical Trade Principles 2nd Edition J Hampson & S Hanssen. Section 6

Electrical Principles for the Electrical Trades. 5th Edition. Jenneson J.R.

Pages 229-231.

1. POWER FLOW & LOSSES

Voltages, currents, and phasor diagrams enable us to understand the detailed behaviour of an induction motor.

However, it is easier to see how electrical energy is converted into mechanical energy by following the active power as it flows through the machine.

Thus, referring to figure 1 -

- active power flows from the line into the three-phase stator:
  - owing to the stator resistance, a portion is dissipated as heat in the windings, called copper losses
  - another portion is dissipated as heat in the stator core, owing to the iron losses - that is, hysteresis and eddy current losses.

- the remaining active power is carried across the air gap and transferred to the rotor by electromagnetic induction:
  - due to the rotor resistance causing copper losses in the rotor, a third portion is dissipated as heat
  - due to hysteresis and eddy current loss in the rotor, called rotor iron losses, another portion is dissipated as heat.

- mechanical power is transferred from the rotor to the shaft:
  - a small fifth portion is lost due to windage and bearing-friction losses

- the remaining mechanical power available is available at the shaft to drive the load.

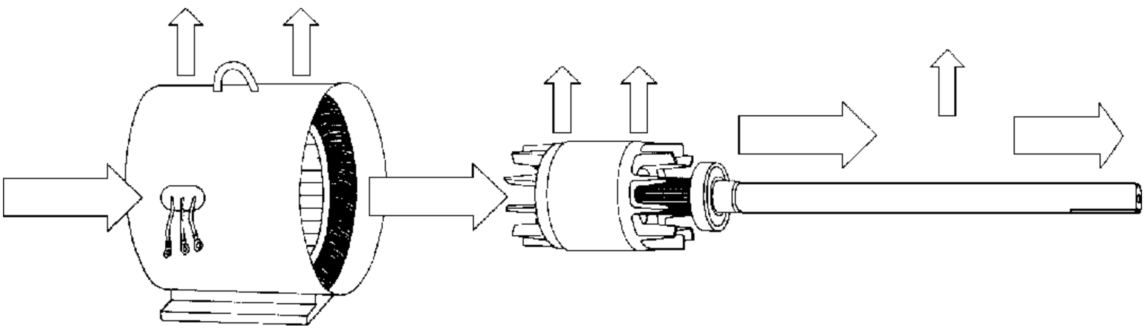

Figure 1

The power flow diagram of figure 1 enables the identification and determination of important properties and characteristics of the induction motor.

2. MOTOR RATING AND EFFICIENCY

Motors convert electrical energy to mechanical energy, as a result motors are always rated in terms of the_____________________________power.

The flow of power through a three phase induction motor is shown in figure 2.

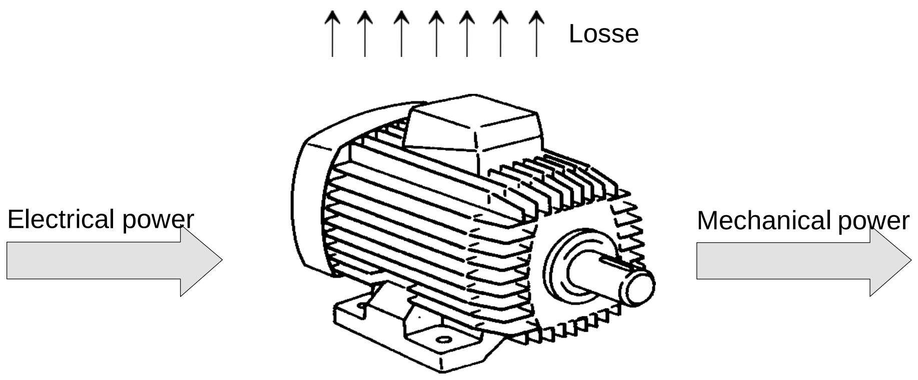

Figure 2

The power input to the three phase motor is determined using -

where: V_L = motor line voltage

I_L = motor line current

λ = motor power factor

The output power from the motor is determined using -

where: n = rotor speed in rpm

T = motor torque in Nm

Motor efficiency varies with changes in load conditions and can be determined by taking the ratio of the output power to the input power -

where: P_{OUT} = motor output power in watts

P_{IN} = motor input power in watts

Note: output power is always less than the input power due to the losses that occur in the energy conversion process.

Example: 1

Calculate the full load efficiency of a three phase induction motor given -

rating = 10kW voltage = 415V

λ = 0.8 lag I_{FL} = 20A

Example: 2

Calculate the power output and full load line current of a three phase induction motor, given the following -

efficiency = 85% voltage = 415V torque = 65Nm

speed = 1440rpm λ = 0.85 lag

3. EFFECT OF ROTOR CURRENT ON STATOR CURRENT

When operating on no-load, an induction motor produces just enough rotor current to provide the torque for overcoming bearing and windage friction.

An increase of load -

- retards the rotor, that is, increases the slip
- thus causing an increase in rotor emf as the rotor conductors are overtaken more rapidly by the stator flux
- consequently, a greater rotor current is provided to meet the demand for greater torque.

The currents in the rotor of an induction motor exert a magnetomotive force which would affect the field strength, if the stator or primary currents retained their original values. But, just as in a transformer, any change in the rotor or secondary current is balanced by an opposite change in the stator or primary current.

The reason for this is the same as for the corresponding action in a transformer, namely, that the field strength is practically proportional to the applied emf, and so is constant, if the applied emf is kept constant.

As in a transformer the stator or primary current of an induction motor is built up of three components -

- magnetising current
- iron-loss current
- current to balance the rotor or secondary mmf

4. OPERATION - NO-LOAD

When operating on no-load, the energy taken by the motor is that required to -

- establish the rotating magnetic field
- overcome the motor losses.

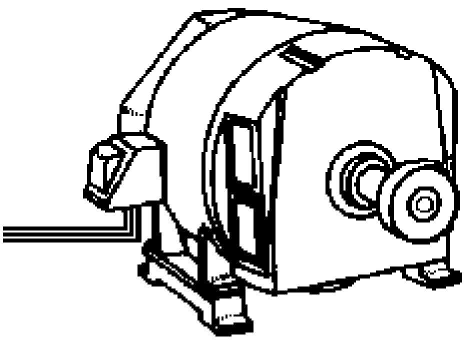

Figure 3

As a result, the stator draws a current that is made up of two components -

- magnetising current, Iμ, which -
  - lags the applied voltage by 90º
  - is typically 25 to 33% of the normal full load current.
- iron-loss current, Iη, which -
  - in phase with the applied voltage
  - is typically 10 to 15% of the normal full load current.

Effectively the stator current on no-load is equal to the phasor sum of these two components of current.

Figure 4 shows the phasor diagram for the induction motor under no-load conditions.

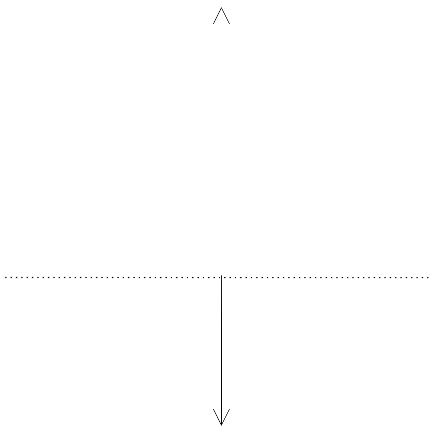

Figure 4

From the phasor diagram it can be seen -

- the power factor is very low in an induction motor on no-load
- the no-load current I_O lags behind the applied voltage V by the angle ϕ_O, the cosine of which is the power factor at the motor terminals
- also, the magnetising current Iμ constitutes the greater portion of the no-load current I_O.

On no-load the power factor may be as low as 0.2, which means that only 20 per cent of the current supplied to the motor will be doing useful work in maintaining rotation against bearing and air friction.

5. OPERATION - WITH LOAD

When operating on load, the energy taken by the motor is that required to -

- establish the rotating magnetic field
- overcome the motor losses
- drive the load.

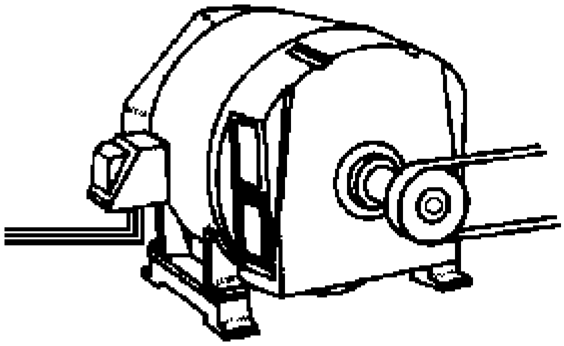

Figure 5

On load, the stator draws a current that is made up of three components -

- magnetising current, Iμ
- iron-loss current, Iη
- load component of primary current.

Effectively the stator current on load is equal to the phasor sum of the three components of current.

Figures 6 and 7 show the phasor diagrams for the induction motor under load conditions. Figure 6 half load and figure 7 full load.

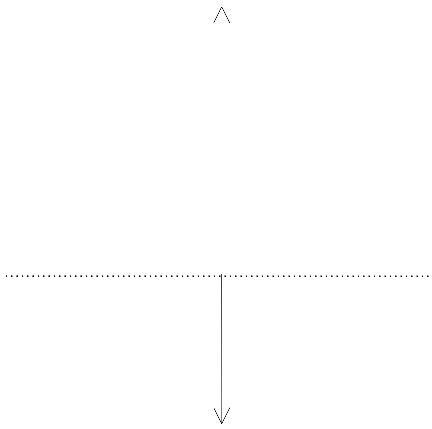

Figure 6

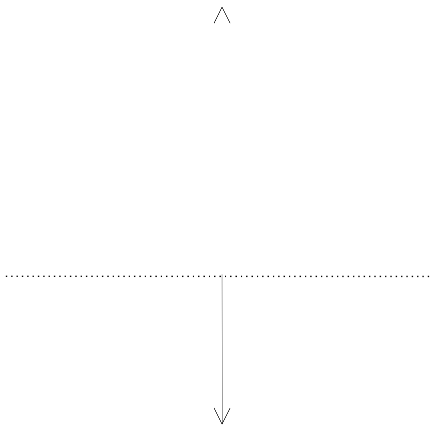

Figure 7

From figures 6 and 7 it should be seen -

- the power factor of an induction motor is much higher on load than on no-load.
  Because as the load is increased, the magnetising current remains practically constant, while the power or load component of the stator current increases on account of the increased load
- the power factor may be as high as 0.95 and depends upon different factors, such as size of motor, number of poles, etc.
- how an improvement in power factor takes place with increase in load.

Note:

The operation of induction motors at less than full load is one of the chief causes of low power factor in distribution systems.

The following table shows representative efficiencies and power factors for moderate voltage, three-phase, 50-cycle squirrel-cage induction motors, at full load.

Table 1

Synchronous Speed rpm	No. of Poles	7.5kW		37kW		75kW		375kW		750kW	
		Eff %	λ	Eff %	λ	Eff %	λ	Eff %	λ	Eff %	λ
375	16	75	0.75	84	0.79	89	0.82	91	0.84	92	0.86
750	8	80	0.83	87	0.86	91	0.87	94	0.88	95	0.89
1500	4	84	0.9	90	0.92	93	0.93	95	0.93	95	0.93

6. INDUCTION MOTOR LOAD TEST

A load test may be applied to an induction motor to determine its performance at various loads.

The motor under test may be either direct-coupled to a generator or loaded by some form of brake. During the course of the test -

- the supply voltage to the motor must be kept constant for the various load values
- the frequency also should remain constant to obtain reliable test results.

If a generator is used as a load, its power output and losses are measured, and the power input obtained by adding the output and the losses. The power output of the motor is equal to the power input to the generator. If a mechanical brake is used, the torque is obtained and the output of the motor calculated from the equation -

The quantities usually determined in a load test are as follows -

- speed - measured by a tachometer
- rotor current - measured using an ammeter or tong tester (slip-ring motors only)
- stator current - measured using ammeter inserted in the stator circuit or tong tester
- power factor - measured using a power factor meter or determined by calculation
- power input - measured by means of the two-wattmeter method
- efficiency - determined by calculation
- power output - determined by calculation.

Note:

Both the stator and rotor currents measured are line values, not phase values.

Figure 8 shows the connections required to carry out a load test on a squirrel cage motor.

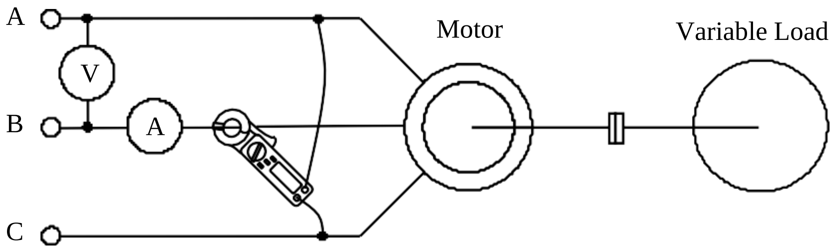

Figure 8

The load performance curves for a 3.75kW slip-ring induction motor are shown in figure 9. These curves are typical performance curves for an induction motor.

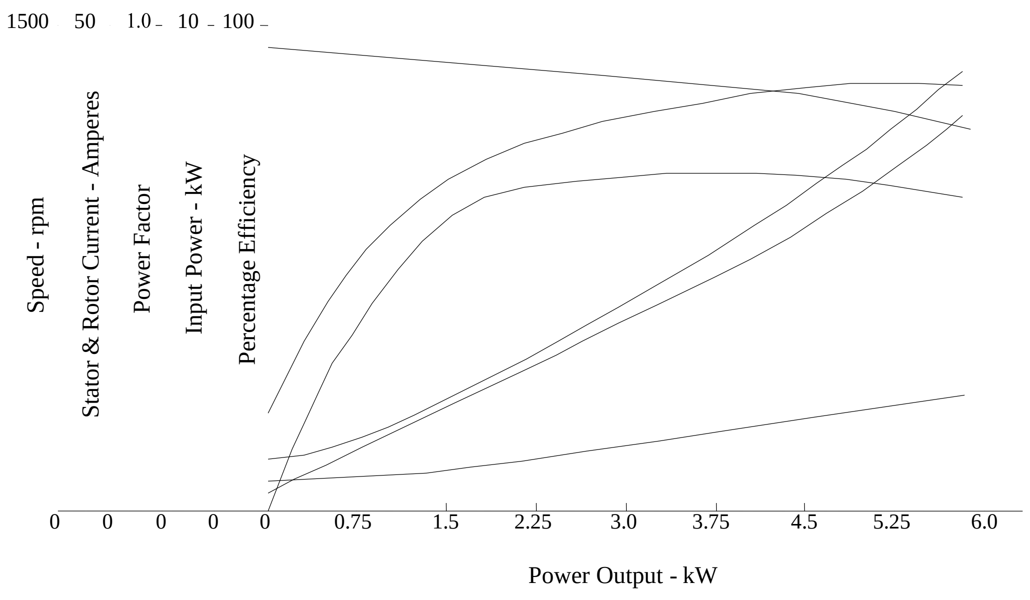

Figure 9

It will be noticed from these curves that the -

- speed falls fairly uniformly as the power output increases.

  The speed of the motor adjusts itself to such a value that the magnitude of the induced emf in the rotor is just sufficient to exert the required torque. As the load increases the speed must decrease, that is, the slip must increase, so that a greater emf will be induced in the rotor to establish a greater current in the rotor circuit, to develop a larger torque, for the purpose of overcoming the increased load. The induction motor therefore has a drooping speed characteristic. Although the motor, for which the curves under consideration were drawn, was overloaded, it can be seen from figure 8 that the reduction in speed was not excessive.

- rotor current curve is observed to rise almost uniformly over the greater range of loads.

  If the supply voltage remains constant, the air gap flux, or rotating magnetic field, remains practically constant from no-load to full-load. The torque of the motor is proportional to the product of the air gap flux and the component of the rotor current in phase with it, therefore as the load increases, the rotor current must increase so that the magnitude of its torque component will be sufficient to develop the required torque to overcome the increased load.

- stator current depends upon the rotor current, therefore it rises almost uniformly over the greater range of loads.

  It has been shown in the phasor diagram for the induction motor that the total stator current is the phasor sum of the no-load current and that component of the stator current required to neutralise the mmf of the rotor current. As the rotor current increases, so must the neutralising component of the stator current. Therefore, for every increase of secondary load current there must be a proportional increase in the stator current.

- power-factor also has a rising characteristic.

  For any increase in load up to full-load there is an improvement in the power-factor. The power-factor of an induction motor running light is very low, because the major portion of the current supplied to the motor is magnetising current, lagging 90º behind the applied stator voltage; this current remains practically constant at all loads. However, as the load increases the component of the stator current required to neutralise the mmf of the rotor current also increases. This has the effect of bringing the resultant stator current more nearly in phase with the applied voltage, that is, reducing the angle of lag of the stator current, resulting in an improvement of the power factor.

- power-input also has a rising characteristic.

  This is to be expected, because the motor is converting energy from one form to another and therefore the rate at which energy is taken in (i.e. power input) must at least equal the rate at which energy is given out (i.e., power output).

- efficiency curve is seen to rise as the load is increased, reaching a maximum at approximately full-load, but it commences to fall when the motor is overloaded.

  The losses occurring in the motor under consideration may be grouped, for all practical purposes, into three classes:

  - the copper (I^2R) losses in the stator and rotor;
  - iron losses in stator and rotor cores;
  - friction and windage losses.

  The iron losses, friction and windage losses remain practically constant at all loads, but the copper losses vary as the square of the current.

  At no-load, the input is required only to supply the losses; the output is zero and consequently the efficiency also is zero. As the load increases, the efficiency increases as the ratio of the output to the input increases. It can be proved that the maximum efficiency occurs at the load which makes the variable I^2R copper losses equal the constant losses, and a motor is usually designed so that this occurs at approximately full-load. When a motor is loaded beyond this value, the variable copper losses increase at a greater rate than the output and the efficiency falls accordingly. This is illustrated in figure 8 by the efficiency curve bending downwards after having passed through a maximum value.

7. EFFECTS OF REDUCED VOLTAGE

There are problems associated with the running of induction motors at reduced voltage. For example, assume that the voltage applied to the motor terminals is reduced to 50 percent of the rated nameplate voltage.

The effects of the reduced voltage are -

- the strength of the rotating magnetic field of the stator is also reduced to _______ of the normal value.
- the voltages and currents induced in the rotor are similarly reduced to________of their normal values.
- the resulting torque output of the motor is reduced to one-fourth of its original value.

The torque equation given previously shows why the large reduction in the torque output occurs.

Both the stator flux (ϕ) and the rotor current (I_R) are reduced to half of their original values. This means that the product (torque) of these terms is only one-fourth of its original value.

For a given value of slip, the torque varies as the square of the applied voltage.

Figure 10 shows that a 50% reduction in voltage causes the torque to decrease to 25 percent of its normal value.

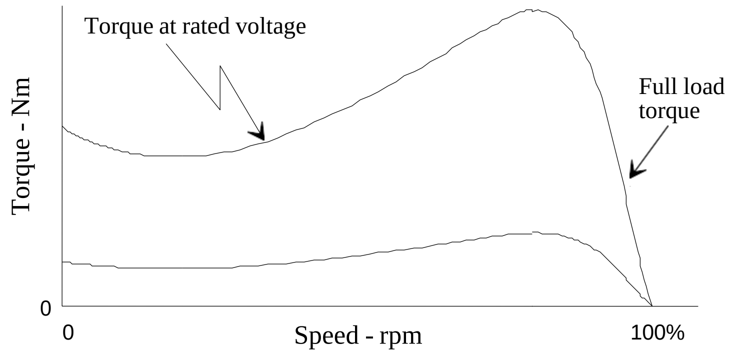

Figure 10

The torque developed as a result of reduced voltage, at any particular value of slip, may be determined provided the following values are known -

- rated voltage
- torque developed at rated voltage
- new voltage.

Example: 3

A 415V squirrel cage induction motor develops a torque of 40Nm. Determine the torque developed by the motor if the supply voltage drops to 380V.

In addition to the decrease in developed torque the other effects of reduced supply voltage include -

- increased supply current
- possible stalling of the motor
- prolonged acceleration period during start up.

Example: 4

A 4-pole, 11kV, 50Hz induction motor operates with a rotor speed of 1485 rpm and takes a line current of 44.6A at a power factor of 0.93 lag when delivering its full load output of 750kW. Determine the -

a) power input
b) efficiency
c) total losses
d) torque developed.

NOTES

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INDUCTION MOTOR LOAD CHARACTERISTICS

PURPOSE:

To carry out a load test on a slip-ring induction motor and plot the load characteristics of the motor.

TO ACHIEVE THE PURPOSE OF THIS SECTION:

At the end of this practical assignment the student will be able to:

- carry out the load test on a three phase induction motor.
- plot the load characteristics of an induction motor.
- determine from the load characteristic full load speed, power factor, power input, stator current and efficiency percent.

EQUIPMENT:

- 1 x 41.5/24V three-phase, 50Hz, AC supply
- 1 x variable DC supply
- 1 x 41.5V three-phase slip-ring induction motor + double machine bed
- 1 x dynamometer
- 2 x digital multimeters
- 1 x AC current clamp
- 1 x optical tachometer
- 1 x Prova Meter
- 4mm connection leads

– REMEMBER –
– WORK SAFELY AT ALL TIMES –
Observe correct isolation procedures

PROCEDURE:

1. LOAD TEST

1. Connect the motor in delta as shown in figure 1, with the slip-rings short circuited.

   Note: Do not couple the dynamometer to the motor at this stage.

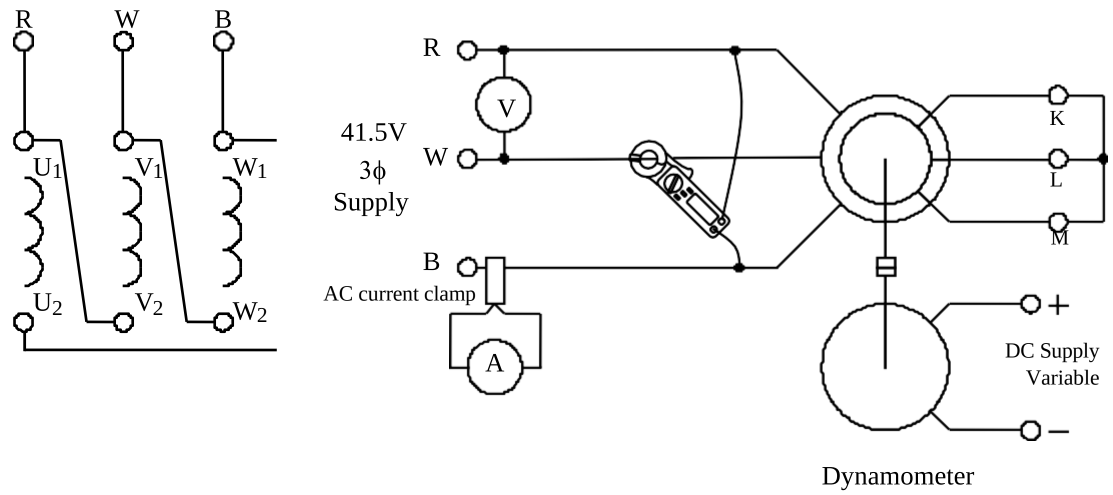

Figure 1

2. **Do not proceed** until the teacher checks your circuit and completes the progress table.

Progress Table 1

attempt 1	attempt 2	attempt 3
5	2	0

3. Switch on the supply, the motor should start.
4. With the motor running on no-load, measure and record the following values -
   - line voltage
   - line current
   - power taken by the motor using the Prova meter
   - power factor using the Prova meter
   - phase angle using the Prova meter
   - rotor speed using the tachometer

   Record all values in table 1.

Table 1

Measured Values							Calculated Values			
Torque Nm	Line Voltage volts	Line Current amps	Input Power watts	Power Factor	Phase Angle	Rotor Speed rpm	Output Power	Power Factor	Phase Angle	Motor Eff. %
0										
0.1										
0.15										
0.2										
0.25										
0.3										
0.35										
0.4										
0.45										

5. Switch off the motor and attach the dynamometer.
6. Switch on the supply
7. Adjust the DC power supply to the dynamometer for a motor torque of 0.1Nm.
8. Measure and record, in table 1, the following values -
   - line voltage
   - line current
   - power taken by the motor
   - power factor
   - phase angle
   - rotor speed.
9. Repeat the procedure for each value of motor torque shown in table 1.
10. **Do not proceed** until the teacher checks your results and completes the progress table.

Progress Table 2

attempt 1	attempt 2	attempt 3
5	2	0

11. Switch off the supply, then disconnect the circuit.
12. Please return all equipment to its proper place, safely and carefully.

2. OBSERVATIONS:

1. Calculate the power output from the motor for each value of motor torque. Use the equation. $P_{OUT} = \frac{2\pi nT}{60}$

   Note: The output power at a torque of 0Nm = 0W.

   Show the calculation for the condition where the motor torque = 0.1Nm. Record your answers in the appropriate column of table 1.

   ___

   ___

2. Calculate the motor power factor for each value of motor torque using the equation. $\lambda = \frac{P}{\sqrt{3}VI}$ Show the calculation for the first set of values.

   Record your answers in the appropriate column of table 1.

   ___

   ___

3. Calculate the motor phase angle for each value of motor torque using the equation: $\emptyset = cos^{-1}\,\lambda$ Show the calculation for the condition where the motor torque = 0.1Nm. Record your answers in the appropriate column of table 1.

   ___

   ___

4. Calculate the motor efficiency for each value of motor torque using the equation. $\eta\% = \frac{POUT}{P_{IN}} \text{ x } 100$ Show the calculation for the condition where the motor torque = 0.1Nm. Record your answers in the appropriate column of table 1.

   ___

   ___

5. On the axes provided in figure 2 draw the load characteristics for the motor tested. The characteristics to be drawn are -
    - motor speed
    - stator current
    - stator power factor
    - motor power input
    - motor efficiency.

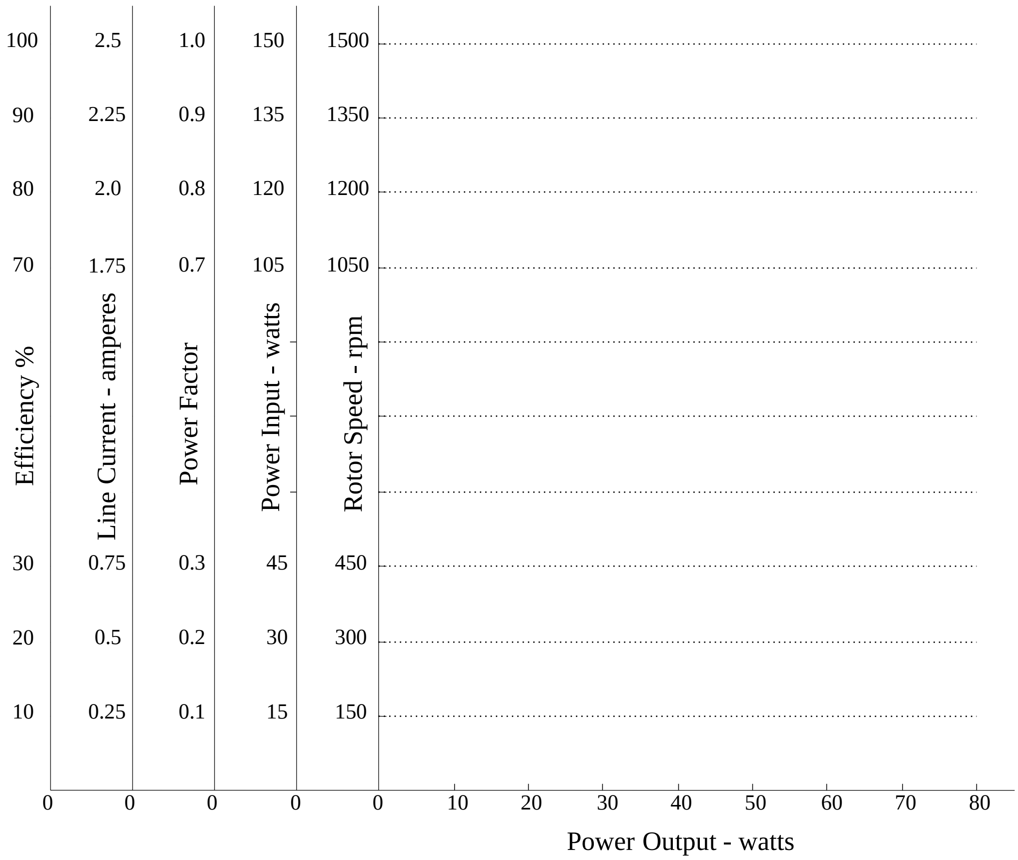

Figure 2

6. From the load characteristics drawn in figure 2 determine the full load -
    - speed - ___________________
    - power input - ___________________
    - power factor - ___________________
    - line current - ___________________
    - efficiency - ___________________.

NOTES

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Tutorial 9 **NAME:**

INDUCTION MOTOR LOAD CHARACTERISTICS

SECTION A

In the following statements one of the suggested answers is best. Place the identifying letter on your answer sheet.

1. Copper loss in an induction motor is due to:-

a) hysteresis in the stator and rotor cores;
b) eddy currents in the stator and rotor core;
c) resistance of the stator and rotor windings;
d) friction and windage loss in the motor.

2. The efficiency of an induction motor on no load is:-

a) 100 percent;
b) about 50 percent;
c) about 10 percent;
d) zero percent.

3. The mechanical losses on no load in an induction motor include:-

a) hysteresis in the stator and rotor cores;
b) eddy currents in the stator and rotor core;
c) resistance of the stator and rotor windings;
d) friction and windage loss in the motor.

4. The difference between the input power to a motor and the output power from a motor is the:-

a) total loss given off as heat;
b) electrical loss given off as resistance;
c) mechanical loss given off as friction;
d) magnetic loss given off as inductance.

5. An increase in rotor current in an induction motor:-

a) reduces stator current to keep stator flux constant;
b) reduces power factor due to rotor inductance;
c) reduces motor efficiency due to increased losses;
d) causes stator current to increase to maintain stator flux.

6. The no load current of an induction motor is shown on a phasor diagram as:-
   a) the magnetising current and the iron loss current;
   b) the rotor current and the stator current;
   c) the copper loss current and the iron loss current;
   d) the copper loss current and the magnetising current.

7. As the load on an induction motor increases:-
   a) both the efficiency and the power factor improve;
   b) efficiency increases but power factor decreases;
   c) efficiency decreases and power factor decreases;
   d) efficiency decreases but power factor increases.

8. The stator component of current due to rotor current is:-
   a) equal to the rotor current and in phase with the rotor current;
   b) dependant on the turns ratio and in phase with the rotor current;
   c) equal to the rotor current and opposite in phase to the rotor current;
   d) dependant on the turns ratio and opposite in phase to the rotor current.

9. Most induction motors are designed to have maximum efficiency:-
   a) when rotor resistance equals rotor inductive reactance;
   b) close to full load as most motors run at this load;
   c) at starting to give increased starting torque;
   d) at about half of full load as a compromise.

10. In a squirrel cage induction motor:-
   a) iron losses vary as the square of the load while other losses are almost constant;
   b) stator losses vary as the square of the load while other losses are almost constant;
   c) rotor losses vary as the square of the load while other losses are almost constant;
   d) copper losses vary as the square of the load while other losses are almost constant.

SECTION B

Blank spaces in the following statements represent omissions. Write the appropriate information on your answer sheet.

Copper losses in a squirrel cage induction motor occur in______(1)______while hysteresis and eddy current losses occur in______(2)______. Mechanical losses occur due to______(3)______and______(4)______.

If voltage and frequency supplying an induction motor remain constant then the _____(5)______losses and______(6)_____losses remain relatively constant. The variable______(7)_____loss varies in proportion to the_______(8)_____.

Maximum efficiency occurs when the______(9)_____losses equal the _____(10)_____losses while maximum torque occurs when the_______(11)_____ equals the______(12)_____.

If a motor running on full load has some load removed the speed of the motor _____(13)_____slightly, causing a_______(14)_____in rotor voltage, a _____(15)_____in rotor current, a_______(16)_____in rotor flux and a _____(17)_____in torque. The motor will settle to a constant speed when _____(18)_____equals______(19)_____.

SECTION C

1. A 4 pole three phase 415 volt 50Hz squirrel cage induction motor runs at 1460 r.p.m. while delivering 9 kilowatts to its load at a maximum efficiency of 88 percent. If the power factor of the motor at this load is 0.86 lag determine:-
   a) the input power to the motor; (10 227W.)
   b) the line current taken by the motor; (16.55A.)
   c) the torque delivered to the load; (58.9Nm.)
   d) the losses in the motor; (1 228W.)
   e) the copper losses in the motor. (614W.)

2. A 415V squirrel cage induction motor delivers 116 Nm of torque when started on full voltage. The voltage to the motor must be reduced to 320 volts to limit starting current in line with supply authority requirements. Determine the starting torque at the reduced voltage. (69Nm.)

SECTION D

1. Figure 1 is a set of performance curves for a 5kW, 6 pole 415 volt squirrel cage induction motor. From the curves determine:-
   a) Line current, speed and efficiency at rated load;
   b) Input power, line current and power factor at no load;
   c) Speed and efficiency when stator current is 8 amperes.

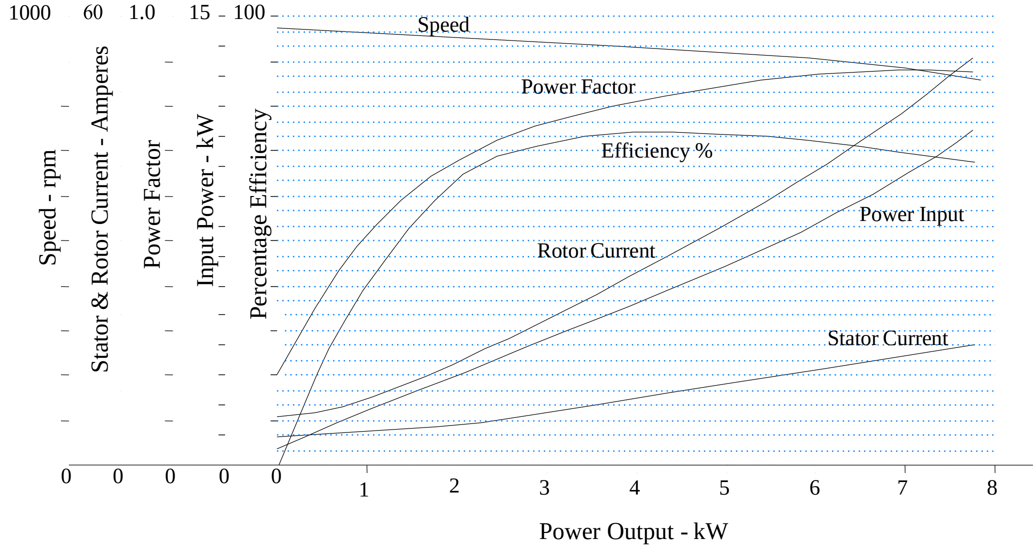


Figure 1

2. Figure 2 is a phasor diagram of a squirrel cage induction motor which shows three components of current in the motor. If the load component of stator current is one third of the rotor current complete the phasor diagram to determine:-
   a) the current scale for the stator currents; (10mm = 1A)
   b) the no load current and power factor; (1.7A @ 0.352lag)
   c) the load component of stator current; (3A @ 16.7^{O}lag)
   d) the total current taken from the supply at this load; (4.26A)
   e) the power factor of the motor at this load. (0.815lag)

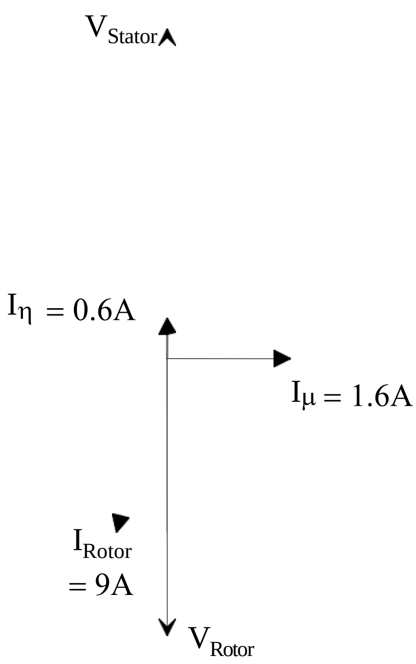


Figure 2

Motor Protection, Faults & Maintenance

PURPOSE:

This section introduces the direct on line motor starter and the AS/NZS 3000 requirements for starting three phase induction motors.

TO ACHIEVE THE PURPOSE OF THIS SECTION:

At the end of this section the student will be able to:

- State the approximate starting current of an induction motor compared to the full load current.
- Interpret the AS/NZS 3000 requirements with regard to protection of induction motors.
- Describe the characteristics and setting of thermal overload relays.
- List the common faults of motors.
- List the steps involved in dismantling and re-assembling a motor.

REFERENCES:

- Electrical Trade Principles 2nd Edition J Hampson & S Hanssen. Section 6
- Electrical Principles for the Electrical Trades. 5th Edition. Jenneson J.R. Pages 297-298, 304-305, 313-318.

1. MOTOR PROTECTION - AS/NZS 3000 REQUIREMENTS

The requirements laid down in AS/NZS 3000 relating to motors include -

- isolation and switching
- overload protection
- over temperature protection
- restarting or reversal.

Isolation and Switching:

4.13.1 Protection against injury from mechanical movement

4.13.1.1 Switching devices

Every motor supply circuit shall be provided with a switching device capable of performing the following functions-

a) starting or stopping the motor; and

b) emergency stopping, in accordance with clause 2.3.5; and

c) isolating the motor for mechanical maintenance, in accordance with Clause 2.3.6

Exceptions:

1. Where a number of motors are required to function as a group, or operate in a coordinated manner, e.g. a split system air conditioning unit, a single switching device may be used to control more than one motor.
2. A switch suitable for disconnection of supply in accordance with item (c) need not be provided for motors that are -
    1. connected by a plug and socket-outlet; or
    2. incorporated in an appliance having no exposed moving parts; or
    3. rated at not greater than 150 VA

4.13.1.3 Devices for staring and stopping

Starting and stopping devices shall be so located as to be easily operated by the person in charge of the motor.

A stopping device or isolating switch shall be provided where danger is likely to occur because of the presence of moving parts

The stopping device shall remain effective in the event of a fault in a motor control circuit.

Where electrical equipment is remotely controlled devices shall be provided for stopping the motors at all points where danger is likely to occur.

Overload Protection:

4.13.2 Protection against overload

Each electric motor having a rating exceeding 370 W shall be provided with control equipment incorporating a means of protection against overload of the motor..

The most common form of overload protection is provided via the thermal overload relay (TOL).

Over Temperature Protection:

4.13.3 Protection against over temperature

4.13.3.1 General

Electric motors shall be provided with over temperature protective devices complying with Clause 4.13.3.3 where they -

a) may be required to run unattended and which have a rating greater than -
   i. for shaded-pole type motors 480 VA; or
   ii. for other unattended motors 240 VA; or
b) have a rating greater than 2.25kW.

******* Notes apply to this clause *******

4.13.3.2 Protection not required

Over temperature protection shall not be provided -

a) in accordance with clause 7.2.9, protection shall not be provided for motors associated with a fire-protection service; or
b) the opening of the motor circuit could create a hazard.

Over temperature protection need not be provided for unattended submersible pump motors, immersed in water, which have a rating not greater than 2250 W.

4.13.3.3 Over temperature protective devices

Over temperature protective devices shall comply with the following:

a) *Protection.* Protection of motor windings against excessive temperatures shall be provided by -

   i. thermal overload protective devices complying with AS 60947.4.1; or

   ii. built in thermal protection, in accordance with AS 60947.8; or

   iii. a device that affords an equivalent degree of protection

b) *Operation.* The protective device shall disconnect, directly or indirectly, not less than the following number of supply conductors to the motor:

   i. For single-phase a.c. motors and d.c. motors supplied from a two-wire supply with one line earthed and single-phase a.c. motors, one.

   ii. For three-phase a.c. motors and d.c. motors supplied from two unearthed lines, two.

c) *Additional requirements for unattended motors* Where thermal protective devices for unattended motors are of the automatic reset type, the device shall protect the motor windings against attaining excessive temperatures under continued tripping conditions.

In practice over temperature protection is provided by -

- thermal overload relay - external to the motor
- Klixon type thermal overload - mounted on or in the motor
- thermistors fitted within the motor windings
- electronic motor protection relays.

Restarting or reversal:

4.13.1.4 Protection against restarting or reversal

Where unexpected restarting of the motor might cause danger, each electric motor shall be provided with a means to prevent automatic restarting after stopping.

Where safety might be impaired by incorrect direction of rotation of a motor, suitable measures shall be taken to prevent danger from reversal of the direction of rotation.

NOTE: This applies particularly where reverse-current braking is used.

Protection of this type is provided by -

- a no volt or low volt coil within the motor starter
- phase failure relay.

2. THERMAL OVERLOAD RELAYS (T.O.L.)

Thermal overload relays, designed for use on AC or DC, provide thermal protection against small and sustained overloads. Overload relays used in these applications have an inverse-time characteristic.

The current-time operating curve of the thermal overload relay is illustrated in figure 9

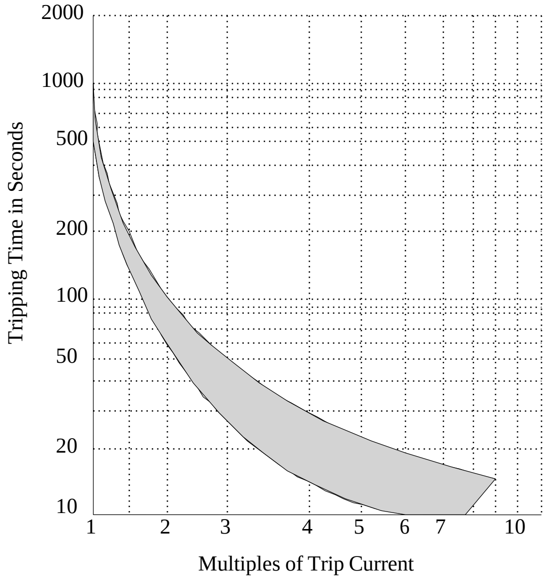


Figure 9

The thermal overload relays produced by various manufacturers include -

- three pole - for use on three phase, but also on single or two phase circuits.
- compensated - unaffected by ambient temperature variations.
- differential - capable of detecting a phase imbalance or failure, thereby providing single phase protection (ie. fuse blown, or failure of one of the phases supplying the motor).
- graduated in motor current - the current settings indicated on each relay correspond to actual motor load values.

Most thermal overloads are fitted with an adjustable current setting, for example 4A to 8A, or 45A to 56A. It is the responsibility of the installing electrician to correctly set the overload current setting to the appropriate value. The question then becomes what is the correct setting? There are two possibilities, depending on whether the overload heaters are connected in series with the motor lines or motor phases. If the thermal overload heaters are connected -

- in series with the motor lines, that is, sensing motor line current, the overload must be set to full load motor line current
- in series with the motor phases, that is, sensing motor phase current, the overload must be set to full load motor phase current, that is $\frac{1}{\sqrt{3}}$ of the rated line current or

  57.7% of rated line current.

Example: 1

A three phase squirrel cage induction motor has a nameplate current of 35A. Determine the correct setting of the adjustable thermal overload protecting the motor, if the overload heaters are connected in the -

a) lines, as would be the case with a direct on line starter
b) phases, as would be the case with a star-delta starter.

____

____

____

Some of the important factors associated with the use of thermal overloads are detailed below.

Resetting:
The overload relay cannot be reset until the bimetal elements have cooled sufficiently.

Ambient temperature compensation:
A bimetal compensation element is added to an overload relay to allow normal operation in response to excessive motor current for temperatures between -40^o and +600^{o}C.

Setting device:
The current setting is adjusted by a lever or knob which moves along a reference scale. The setting plate is graduated directly in motor current.
The current setting on the overload is adjusted to the full load current of the motor.

Differential device:
The differential device causes the relay to trip when the currents flowing through the 3 elements are not identical (unbalanced mains supply, single phase condition). The greater the difference, the faster the tripping time.

Thermal overload relays equipped with a differential device can be used on unbalanced supplies, for instance three phase circuits supplying single phase loads. In this case the placing of two bimetal strips in series cancels the effect of the differential (see circuit diagram below).

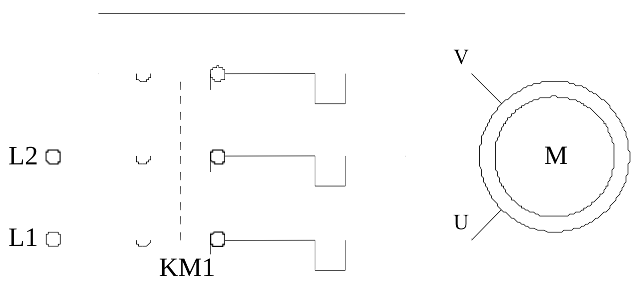


Figure 10

To overcome this problem manufacturers also produce non-differential relays.

Automatic reset device:

This is generally used with equipment not easily accessible. For example - unit heaters, air conditioning units, refrigeration units mounted on trucks, pumps, small hoists.

These relays do not lock out after the thermal tripping; they reset automatically when the bimetal elements are sufficiently cooled. As restarting of the protected motor is dependent on the automatic reset of the overload relay, it is important that any unexpected start up of the machine does not involve any risks to the safety of the operating personnel.

Example: 2

In relation to the motor starter circuit shown in figure 11.

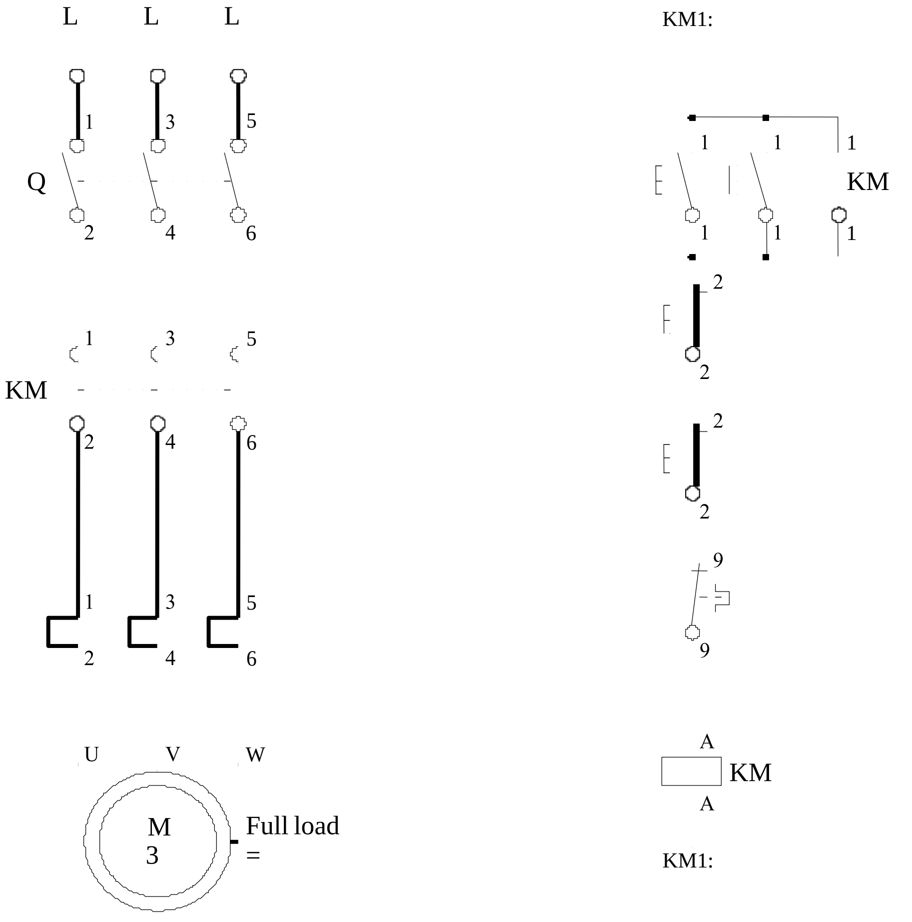


Figure 11

a) What is the name given to the type of motor starter shown?

____

b) What type of push button control is incorporated?

____

c) What would be the correct current setting for the thermal overload?

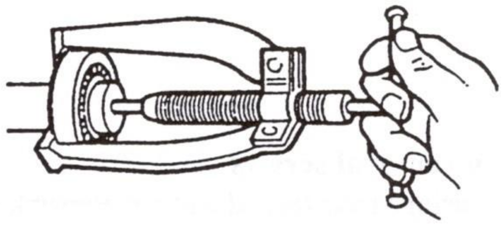
____

3. DISMANTLING AND RE-ASSEMBLING A MOTOR

When it is necessary to dismantle a machine, it is important to follow a set procedure. Wherever possible use the manufacturer's data as a guide. Failure to do so could cause damage to machine components and unnecessary expense.

Inspection of the machine before dismantling helps determine which parts are satisfactory, need repair or need replacement. Inspection should be done during dismantling as well. At this time any special tools or equipment can be collected. These might include:

a. Bearing and wheel pullers.
b. A tension wrench.
c. Correct type and size spanners, screwdrivers etc



Bearing puller

d. Cleaning solvents.
e. Heating equipment.
f. Suitable drifts and dollies to apply force.
g. Feeler gauges

Tension (torque) wrench

Of course it is important to be able to use this equipment correctly so not to cause damage to the machine or an unsafe work environment.

In the absence of manufacturer's details, you may be able to dismantle relatively simple machines by following a general procedure developed after thoroughly inspecting the machine.

It is important to mark components such as end shields and frame to ensure correct alignment when reassembled. It is very important to document what you do at every step. This will be of great importance when it comes time to reassemble the machine. Remember it could be several months before you reassemble.

Electrical machines must be thoroughly cleaned before dismantling or reassembly to ensure that:

- Good electrical contact exists between the mating surfaces of moving and stationary parts, for example brushes and commutator.
- Short circuits will not occur between the insulated components and earth.

Care should be taken when cleaning because some solvents will:

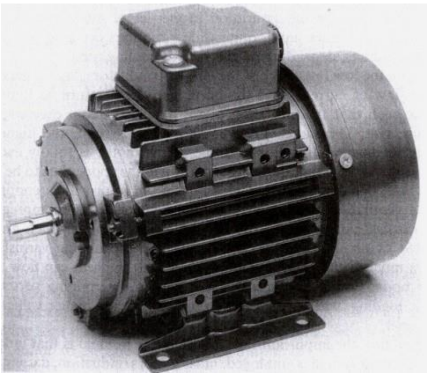
- Damage the insulation of the electrical conductors.
- Present a fire hazard.
- Affect moulded plastic components.

Electrical machines require a different cleaning method for each of their surfaces. The three surfaces that require cleaning are external surfaces, internal surfaces and electrical mating surfaces.

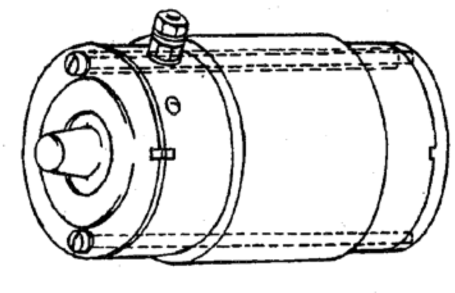
- Large dirt deposits on external surfaces can be cleaned by scraping or using a wire brush. Wash with a mild solvent such as kerosene.
- Blow internal surfaces clean with compressed air and wipe with a lint free cloth.
- Clean electrical mating surfaces with compressed air and a solvent soaked lint free cloth.

Always wear safety goggles and protective clothing when cleaning.

Another important facet is to draw an exploded diagram of the machine. This does not need to be a work of art but remember a picture is worth a thousand words. Let us now look at dismantling the sample machine shown below.



Enclosed, fan-ventilated induction motor



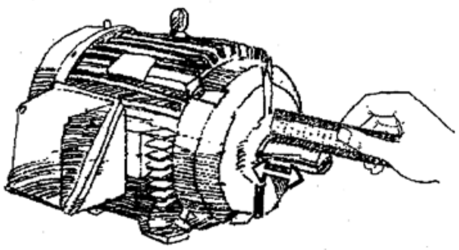
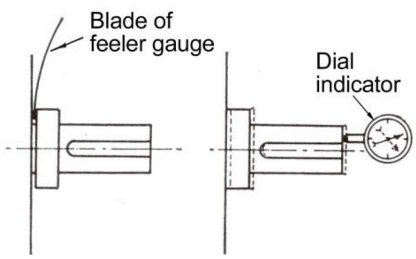
Motor vehicle starter motor

After cleaning:

1. Inspect the motor to determine readily removable items such as pulleys and gears. For d.c. machines and single phase squirrel cage motors it is important to remove the end shield at the drive end first to avoid damage to brushes or the centrifugal switch.

2. Remove components mounted on the shaft at the drive end. For the sample machine remove securing nut and withdraw washers, pinion gear, helix and spring.

3. Check the axial or end float of the machine. That is the movement of the shaft along the machine.
   If you do not provide enough axial float when reassembling the machine it may be too tight and overheat. To measure axial float one of the following methods can be used. In order of accuracy they are:

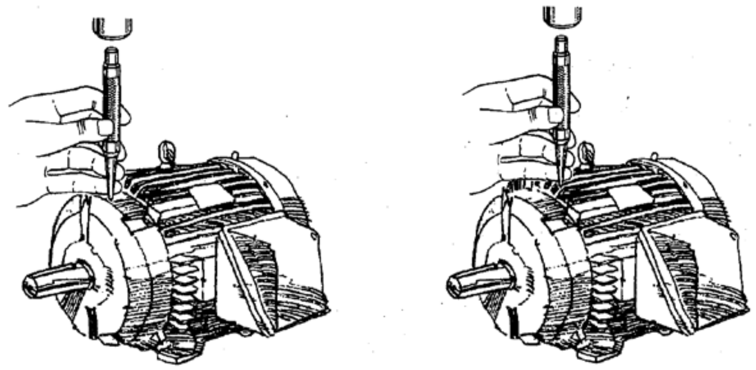
a. Measuring axial or end float using a rule, feeler gauges or dial indicator

i. Pushing the shaft into the machine and using a rule to measure how far the shaft protrudes from the end shield. Next, pull the shaft outwards and measure how far the shaft protrudes from the end shield. Document both measurements - the difference between them is the axial float.

ii. Use feeler gauges to determine end float. Clamp a collar to the shaft and move the shaft back as far as it will go. Measure gap. Move in the opposite direction and again measure the gap. The difference in the readings is the end float.

iii. The most accurate method of measurement involves the use of a dial indicator to measure total axial movement.

4. Check the motor frame and end shields for location witness marks. These show which end shield goes where and their correct orientation. In the absence of such marks, you need to make your own. Use a centre punch to witness mark the end shield at the drive-end and corresponding witness mark in the frame - use only one witness mark in each. Make sure the marks clearly indicate relationship. Repeat the process for the other end shield but use two witness marks close to each other on both end shield and frame. In this manner, one mark indicates drive-end and two marks indicate opposite drive end.



Witness marking motor end shield and frame to assist in reassembly

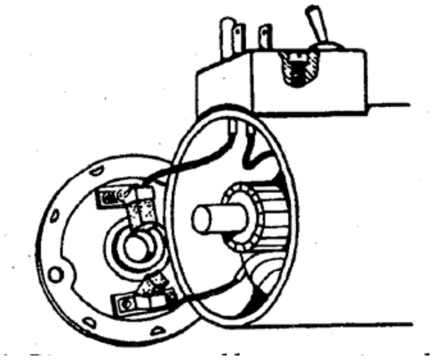
4. Check the end shield around the shaft for bearing retainer screws. If present, remove these.

5. As parts are removed clean and inspect them for damage. Place them in a tray or container in logical order so they can be identified and reassembled, when the time comes. Make sketches if necessary.

6. Loosen any screws holding the drive-end, end shield to the motor frame. Loosen the end shield. You may need to use a soft (metal) drift and soft-faced mallet. Exercise care not to damage cast end shields.

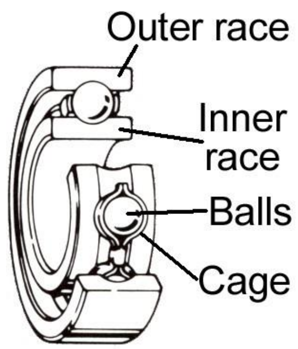
7. Look around the loosened end shield. Can you safely remove it? If not, clear any obstructions. Next, remove the screws and carefully remove the end shield.

8. Now we want to remove the opposite end shield complete with the rotor. For d.c. machines and single-phase squirrel cage motors, you will need to disconnect brushes or centrifugal switch. As the diagram below shows it is necessary to remove the brushes from their holders. Do not force any components.

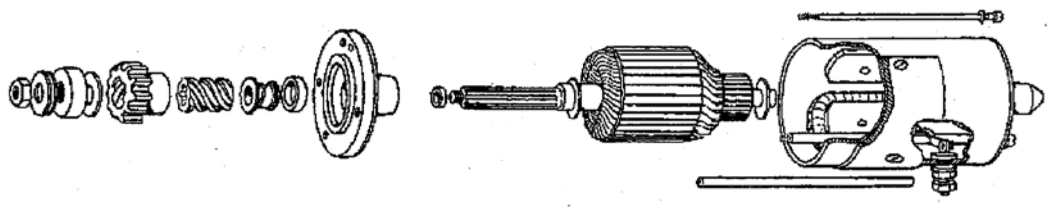


Disconnect any cables at opposite end shield – starter motor

9. Withdraw the armature/rotor from the end shield.
10. Note position and thickness of every spacer on your diagram.
11. To remove bearings that are to be re-used exert force only on the race with the tight fit, that is if the bearing is being removed from a shaft, apply force to the inner race. Whenever possible remove the free or push fit race first.
    Only wash the bearing if it is not a sealed type. Blow dry with clean compressed air but don't allow the bearing race to spin as this will damage the bearing track.
    Care should be taken not to damage the bearing surfaces on the shaft or in the end shield.



12. Recheck your assembly diagram and make any additional notes.



Exploded view of starter motor

Reassembly

Reassembly usually follows the reverse procedure to disassembly. Care needs to be taken when assembling bearings, gaskets, seals etc. to avoid damage. Of course cleanliness of the work area is most important to avoid contamination of the assembly.

- When installing ball or roller bearings it is very important to note that only one race is a tight fit. Normally the revolving race is a press fit, so it is fitted to the machine part first, and the stationary race is a light push fit, so it is assembled with the machine part. In the case of an electrical machine this means the bearing would be fitted to the shaft first, the shaft rotates and the inner race is a tight fit on it, and then the shaft and bearing are fitted to the end shield or housing.
  To avoid damage to the bearing it is important to only apply force to the race that is being assembled, inner or outer. This prevents causing indentations in the tracks of the race or to the balls or rollers.

- Do not take a new bearing from its packaging until it is actually needed.

- Any gaskets, seals or spacers need to the correct type and size and must go in their correct positions.

- Proper tightening of nuts or setscrews etc., is frequently the difference between a machine that operates correctly and one that doesn’t. They can be tightened too tight or too loose. If the manufacturer gives a recommended torque for the nuts in an assembly a tension wrench must be used for tightening to the correct tension.

- On assembly of end shields make sure that witness marks are re-aligned.

INDUCTION MOTOR STARTING

PURPOSE:

To investigate the operating characteristics of the squirrel cage induction motor.

TO ACHIEVE THE PURPOSE OF THIS SECTION:

At the end of this practical assignment the student will be able to determine by test and measurement the:

- full load line current.
- starting current and torque - delta connected.
- starting current and torque - star connected.

EQUIPMENT:

- 1 x 41.5/24V three-phase, 50Hz, AC supply
- 1 x 41.5V three-phase squirrel cage induction motor + double machine bed
- 1 x eddy current load
- 1 x variable DC power supply
- 1 x digital multimeter
- 1 x AC current clamp
- 4mm connection leads

– REMEMBER –
– WORK SAFELY AT ALL TIMES –
Observe correct isolation procedures

PROCEDURE:

1. FULL LOAD OPERATION

1. The squirrel cage motor used in this practical has a rating of 50W. When delivering rated output, the motor develops approximately 0.34Nm of torque at a speed of about 1420 rpm.
2. Connect the motor in delta as shown in figure 1 with the dynamometer attached.

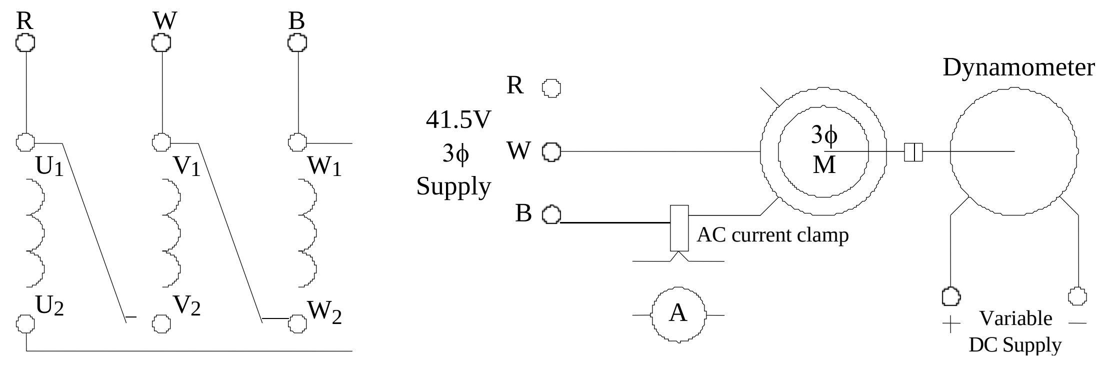


Figure 1

3. **Do not proceed** until the teacher checks your circuit and completes the progress table.
4. Switch on the three phase supply, the motor will start and accelerate up to operating speed.
5. Adjust the DC power supply to the dynamometer for a motor torque of 0.34Nm, that is full load.

Progress Table 1

attempt 1	attempt 2	attempt 3
5	2	0

6. Using a digital multimeter measure the line voltage applied to the motor and record in table 1.
7. Measure the motor line current and record in table 1.

Table 1

Torque Nm	Line Voltage volts	Line Current amperes
0.34 Nm		

8. **Do not proceed** until the teacher checks your results and completes the progress table.

Progress Table 2

attempt 1	attempt 2	attempt 3
5	2	0

9. Switch off the three phase supply.
10. Switch off the DC power supply to the dynamometer, then disconnect.

2. STARTING - DELTA CONNECTED

1. To allow the measurement of starting torque, motor starting must be done using reduced voltage. In this case the line voltage will be reduced to 35V.
2. Use the circuit connection shown in figure 1.
3. Lock the rotor of the dynamometer, using the locking device fitted at the drive end.
4. Switch on the three phase supply and quickly measure the starting torque and the starting current. Record in table 2.

Table 2

Line Voltage volts	Starting Torque Nm	Starting Current amperes
35V		

5. As soon as you have the required values switch off the supply.
6. Determine the starting torque that would have been developed, had the motor been started with full line voltage applied. Record the value in table 3.

$$T_{DELTA} = \left(\frac{V_{SUPPLY}}{V_{START}}\right)^2 \text{ x } T_{START} \ =$$

7. Determine the starting current that would have been taken, had the motor been started with full line voltage applied. Record the value in table 3.

$$\mathbf{I_{DELTA} = \frac{V_{SUPPLY}}{V_{START}} \text{ x } I_{START}} \ =$$

Table 3

Line Voltage volts	Starting Torque Nm	Starting Current amperes
_____ V		

8. Do not proceed until the teacher checks your results and completes the progress table.

Progress Table 3

attempt 1	attempt 2	attempt 3
5	2	0

3. STARTING - STAR CONNECTED

1. Use the circuit connection shown in figure 2.

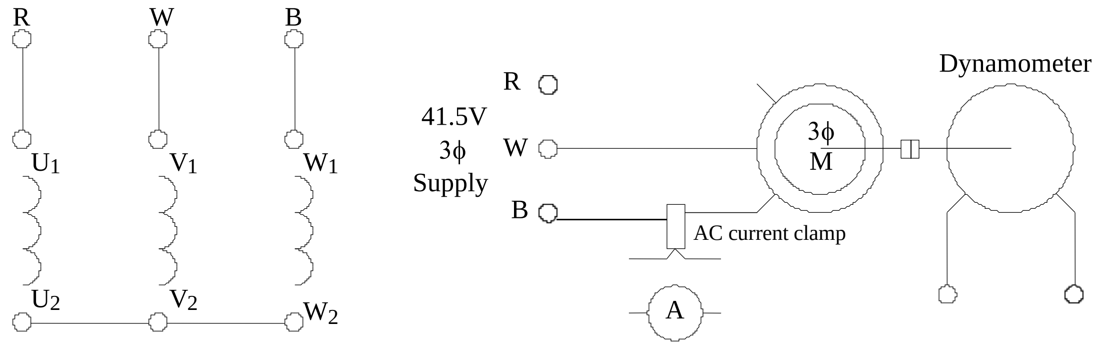


Figure 2

2. Lock the rotor of the dynamometer, using the locking device fitted at the drive end.
3. Switch on the three phase supply and quickly measure the starting torque and the starting current. Record in table 4.

Table 4

Line Voltage volts	Starting Torque Nm	Starting Current amperes
35V		

4. As soon as you have the required values switch off the supply.
5. Determine the starting torque that would have been developed, had the motor been started with full line voltage applied. Record the value in table 5.

$$T_{STAR} = \left(\frac{V_{SUPPLY}}{V_{START}}\right)^2 \times T_{START} =$$

6. Determine the starting current that would have been taken, had the motor been started with full line voltage applied. Record the value in table 5.

$$\mathbf{I_{STAR} = \frac{V_{SUPPLY}}{V_{START}} \times I_{START}} =$$

Table 5

Line Voltage volts	Starting Torque Nm	Starting Current amperes
_____ V		

7. Do not proceed until the teacher checks your results and completes the progress table.

Progress Table 4

attempt 1	attempt 2	attempt 3
5	2	0

8. Disconnect the circuit.
9. Please return all equipment to its proper place, safely and carefully.

4. OBSERVATIONS:

1. For the motor tested, how large was the starting current in delta compared to the full load running current?

____

____

____

2. For the motor tested, how large was the starting torque in delta compared to the full load torque?

____

____

____

3. What is the effect on starting current of starting the motor with a star connection as opposed to a delta connection?

____

____

____

4. What is the effect on starting torque of starting the motor with a star connection as opposed to a delta connection?

____

____

____

5. What would be the likely line current taken by the motor if the motor were to be run using a star connection?

____

____

____

6. Is there any advantage, if a motor is started with a reduced voltage?

____

____

____

7. Is there any disadvantage, if a motor is started with a reduced voltage?

____

____

____

INDUCTION MOTOR STARTING

SECTION A

In the following statements one of the suggested answers is best. Place the identifying letter on your answer sheet.

1. The overload device in a motor stater provides:-
   a) protection against short circuits inside the motor;
   b) overload protection for the motor and its supply conductors;
   c) short circuit protection for the motor supply conductors;
   d) all of the above.

2. Thermal overloads need to cool after tripping before they can be reset. This is:-
   a) a problem because the motor cannot be turned back on immediately;
   b) overcome by using magnetic overloads to allow faster reset times;
   c) to prevent the circuit breaker at the switchboard from tripping unnecessarily;
   d) to allow the motor windings to cool before being reconnected to the supply.

3. The motor starter that **does not** reduce the starting current to a squirrel cage induction motor is:-
   a) the direct on line motor starter;
   b) the star delta starter;
   c) the primary resistance starter;
   d) the auto transformer starter.

4. The main problem with starting large squirrel cage induction motors direct on line is:-
   a) starting torque is greater if a primary resistance starter is used;
   b) the large starting current causes fluctuations in the supply voltage;
   c) the large starting current will cause the motor windings to burn out;
   d) the motor may not produce enough starting torque to start the load.

5. The problem with starting squirrel cage motors with any of the voltage reduction starters is:-
   a) the motor must have all six winding ends brought out to the terminal block;
   b) six wires must be run between the switchboard and the starter;
   c) reducing the voltage causes an even greater reduction in starting torque;
   d) the increased starting torque may damage the load or couplings.

6. The thermal overload used on motor protection:-
    a) interrupts all overloads very quickly;
    b) only isolates short circuits instantly;
    c) allows slight overloads for longer periods;
    d) takes several minutes to isolate any overload.

7. A motor started with a star-delta starter with overloads fitted between the motor and starter would:-
    a) require a thermal overload with six bimetallic elements;
    b) require an overload current rating equal to rated current times $\frac{1}{\sqrt{3}}$
    c) require an overload current rating equal to rated motor current;
    d) require an overload current rating equal to rated current times $\sqrt{3}$

8. An advantage of differential thermal overloads over normal overloads is:-
    a) they can detect the difference between a short circuit and overload fault;
    b) they will protect the motor from loss of one phase of the supply;
    c) they can be used on single, two or three phase motors;
    d) they can also protect against loss of load (ie underload);.

9. Stop buttons and thermal overloads use normally closed contacts because:-
    a) if they get dirty and will not close the machine will not start (fail safe);
    b) normally closed contacts operate quicker than normally open contacts;
    c) normally open contacts would need to be connected in parallel;
    d) normally closed contacts stay cleaner as the dirt cannot get in.

10. AS/NZS 3000 Clause 4.2.1.2 would be satisfied if:-
    a) an automatic reclosing overload device protects the motor under all conditions;
    b) the isolating switch can be locked in the off position if not located next to the motor;
    c) the motor on a saw bench was controlled by a DOL starter operated by pushbuttons;
    d) copper losses vary as the square of the load while other losses are almost constant.

SECTION B

Blank spaces in the following statements represent omissions. Write the appropriate information on your answer sheet.

All starters incorporate one or more______(1)_____to control the motor and _____(2)_____to protect the motor from______(3)_____.At the beginning of the motor circuit (switchboard) either______(4)_____or______(5)_____are used to provide______(6)_____protection for the circuit conductors and the motor.

Starting current to larger motors is required by the______(7)_____Authority to be limited to reduce______(8)_____in the supply. If this is the case the_______(9)_____ cannot be used. However, one of the______(10)_____type starters may be used, depending on current limits and starting torque requirements.

If additional remote pushbuttons are added to a starter all start pushbuttons, which are of the normally______(11)_____contact type, are connected in_______(12)_____and all stop pushbuttons, which are of the normally______(13)_____contact type, are connected in______(14)_____.

When started DOL the starting current of the squirrel cage induction motor is _____(15)_____to_______(16)_____times rated current while starting torque is about _____(17)_____times rated torque. If starting current is reduced the starting torque is reduced in proportion to the______(18)_____. If the reduction of torque is excessive a _____(19)_____induction motor may need to be used.

SECTION C

1. A three phase 415 volt 22 kilowatt delta connected squirrel cage induction motor has a rated line current of 45 amperes and a rated full load speed of 1440 r.p.m. If the motor takes six times rated current, and provides 150 percent of full load torque when started direct on line determine:-

   a) the rated torque produced by the motor; (145.9Nm.)
   b) the starting current taken by the motor; (270A.)
   c) the starting torque delivered by the motor; (218.9Nm.)
   d) the phase current at starting in each winding when connected in delta; (155.9A.)
   e) the current in each winding, and the line current taken from the supply if they were re-connected in star to the supply. (90A.)
   f) the starting torque if the motor were connected in star (hint;- torque produced is proportional to **phase** voltage squared, ie $T_2 = T_1 \; x \left(\frac{V_2}{V_1}\right)^2$) (72.95Nm)

SECTION D

1. Figure 1 is a Torque - Speed curve for a particular motor which takes 140 amperes from the supply when started direct on line. The supply authority requires the starting current to be reduced to a maximum of 100 amperes. To do this the motor voltage is reduced to 0.7 of normal voltage using resistors in series with the motor at starting (primary resistance starter).

   a) Calculate the effect that the reduction of starting voltage would have on the starting torque of the motor; (Hint - reduction of torque = (reduction of voltage)^2).

   b) On Figure 1, draw a new Torque - Speed curve for the motor at the reduced voltage. (Hint - the curve will be reduced vertically by the proportion calculated in (a))

   c) At the reduced voltage would the motor still be able to start:-

      i. the fan (Load A)?

      ii. the pump (Load B)?

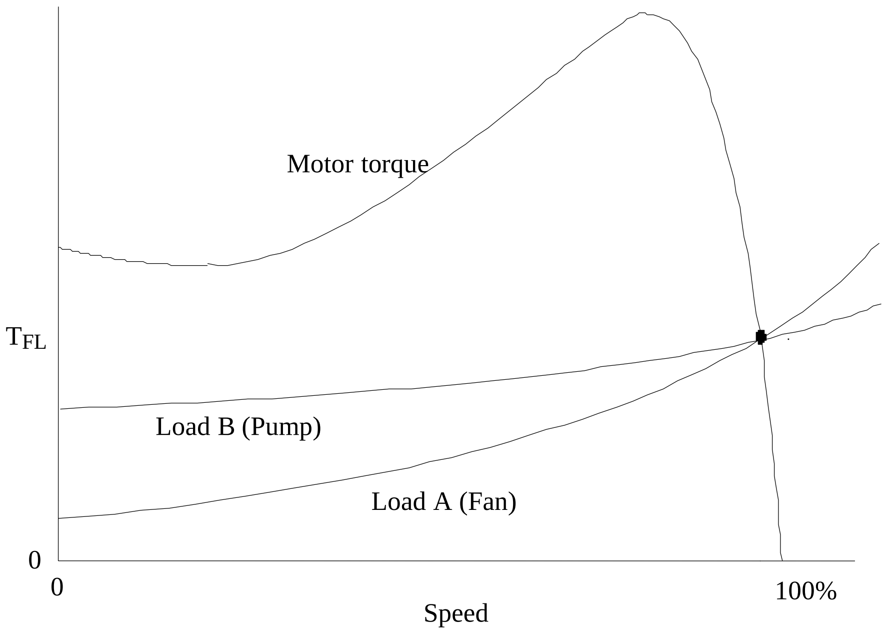


Figure 1

SINGLE PHASE SPLIT PHASE MOTOR

PURPOSE:

This section introduces the single phase split phase induction motor.

TO ACHIEVE THE PURPOSE OF THIS SECTION:

At the end of this section the student will be able to:

- Describe the principle of operation of the single phase split phase motor.
- Outline the construction and basic characteristics of the single phase split phase induction motor.
- List at least three applications of the split phase induction motor.
- Connect, run and reverse a split phase induction motor.
- List typical faults associated with split phase induction motors.
- Name the tests and describe the testing procedures for the identification of faults associated with split phase induction motors.

REFERENCES:

Electrical Trade Principles 2nd Edition J Hampson & S Hanssen. Section 6

Electrical Principles for the Electrical Trades. 5th Edition. Jenneson J.R.

Pages 232-235.

1. INTRODUCTION

Single phase motors may be divided into two general classes, and in turn, these classes can be broken down into the individual types of motor. Figure 1 illustrates this type of motor classification.

- Single Phase Motors
  - Those with squirrel cage rotors
    - Split phase motors
    - Capacitor Motors
    - Shaded Pole Motors
  - Those with wound rotors
    - Repulsion motors
    - Repulsion start, induction run motors
    - Universal or series motors

Figure 1

The reason for the use of these various types is that a normal single phase winding on the stator -

- does not produce any starting torque,
- because it cannot develop a rotating magnetic field.

It has already been shown that the single phase magnetic field simply

- pulsates or alternates in direction with the changes in the current,
- without producing any tendency to rotate.

Single phase motors constructed on the rotating magnetic field principle must have some auxiliary help to enable a rotating magnetic field to be produced. Such auxiliary help may be in the form of a split phase, shaded pole, etc, as will be explained.

2. POLYPHASE INDUCTION MOTOR RUNNING AS A SINGLE PHASE MOTOR

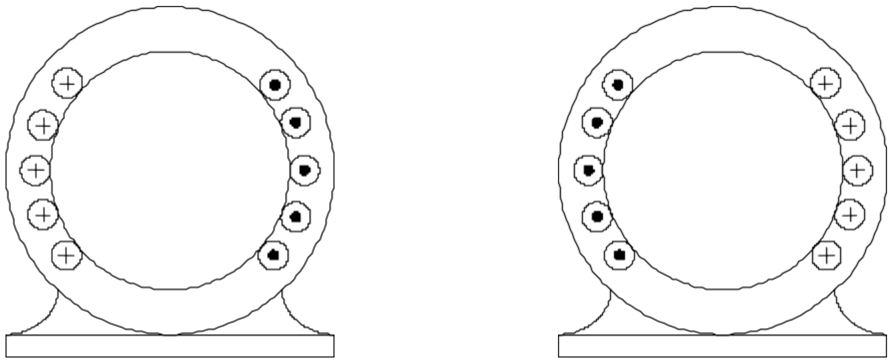
As has been demonstrated, if a polyphase induction motor is running and then has two of its phase windings open circuited, it will

- continue to run (as a single phase motor),
- but it will not re-start after having been shut down.

However, if it is again started and partly brought up to speed mechanically by spinning the shaft, it will run and carry its load as a polyphase motor does, but not as efficiently. The motor can be started and run as a single phase motor in either direction, regardless of its original direction of rotation as a polyphase motor.

3. SINGLE PHASE INDUCTION MOTOR

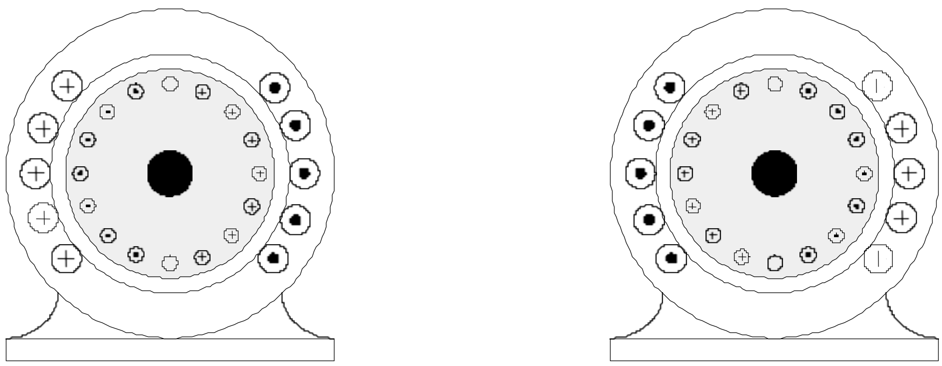
A single phase winding supplied from an alternating current source produces a field that is alternating in magnitude and direction, but with a constant axis. This pulsating field will not produce a torque.



Positive half cycle　　Negative half cycle

Figure 2

The reason for this can be seen in figure 3. If a rotor is placed in the magnetic field produced by a single phase field system, the squirrel cage winding acts as the secondary of a transformer and emfs are induced in the rotor conductors by transformer action. These induced emfs cause rotor currents to flow which are at all times in such a direction as to oppose any change in the magnetic field of the stator (Lenz's Law). For the arrangement shown in figure 3, the rotor currents form two bands in opposite directions, one to the left and one to the right of vertical, which establish a rotor field along the axis of the stator field.

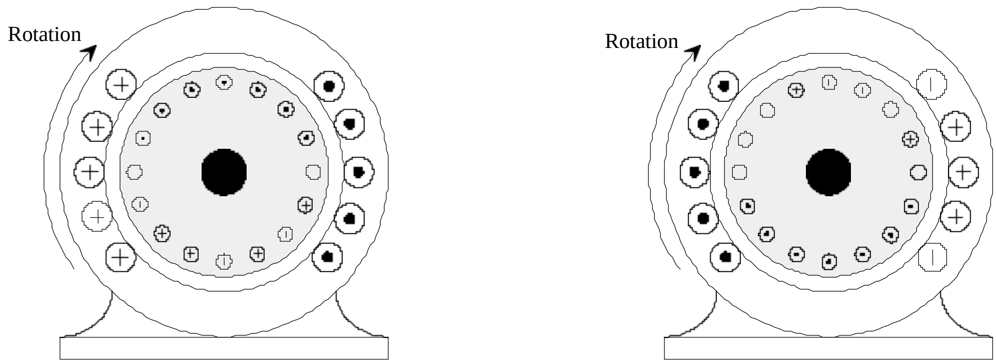


Positive half cycle　　Negative half cycle

Figure 3

The net effect of this action is that the rotor is locked in position by the magnetic attraction of the primary and secondary fields. Thus not only is there no starting torque developed by the motor, but also a torque must be applied to cause the rotor to rotate.

When the rotor is started mechanically by spinning the shaft, the rotor conductors cut the stator magnetic field and cause emfs to be induced. The currents circulating in the rotor bars as a result of these induced emfs produce a field with an axis at right angles to the stator field. This is shown in figure 4.



Positive half cycle

Negative half cycle

Figure 4

The combination of the two magnetic fields at right angles results in a rotating flux which serves the same purpose as that produced by the stator windings of a three phase induction motor. The result of these two fields is a rotating magnetic field which, when applied to the rotor, maintains the rotor in motion. The speed at which this field rotates is known as the "***synchronous speed***", and can be determined using the equation -

where: n_S = synchronous speed in rpm

f = supply frequency in hertz

P = number of stator poles

Figure 5 shows the typical torque-speed curve for a single phase stator winding. Although the starting torque is zero, the motor develops a reasonable value of torque as it approaches synchronous speed. As a result, once a single phase motor has started to rotate, the motion is maintained and the rotor develops a torque that can drive a load.

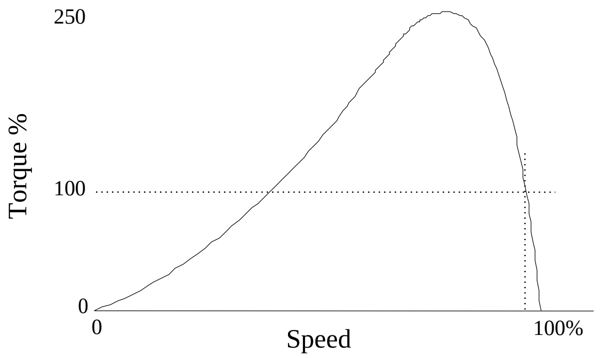


Figure 5

The various modifications of single phase motors are designed essentially to create the initial torque that can start the rotor spinning.

4. SPLIT PHASE MOTOR

To produce a starting torque in a single phase motor, a rotating field must be created. This is done by fitting two windings to the stator, as shown in figure 6. These windings are known as the -

- ____
- ____

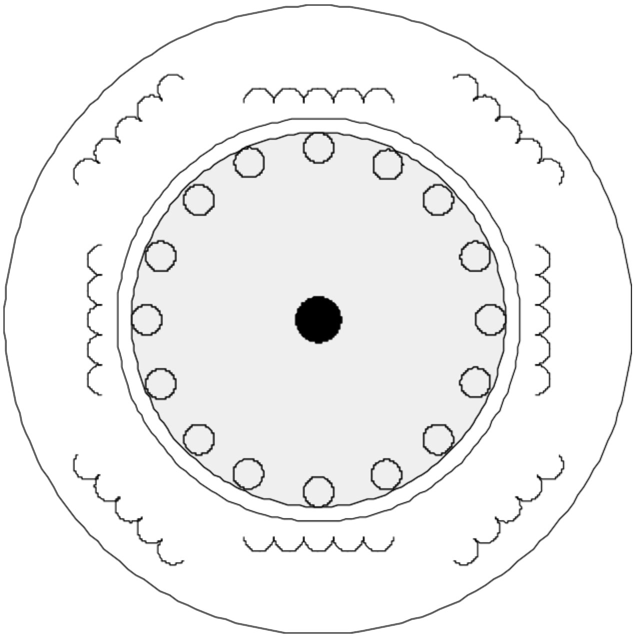


Figure 6

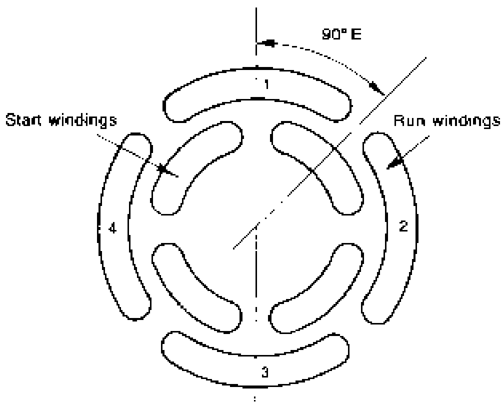


Figure 7

The start winding is placed near the tops of the slots and is displaced from the main or run winding by 90 electrical degrees. See figure 7.

To make the two windings electrically dissimilar they are wound with different gauge wires, with a different number of turns and are physically positioned at different depths in the stator slots. The windings are named by the function that they serve with respect to the operation of the motor.

It is important to note that the two windings are always wound to produce the same number of poles. That is, if the main winding is wound with four poles the auxiliary winding will also be wound with four poles.

5. WINDING CHARACTERISTICS

Table 1 highlights the characteristics of the main and auxiliary windings of the split phase motor.

Table 1

	Main Winding (run or working winding)	Auxiliary Winding (start winding)
Physical Characteristics	heavy gauge wire	fine gauge wire
	large number of turns	small number of turns
	wound deep in stator slots	wound in the top of stator slots
Electrical Characteristics		

Because of the characteristics of the auxiliary winding, high resistance wire and low inductance, the winding cannot be left connected to the supply for an extended period. If it was, the winding would overheat and burn out. To eliminate this problem, the auxiliary winding is connected to the supply only during the starting period and once the rotor has reached

- approximately__________________________________the winding is disconnected
- via a____.

The circuit diagram for the split phase motor is shown in figure 8.

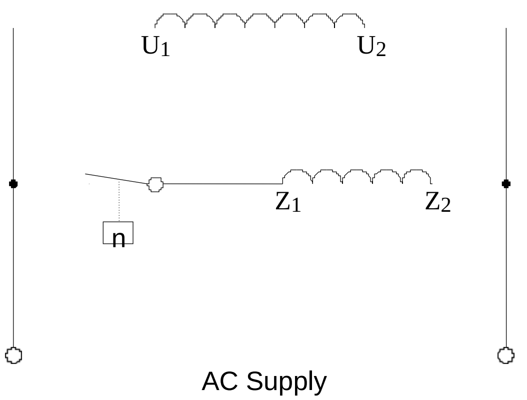


Figure 8

The phasor diagram of figure 9 shows the phase relationship between the currents (and flux) in the windings of the split phase motor.

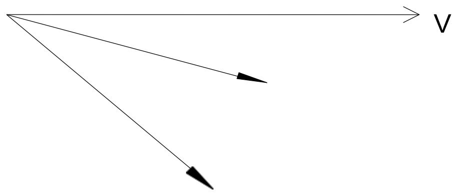


Figure 9

Since the winding currents are out of phase (split) by approximately 30 electrical degrees, their resultant magnetic fields will also be out of phase by the same amount.

The phasor addition of the two fields will produce a non-uniform, rotating magnetic field during the starting period. This non-uniform field acting on the rotor produces sufficient starting torque for the rotor to commence rotation and accelerate up to speed. After the motor has run up to speed, the auxiliary winding is open circuited.

The vibration and humming noise associated with split phase motors when they are started is due to the non-uniformity of the rotating magnetic field.

6. CONSTRUCTION

The constructional breakdown of the split phase motor is shown in figure 10.

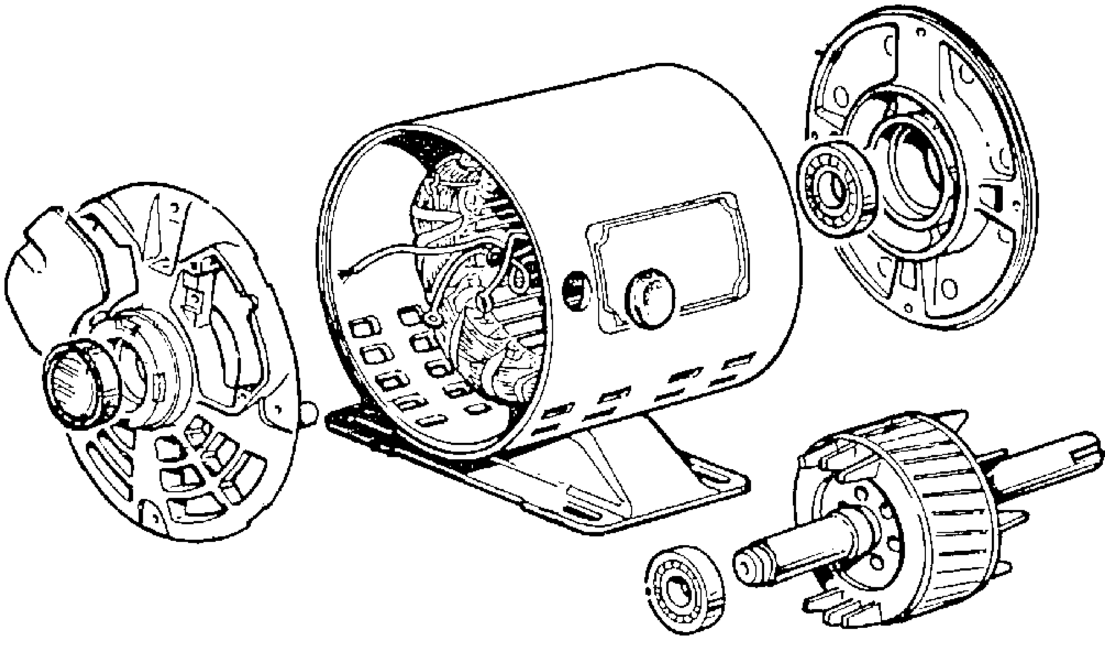


Figure 10

7. STARTING

There are two methods that are commonly used to disconnect the auxiliary winding from the supply once the motor has started -

- ____
- ____

As shown in figure 11, the centrifugal switch is made up of basically two parts -

- the switch contacts - which are usually mounted on the inside of the end shield
- the centrifugal device - which is mounted on the shaft of the rotor.

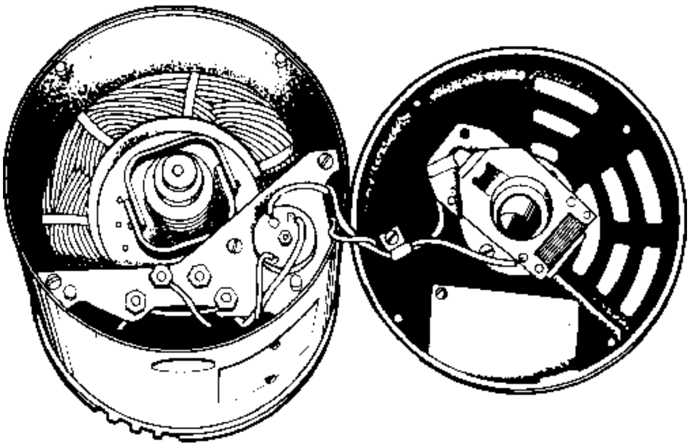


Figure 11

With the rotor at standstill the force exerted by the springs on the centrifugal device hold a sliding collar back away from the rotor and the contacts are closed.
See figure 12.

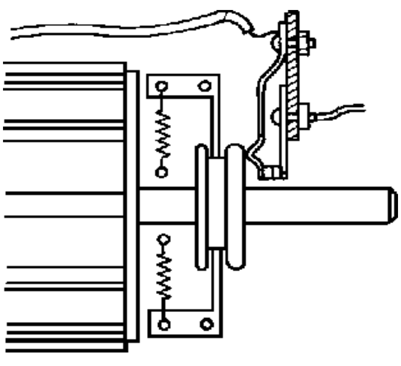


Figure 12

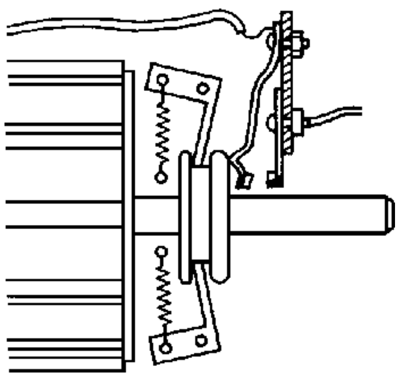


Figure 13

When the motor is started, the rotor accelerates towards synchronous speed. At approximately 75% of rated speed the forces exerted on the weights of the centrifugal device overcome the spring tension, causing the weights to fly out from the shaft and the collar to slide along the shaft toward the rotor and open the contacts. See figure 13.

When the motor is turned off, the switch closes at approximately 25% of rated speed.

The alternative to the centrifugal switch is the current relay, which consists of a few turns of heavy gauge winding wire as shown in figures 14 and 15.

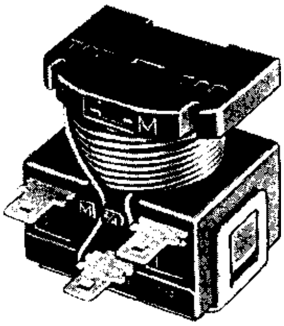


Figure 14

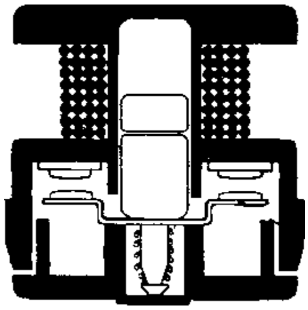


Figure 15

The coil of the current relay is connected in series with the main winding and the contacts of the current relay are connected in series with the auxiliary winding. See figure 16.

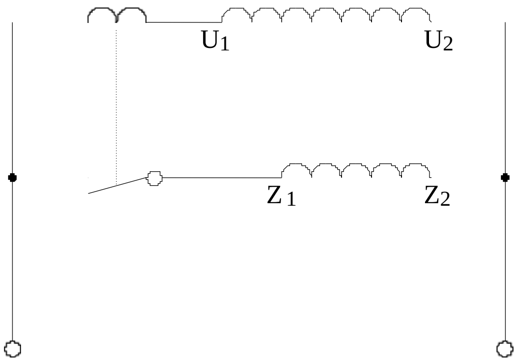


Figure 16

The large starting current of the main winding causes the relay to close its contacts, connecting the auxiliary winding to the supply and allowing the motor to start.

With the motor started the main winding current decreases and the relay contacts open, disconnecting the auxiliary winding.

8. SPLIT PHASE MOTOR CHARACTERISTICS

The characteristics of the split phase motor are as detailed below -

- typically the starting current is________________________________the rated current.
- starting current is____________and___________as the motor accelerates up to speed.
- typically the starting torque is_________________________the rated full load torque.
- typical output power ratings are________________________________.
- the number of starts/unit time is limited due to heating of the ____________ winding.

A generalised torque-speed characteristic for the split phase motor is shown in figure 17.

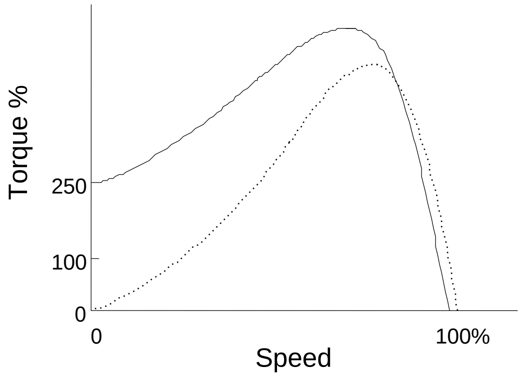


Figure 17

The main advantage of this type of motor is that it is operated from a single phase supply, whereas the main disadvantages are -

- ____ and
- ____.

Practical applications include -

- washing machines
- blowers
- buffing and polishing machines
- grinders
- machine tools.

9. SPLIT PHASE MOTOR REVERSAL

The split phase motor will rotate in a direction governed by the instantaneous direction of current flow in the main and auxiliary windings.

To reverse a split phase motor it is necessary to reverse the connections to the -

- ____ or the
- ____, but not both.

Figure 18 shows the connections for a split phase motor to operate in the forward direction.

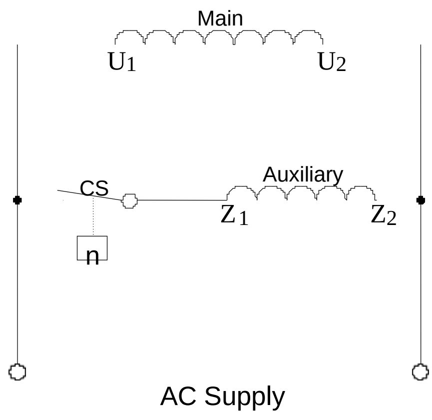


Figure 18

Example: 1

Draw the necessary connections on figures 19 and 20 to reverse the direction of rotation of the motor, firstly by reversing the auxiliary winding and secondly the main winding.

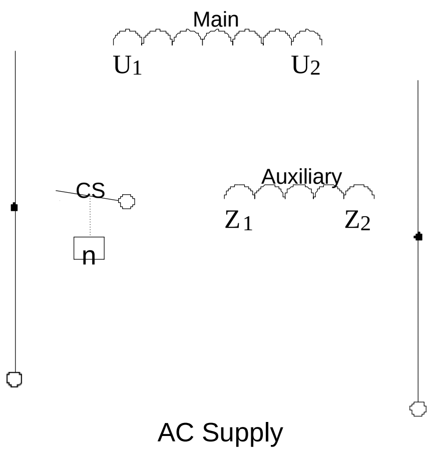


Figure 19

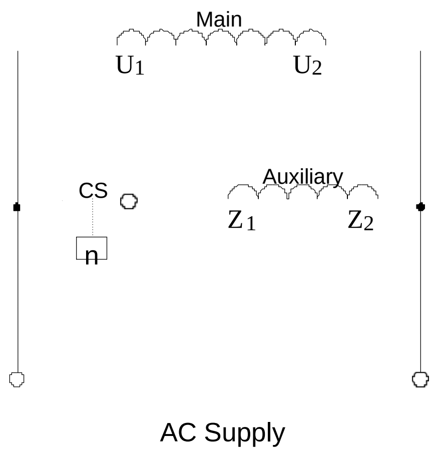


Figure 20

Note - because of the low starting torque produced, the split phase motor does not lend itself to reversal from a running condition.

10. OVERTEMPERATURE PROTECTION

Small single phase motors are often too small to use separate 3 terminal thermal overload protection devices. Protection is often accomplished by the use of thermistors or 'Klixons'.

Thermistors are made from semiconducting metal oxides and are embedded into the stator windings of a motor to detect temperature change. The thermistors have a positive temperature co-efficient (PTC), that is, as their temperature goes up, so does their resistance. These devices are connected to external control equipment and are designed to stop the motor should the operating temperature exceed 150% of normal. Thermistors are ideally suited to motors that have poor ventilation.

Klixons are placed on the end shield of a motor and detect the heat being radiated out from the windings. These devices are wired in series with the main winding and disconnect supply should the motor get too hot. Klixons can be of the manual or automatic reset type. Klixons are usually used for motors rated 550W or less.

11. TESTING AND FAULT FINDING

The insulation resistance between windings and between windings and earth must be at least equal to or greater than 1MΩ.

The motor frame and associated exposed metal parts must be suitably earthed.

Given that the auxiliary winding is designed for intermittent operation only, it is the winding which is generally affected by fault conditions. This comes about primarily because of the fine gauge wire with which it is wound, and the associated faults are usually caused by overheating.

Table 2 lists some of the common faults associated with split phase motors.

Table 2

Damage to Auxiliary Winding may be due to	Possible Causes for Not Starting
contacts of the centrifugal switch fused	loss of supply
current relay contacts fused	thermal cut-out needs resetting
too frequent start/stop actions	oxidation of centrifugal switch contacts
overload - causing prolonged acceleration	open circuit in either winding
incorrectly connected windings	locked rotor
low supply voltage	

SINGLE PHASE SPLIT PHASE MOTOR

PURPOSE:

To develop the students ability to carry out the testing of a single phase motor to correctly connect its windings, and determine whether the motor can be safely connected to the supply.

TO ACHIEVE THE PURPOSE OF THIS SECTION:

At the end of this practical assignment the student will be able to:

- measure the resistance and inductance of the start and run windings of a single phase split field motor.
- correctly connect the motor to run in a specified direction.
- carry out tests to determine whether the motor is safe to connect to the supply.

EQUIPMENT:

- 1 x 24 volt split phase induction motor + single bed
- 1 x LCR meter
- 1 x insulation resistance tester
- 2 x digital multimeters
- 1 x AC current clamp
- 4mm connection leads

NOTE:

This practical segment is to be completed by students on an individual basis.

The time given per student is to be no longer than 40 minutes at the bench.

– REMEMBER –
– WORK SAFELY AT ALL TIMES –
Observe correct isolation procedures

PROCEDURE:

1. WINDING CHARACTERISTICS

1. Using an LCR meter as an ohmmeter measure the resistance of the main and auxiliary windings of the motor. Use the resistance range which gives the most accurate value. Record your results in table 1.

Table 1

	Main Winding	Auxiliary Winding
Resistance - Ω		
Inductance - mH		

2. Using the LCR meter measure the inductance of the main and auxiliary windings of the motor. Use the inductance range which gives the most accurate value. Record your results in table 1.
3. Connect the main winding to the single phase supply as shown in figure 1.

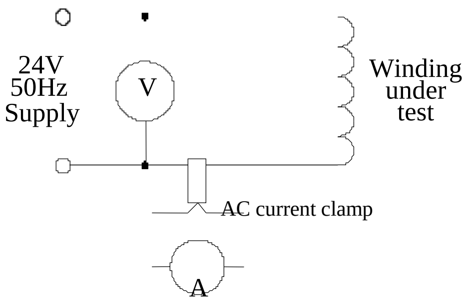


Figure 1

4. Measure the voltage applied and the current through the winding and record these values in table 2.

Table 2

	Main Winding	Auxiliary Winding
Applied Voltage volts		
Current amperes		
Impedance Ω		
Power Factor		

5. Repeat the procedure with the auxiliary winding.

6. Complete table 2 by calculating for each winding, the -

   impedance $Z = \frac{V}{I}$

   power factor $\cos \emptyset = \frac{R}{Z}$

7. **<u>Do not proceed</u>** until the teacher checks your results and completes the progress table.

Progress Table 1

attempt 1	attempt 2	attempt 3
5	2	0

2. MOTOR TESTING

1. Connect the windings of the motor as shown in figure 2.

   <u>Do not</u> connect the motor to the supply.

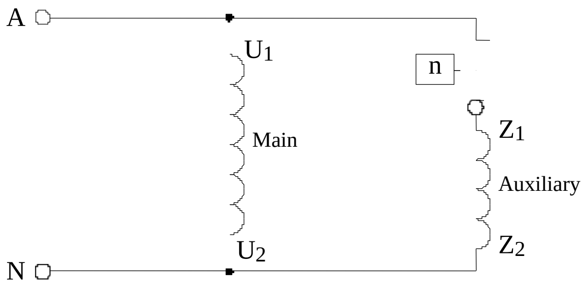


Figure 2

2. Use appropriate instruments to carry out insulation resistance and continuity tests on the motor and supply leads. Record all results.

   Insulation resistance: active and neutral (joined) to earth_____________ohms.

   Winding continuity: active to neutral resistance _____________ohms.

3. Check that the shaft rotates freely by hand. YES / NO (tick one)

Yes	No

4. Do the results of procedures 2 and 3 show that the motor is in a suitable condition to be connected to the supply? YES / NO (tick one)

Yes	No

5. If the answer to 3 is YES, proceed to Motor Operation, if the answer is NO, check with your teacher.

3. MOTOR OPERATION

1. Connect the motor to the single phase 24V supply, switch on and record the motor direction of rotation looking at the drive end.

   Drive end direction of rotation = ______________________________

2. Switch off the supply and disconnect the motor from the supply.
3. To reverse the motor direction of rotation, reconnect as shown in figure 3.

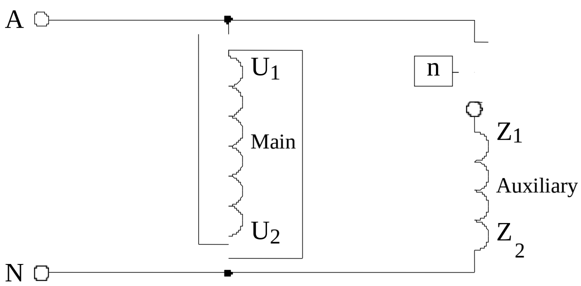


Figure 3

4. Reconnect the motor to the single phase 24V supply, switch on and record the direction of rotation.

   Drive end direction of rotation = ______________________________

5. **<u>Do not proceed</u>** until the teacher checks your results and completes the progress table.

Progress Table 2

attempt 1	attempt 2	attempt 3
5	2	0

6. Switch off the supply, then disconnect the circuit.
7. Please return all equipment to its proper place, safely and carefully.

4. OBSERVATIONS:

1. Based on the values determined in step 1, compare the electrical characteristics of the two windings of the split phase motor tested? That is, compare the resistance and inductance of the two windings.

2. Which of the two windings of a split phase motor has the lower power factor?

3. What determines the direction of rotation of the split phase induction motor?

4. Given the split phase motor tested was a 4 pole machine, determine the motors synchronous speed, when supplied from a single-phase 50Hz, AC supply.

5. What tests need to be carried out to ensure a split phase motor is safe to connect to the supply?

6. Explain how to reverse the direction of rotation of a split phase motor.

NOTES

****

SINGLE PHASE SPLIT PHASE MOTOR

SECTION A

In the following statements one of the suggested answers is best. Place the identifying letter on your answer sheet.

1. A single phase winding produces:-
   a) a stationary magnetic field;
   b) a rotating magnetic field;
   c) a steady magnetic field;
   d) an alternating magnetic field.

2. To develop a rotating magnetic field a split phase induction motor simulates a:-
   a) two phase motor;
   b) three phase motor;
   c) series universal motor;
   d) shaded pole motor.

3. If motor load is reduced from full load to three quarters of full load you would expect that:-
   a) speed would increase and current would increase;
   b) speed would decrease and current would decrease;
   c) speed would increase and current would decrease;
   d) speed would decrease and current would increase;

4. The angle of phase displacement between the start and run winding currents of a split phase induction motor is approximately:-
   a) 10 degrees;
   b) 30 degrees;
   c) 90 degrees;
   d) 120 degrees.

5. The single phase split phase motor is reversed by:-
   a) reversing the supply connections;
   b) reversing the auxiliary winding connection;
   c) reversing the armature connection;
   d) reversing both the auxiliary winding and armature connections.

6. If the centrifugal switch on a split phase motor goes permanently open circuit:-
   a) the motor will not start;
   b) the start winding will burn out;
   c) the start capacitor will burn out;
   d) starting torque will drop to about half of normal value.

7. The auxiliary winding switch should open when:-
   a) rotor speed is about 25 percent of rated speed;
   b) rated speed is about 25 percent of synchronous speed;
   c) rotor speed is about 75 percent of synchronous speed;
   d) slip speed is about 75 percent of synchronous speed.

8. The run winding in a split phase induction motor is placed in:-
   a) the top of the slot to increase inductance;
   b) the top of the slot to decrease inductance;
   c) the bottom of the slot to decrease inductance;
   d) the bottom of the slot to increase inductance.

9. Variable frequency speed control of split phase motors is not generally used because:-
   a) the capacitor start motor has higher torque;
   b) the starting switch might not operate;
   c) voltage speed control in more efficient;
   d) pole changing gives smoother speed changes.

10. The auxiliary winding of a split phase motor always has:-
    a) a lower power factor than the main winding;
    b) a higher resistance than the main winding;
    c) a lower resistance than the main winding;
    d) a higher power factor than the main winding.

SECTION B

Blank spaces in the following statements represent omissions. Write the appropriate information on your answer sheet.

The single phase split phase induction motor has two windings. The______(1)_____or _____(2)_____winding in designed to be permanently connected to the supply, and is placed in the______(3)_____of the slot to_______(4)_____the inductive reactance of the winding to give the current a______(5)_____angle of phase difference with the voltage. The winding is wound with a relatively_____(6)_____winding wire so that it does not overheat, giving the winding a relatively______(7)_____ resistance.

The other winding, called the______(8)_____or_______(9)_____ winding is designed

for short periods of operation and will______(10)_____if left connected for long periods. It is wound with_____(11)_____wire than the other winding and has a _____(12)_____number of turns. This gives it a relatively_______(13)_____resistance and______(14)_____inductive reactance, making the phase angle between the winding current and voltage_____(15)_____than that of the first winding.

The winding is turned off at about___(16)___ percent of synchronous speed by either a_____(17)_____ switch in the motor or a_____(18)_____ relay which turns off when the current in the____(19)____ winding____(20)____ to almost rated current.

The windings are displaced by______(21)_____electrical degrees around the stator, and the phase angle between the two currents, which is typically______(22)_____ electrical degrees is adequate to produce an imperfect rotating magnetic field sufficient to start the motor on______(23)_____torque loads. The motor is reversed by reversing the connections on______(24)_____winding.

SECTION C

1. A single phase 240 volt 50 hertz 4 pole split phase motor runs at rated speed of 1425 r.p.m. For full load determine:-
   a) the synchronous speed of the motor; (1 500 r.p.m.)
   b) the slip speed; (75 r.p.m..)
   c) the slip percent; (5%.)
   d) the rotor frequency. (2.5Hz)

SECTION D.

1. Figure 1 represents some torque speed curves for a single phase split phase induction motor.

   a) Which curve represents the torque speed characteristic for the main winding only.

   ____

   b) If the centrifugal switch opens when the slip is 25 percent trace on the curves the total torque speed characteristic for the motor showing the transition from start to run condition.

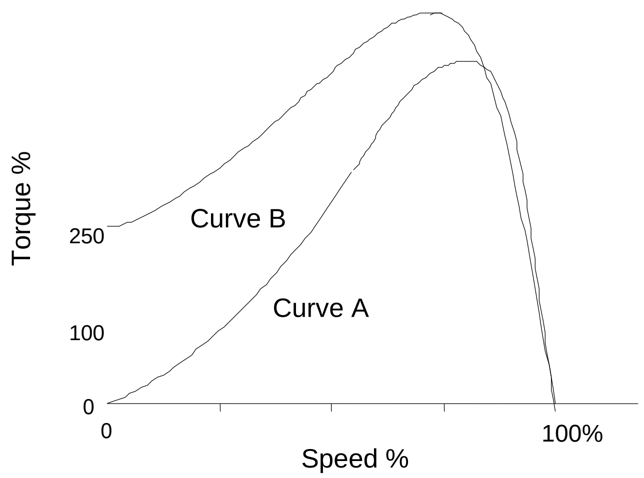


Figure 1

2. Figures 2(a) and (b) show the windings and centrifugal switch for a single phase split phase motor. Complete the circuit to show the connections for both forward and reverse rotations.

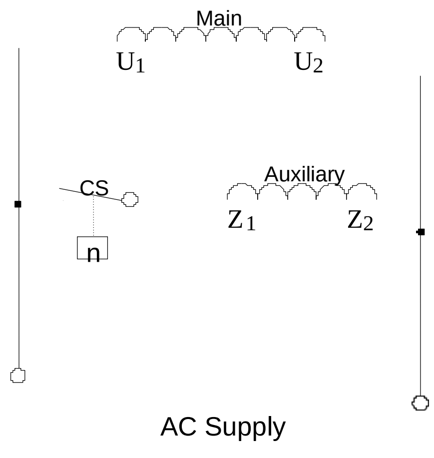


Figure 2 (a)

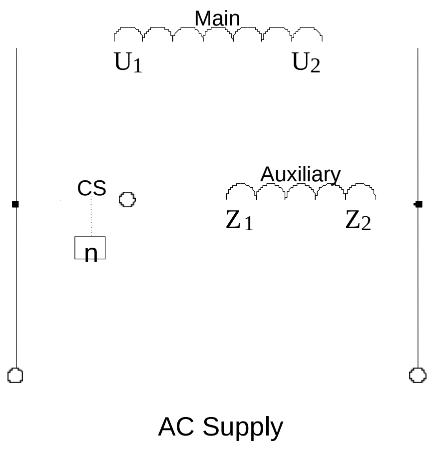


Figure 2 (b)

CAPACITOR & SHADED POLE MOTORS

PURPOSE:

This section introduces the single phase capacitor motors and the shaded pole motor.

TO ACHIEVE THE PURPOSE OF THIS SECTION:

At the end of this section the student will be able to:

- Identify the four single phase induction motors listed -
  - capacitor start
  - capacitor start - capacitor run
  - permanently split capacitor
  - shaded pole
- Explain the principle of operation for each type of motor.
- List the operating characteristics and typical applications for each type of motor.
- Connect, run and reverse each of the motors listed.
- List common motor faults, and demonstrate testing procedures to identify these faults for each type of motor.

REFERENCES:

Electrical Trade Principles 2nd Edition J Hampson & S Hanssen. Section 6

Electrical Principles for the Electrical Trades. 5th Edition. Jenneson J.R. Pages 235-238.

1. THE CAPACITOR START MOTOR

Design limitations restrict the split phase motor to a maximum phase angle between the main and auxiliary winding currents, at start, to approximately_________.

To increase this angle and produce improved starting characteristics a capacitor is connected in series with the auxiliary winding, as shown in figure 1.

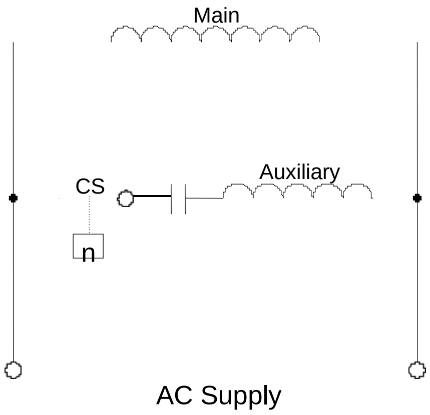


Figure 1

As shown in figure 2, if the correct size capacitor is selected then the two currents will be -

- approximately____and
- improved____is obtained.

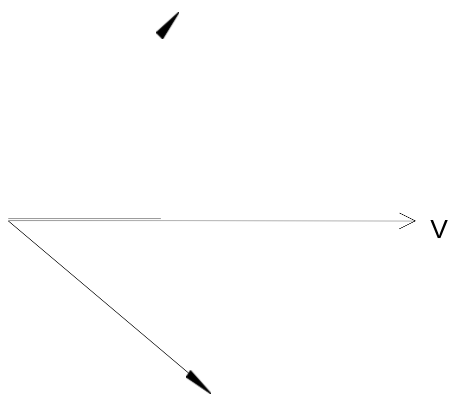


Figure 2

The 90º angle of phase displacement between I_M and I_A provides a more uniform strength of stator flux during starting. Due to this more even field strength, the starting torque -

- is___________________than the equivalent sized split phase motor
- can be up to_____________________________the rated full load torque of the motor.

- Figure 3 shows the torque speed characteristic for a capacitor start motor.

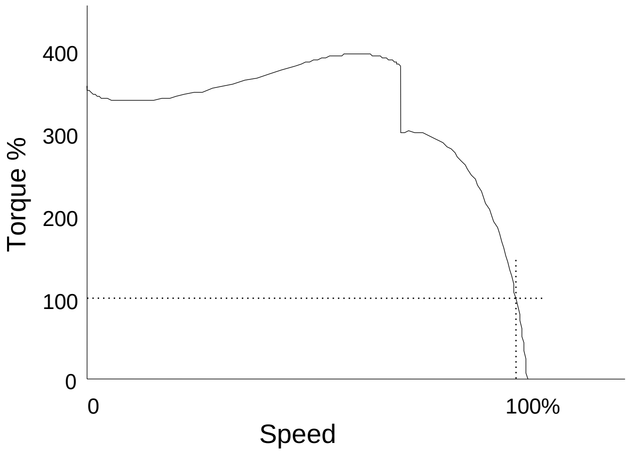


Figure 3

It can be seen that there is a large increase in starting torque due to the addition of the capacitor, while the torque produced is the same as the split phase motor after the switch has operated. In a similar fashion to the split phase motor the centrifugal switch operates at approximately -

- ____.

As with any induction motor, the initial starting current of the capacitor start motor is high and decreases as the motor accelerates to its operating speed. The addition of the capacitor in series with the auxiliary winding requires the centrifugal switch to break a large current at the instant of opening. The breaking of this large starting current can be detrimental to the contacts of the switch, particularly in motors rated at 750W and above.

To overcome this problem, in motors with rating equal to or greater than 750W, it is general practice to switch the auxiliary winding and capacitor out of circuit via a current relay rather than a centrifugal switch. Figure 4 shows the connection of a current relay in a capacitor start motor.

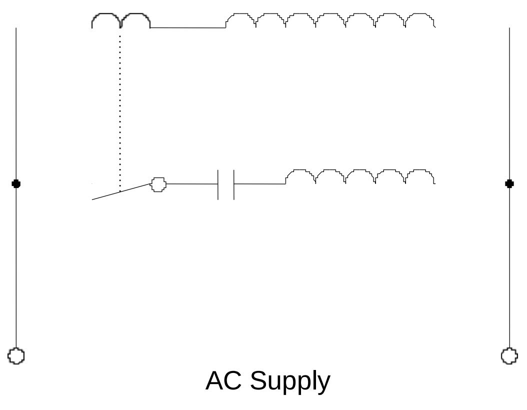


Figure 4

To obtain optimum starting torque the capacitance of the starting capacitor must be -

- matched to the electrical characteristics of the auxiliary winding
- selected to prevent series resonance.

Motor manufacturers specify the capacitance required for a particular motor rating. Typical values include -

- 180W motor - ________________
- 250W motor -_________________.

Motor starting capacitors are usually AC electrolytic capacitors which are rated for a short duration connection time, typically -

- _____________________________________.

Since the starting torque of the capacitor start motor is much higher than that of the basic split phase motor, it is suitable for uses requiring -

- ____ and/or
- ____.

For example -

- washing machines, dishwashers
- fans and blowers
- pumps and compressors.

The capacitor start motor will rotate in a direction governed by the instantaneous direction of current flow in the main and auxiliary windings.

To reverse a capacitor start motor it is necessary to reverse the connections to the -

- _________________________________ or the
- ____________________________, but not both.

Figure 5 shows the connections for a capacitor start motor to operate in the forward direction.

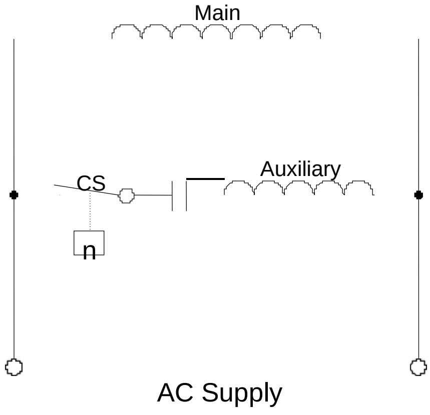


Figure 5

Draw the necessary connections on figures 6 and 7 to reverse the direction of rotation of the motor, firstly by reversing the auxiliary winding and secondly the main winding.

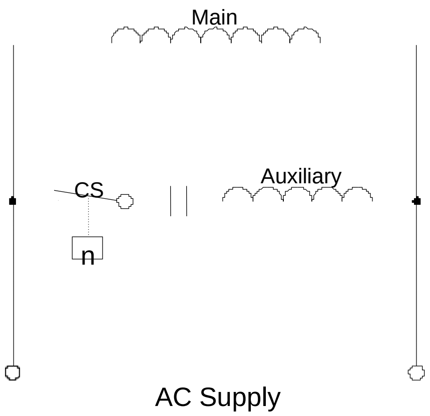


Figure 6

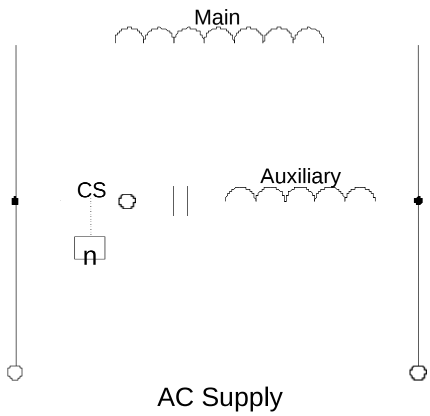


Figure 7

2. CAPACITOR START - CAPACITOR RUN MOTORS

The capacitor start motor just discussed still has a relatively low starting torque, although as we have seen, it is considerably better than the split phase motor. For many applications this does not present a serious limitation.

In cases where high starting torques are required, best results will be obtained if a large value of capacitance is used at starting which is then decreased as the speed increases. In practice, two capacitors are used for starting and one is switched out of circuit by a centrifugal switch once a certain speed is reached, usually at about 75% of rated speed.

As shown in figure 8, the capacitor start - capacitor run motor has two windings permanently connected across the supply. These windings are known as the -

- main winding
- auxiliary winding.

The starting capacitor is of a fairly high capacity, usually of the order of 10 to 15 times the value of the run capacitor.

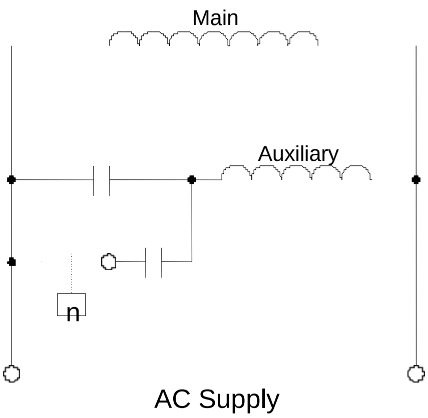


Figure 8

The combined effects of the two windings permanently connected to the supply and the varying values of capacitance result in a rotating magnetic field which tends to be more constant in strength, so producing -

- ____
- ____
- ____.

Consequently, a motor of this type is used to drive heavy duty loads which require substantial starting torque and quietness in running, for example -

- wall mounted air conditioning units
- compressors
- industrial floor polishers.

The important features of the start and run capacitors are listed in table 1.

Table 1

	Run Capacitor	Start Capacitor
Capacitance	10 - 20μF	180W motor ≈ 135μF 370W motor ≈ 150-200μF 550W motor ≈ 180-240μF
Type	AC electrolytic	Oil bath Metallised polypropylene film Soggy foil (high voltage)
Connection	Permanent	Only during starting Limited connection time ≈ 3 seconds Limited number of starts ≈ 20/hour

To reverse a capacitor start - capacitor run motor it is necessary to reverse the connections to the -

- ______________________________

or the

- ______________________________, but not both.

3. PERMANENTLY SPLIT CAPACITOR MOTOR (PSC)

The permanently split capacitor motor also has both windings permanently connected across the supply, with a capacitor in series with one of the windings as shown in figure 9.

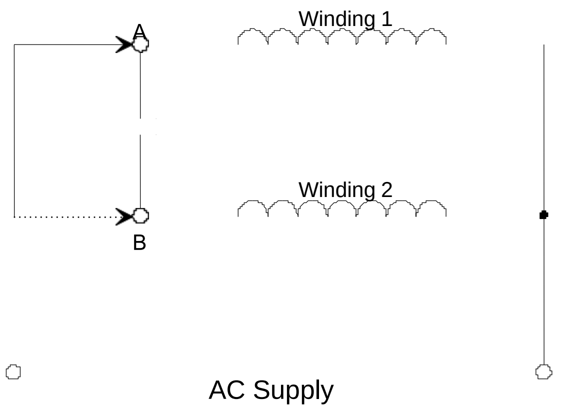


Figure 9

Both windings are identical and because the AC electrolytic capacitor is connected in series with one winding, the current in that winding leads the current in the other, providing the necessary phase displacement to produce a stator rotating magnetic field. However, the phase displacement between the two currents and hence the two fluxes is small, and so the starting torque is low.

By interchanging the supply connection from terminal A to terminal B in figure 9, the capacitor is then in series with winding 1 instead of winding 2. The current in winding 1 leads that in winding 2 and the rotor runs in the reverse direction.

The permanently split capacitor motor has the following advantages -

- ____
- ____
- ____
- ____.

Motors of this type are used to drive low torque loads which may require frequent reversal or speed control, for example -

- ceiling fans
- blowers
- dampers for regulating air flow in air conditioning systems.

4. SHADED POLE INDUCTION MOTORS

In the shaded pole motor, a short circuited turn of copper, called a "***shading coil***", is fitted around one tip of each pole of the motor as shown in figure 10. A squirrel cage rotor is used.

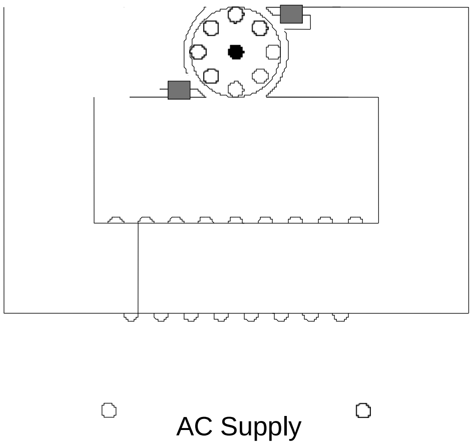


Figure 10

The alternating magnetic flux in the poles, produced by the alternating current in the stator windings, induces emfs in the shading coils. Because of the low resistance path of the shading coil, the currents due to these induced emfs are relatively high and according to Lenz's Law, in such a direction as to oppose the flux change causing them. Consequently the fluxes in the shaded portions of the poles lag behind the fluxes in the unshaded parts and an imperfect rotating magnetic field is produced.

Consider the operation during the positive half cycle of the supply as shown in figure 11.

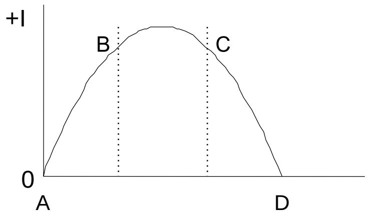


Figure 11

When the supply current rises from A to B, an induced voltage is established in the shading coil. This current produces a flux which opposes the build up of the main flux. As a result the main flux is concentrated in the unshaded section of the pole, as in figure 12.

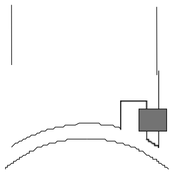


Figure 12

Between B and C there is little current change and very little induced voltage in the shading coil. Consequently, practically no current nor flux is produced in the shading coil. The main flux is at this time nearly always at a maximum value, and is uniformly distributed over the whole pole face, as shown in figure 13.

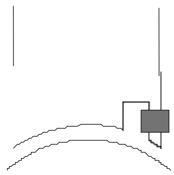


Figure 13

When the current decreases from C to D, an induced voltage is established in the shading coil. The current in the shading coil produces a flux which opposes the collapse of the main flux. The concentration of flux therefore occurs in the shaded section of the pole, as shown in figure 14.

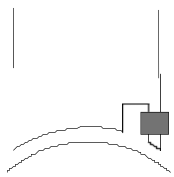


Figure 14

The magnetic field shifts across the pole face, from the -

- ____________________ section to the____________________section of the pole.

This shifting flux is similar to a rotating magnetic field, and produces a small torque, causing the rotor to rotate in the direction of the flux.

The advantages and disadvantages of the shaded pole motor are listed in table 2.

Table 2

Advantages	Disadvantages
simple construction	very low starting torque
low cost	low efficiency (5 - 35%)
high reliability	not easily reversed
low maintenance	limited speed control
simple speed control	

Generally shaded pole motors are not used in applications which require the motor to be reversed. However, if reversal is required it may be done by -

- ____
- ____

Applications of the shaded pole motor include -

- fans
- small pumps
- low power applications where starting torque and motor efficiency is not a concern.

5. MOTOR FAULTS

The faults that occur in split phase motors can also occur in capacitor motors. However, the capacitor motor has an additional component which can fail, that is, the capacitor. Capacitor failure will dramatically alter the performance of all capacitor motors.

The capacitor may fail due to being -

- ______________________________________
- ______________________________________
- ______________________________________.

The following basic tests can be carried out on the job to determine the condition of a capacitor –

- **visual inspection**: replace any capacitor if -
  - it is ________________
  - the capacitor container is_______________or________________.

- **static test**: performed as follows -
  - short the capacitor leads together to ensure the capacitor is fully _________________.
  - set the ohmmeter to the________________resistance range.
  - connect the ohmmeter leads across the___________________.
  - note the_____________________of the ohmmeter pointer.

Capacitors in good condition will cause the ohmmeter pointer to kick to a low resistance indication, gradually increasing in value until a fixed value is obtained -

- start capacitors should have a resistance which is greater than _____________
- run capacitors should have a value of______________.

Capacitors in poor condition will indicate -

- open circuit - ______________________________________
- short circuit - ______________________________________
- readings less than that quoted for start and run capacitors.

A faulty capacitor should always be replaced with one of the same type, capacitance and voltage rating.

Due to their simple construction there is not a great deal that can go wrong with shaded pole motors. Even if the motor stalls it is not uncommon to find that the stator winding is unaffected. The most common fault is dry or sticky bearings which stall the rotor, since the developed torque is very low.

CAPACITOR START MOTOR

PURPOSE:

To compare the operating characteristics of the split phase and capacitor start motors.

TO ACHIEVE THE PURPOSE OF THIS SECTION:

At the end of this practical assignment the student will be able to:

- use appropriate test instruments to test capacitors and determine their serviceability.
- connect a capacitor in series with the start winding of a split phase motor to produce a capacitor start motor.
- measure the starting torque, starting current and full load speed of a split phase motor and a capacitor start motor.
- describe the effect of increasing the value of capacitance connected in series with the start winding of a capacitor start motor.

EQUIPMENT:

- 1 x 24 volt split phase induction motor + double machine bed
- 1 x eddy current load + 1 x inertia wheel
- 1 x insulation resistance tester
- 2 x digital multimeters + 1 x AC current clamp
- 1 x optical tachometer + 1 x stopwatch
- 4 x motor starting capacitors: 1 each - 190-240µF, 240-320µF, 320-400µF and 2500µF
- 4 x used motor starting capacitors: various values - for testing
- 4mm connection leads

NOTE:

This practical segment is to be completed by students on an individual basis.

The time given per student is to be no longer than 40 minutes at the bench.

– REMEMBER –
– WORK SAFELY AT ALL TIMES –
Observe correct isolation procedures

PROCEDURE:

1. CAPACITOR TESTING

1. Select four used motor capacitors. Do not touch the capacitor terminals.

> Using a 4mm lead short circuit each capacitor in turn to ensure that they are fully discharged

2. Read the size of each capacitor as indicated on the package and record in table 1.

Table 1

Capacitor No.	Capacitance Value		Insulation Resistance Ω	Capacitor Condition	
	Named μF	Measured μF		Serviceable (yes or no)	Unserviceable (give reason)
1					
2					
3					
4					

3. Using an LCR meter set to an appropriate capacitance range measure the capacitance of each capacitor. Record your results in table 1.
4. Using an insulation resistance tester (megger) measure the resistance of the dielectric of each capacitor. Record your results in table 1.

> Discharge each capacitor immediately after measuring the insulation resistance of the dielectric

5. <u>**Do not proceed**</u> until the teacher checks your results and completes the progress table.

Progress Table 1

attempt 1	attempt 2	attempt 3
5	2	0

2. SPLIT PHASE MOTOR CHARACTERISTICS

1. Connect the 24V split phase motor as shown in figure 1.

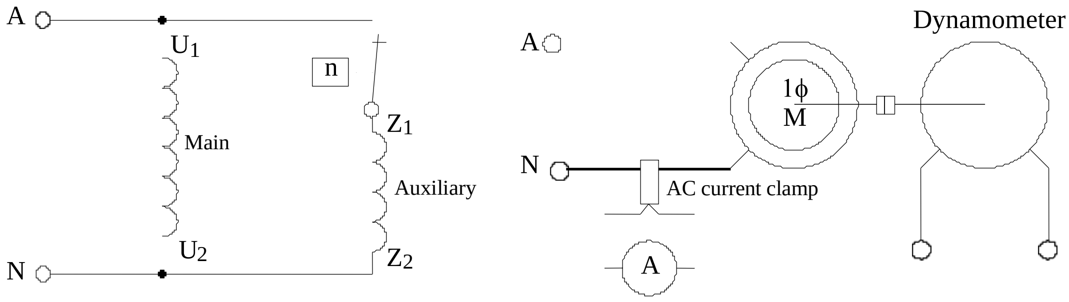


Figure 1

2. Couple the dynamometer to the motor shaft and lock the dynamometer shaft.

> **NOTE**
>
> The following step must be carried out very quickly. The motor has a locked rotor and may be damaged due to excessive current.

3. Switch on the supply and quickly measure and record the locked rotor torque and starting current. Record in table 2.

Table 2

Starting Torque Nm	Starting Current amperes

4. Switch off the supply.
5. Replace the dynamometer with the inertia wheel.
6. Switch on the supply and allow the motor time to accelerate to its final operating speed. Measure and record the speed and current. Record in table 3.

Table 3

Full-load Speed rpm	Full-load Current amperes

7. Switch off the supply.
8. Measure and record the time taken for the motor to reach full load speed and current.

Accelerating time = ________________

9. **<u>Do not proceed</u>** until the teacher checks your results and completes the progress table.

Progress Table 2

attempt 1	attempt 2	attempt 3
5	2	0

3. CAPACITOR START MOTOR CHARACTERISTICS

1. Connect the 24V capacitor start motor as shown in figure 2.

   Note: The capacitor in series with the auxiliary winding has a value of 560µF.

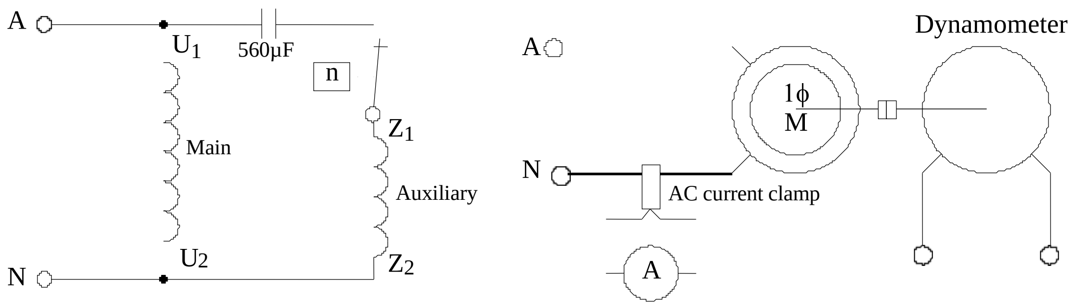


Figure 2

NOTE

The following step must be carried out very quickly.
The motor has a locked rotor and may be damaged due to excessive current.

2. Switch on the supply and quickly measure and record the locked rotor torque and starting current. Record in table 4.

Table 4

Starting Capacitor µF	Starting Torque Nm	Starting Current amperes
190-240µF + 240-320µF = 560µF		
560µF + 320-400µF = 960µF		
2500µF		

3. Switch off the supply.
4. Discharge the capacitor.
5. Adjust the capacitance to 960µF.
6. Switch on the supply and quickly measure and record the locked rotor torque and starting current. Record in table 3.
7. Repeat the procedure for a starting capacitance of 2500µF.
8. Switch off the supply.
9. Replace the dynamometer with the inertia wheel.
10. Using a starting capacitance of 960µF, switch on the supply and allow the motor time to accelerate to its final operating speed. Measure and record the speed and current. Record in table 5.

Table 5

Full-load Speed rpm	Full-load Current amperes

11. Switch off the supply.
12. Measure and record the time taken for the motor to reach full load speed and current.

Accelerating time = ________________

13. Note the direction of rotation of the motor looking at the drive end.

Drive end direction of rotation = __________________________

14. To reverse the motor direction of rotation, reconnect as shown in figure 3.

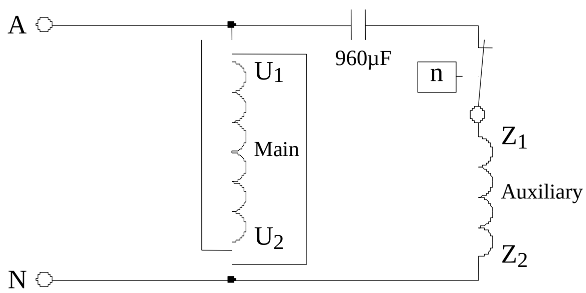


Figure 3

15. Reconnect the motor to the single phase 24V supply, switch on and record the direction of rotation.

Drive end direction of rotation = __________________________

16. **Do not proceed** until the teacher checks your results and completes the progress table.

Progress Table 3

attempt 1	attempt 2	attempt 3
5	2	0

17. Switch off the supply, then disconnect the circuit.

18. Please return all equipment to its proper place, safely and carefully.

4. OBSERVATIONS:

1. Compare the starting torques of the split phase and capacitor start motors.

___

___

___

2. Compare the starting currents of the split phase and capacitor start motors.

___

___

___

3. Compare the accelerating times of the split phase and capacitor start motors.

___

___

___

4. Compare the full-load speeds and currents of the split phase and capacitor start motors.

___

___

___

5. What is the effect of increasing the value of starting capacitance on the starting torque developed by a capacitor start motor?

____

____

____

6. Explain how to reverse the direction of rotation of a capacitor start motor.

____

____

____

7. Based on the results of this practical assignment, which motor, split phase or capacitor start, would be best to drive a load requiring a high starting torque?

____

____

____

NOTES

****

Tutorial 12 **NAME:**

CAPACITOR & SHADED POLE MOTORS

SECTION A

In the following statements one of the suggested answers is best. Place the identifying letter on your answer sheet.

1. The capacitor start induction motor has a capacitor connected:-

a) in series with the auxiliary winding during starting;
b) in series with the running winding during starting;
c) in parallel with the main winding during starting;
d) in parallel with the start winding during starting.

2. The single phase induction motor that is commonly used to drive cooling fans in small appliances is the:-

a) permanently split capacitor motor;
b) shaded pole motor;
c) series universal motor;
d) split phase induction motor.

3. A capacitor start induction motor has an open circuited capacitor. The motor will:-

a) start with reduced torque;
b) fail to start;
c) start normally but stop when the centrifugal switch operates;
d) start in the reverse direction.

4. Impedance protection of shaded pole motors:-

a) reduces overheating when stalled;
b) reduces the starting current;
c) reduces unwanted tripping of overload devices;
d) limits motor current on no load.

5. Electrolytic capacitors are used in starting circuits:-

a) because of their low leakage current;
b) because of their small size;
c) because they are continuously rated;
d) because of their high dielectric strength.

6. If the centrifugal switch on a split phase motor goes permanently open circuit:-

a) the motor will not start;
b) the start winding will burn out;
c) the start capacitor will burn out;
d) starting torque will drop to about half of normal value.

7. The shading coils on a shaded pole motor are used to:-
   a) cause the flux to move across the pole face;
   b) reduce the noise of the motor;
   c) prevent the rotor "poling" or "cogging" with the stator;
   d) allow the motor to be reversed easily.

8. A starting switch is not required in:-
   a) a capacitor start, capacitor run motor;
   b) a split phase motor;
   c) a capacitor start motor;
   d) a shaded pole motor.

9. The single phase motor which would produce the highest starting torque when compared to other motors of a similar rating is the:-
   a) split phase capacitor start;
   b) shaded pole;
   c) split phase;
   d) universal.

10. On a capacitor start, capacitor run induction motor the start capacitor may be identified as having:-
    a) the lower capacitance and a continuous rating;
    b) the higher capacitance and a continuous rating;
    c) the lower capacitance and a short term rating;
    d) the higher capacitance and a short term rating.

SECTION B

Blank spaces in the following statements represent omissions. Write the appropriate information on your answer sheet.

The split phase motor has a maximum phase angle between the main and auxiliary winding currents of approximately______(1)_____degrees. This angle is increased to approximately______(2)_____degrees to produce improved starting characteristics by connecting a capacitor in_______(3)_____with the_______(4)_____winding. This makes the current in the start winding ___(5)___ the current in the run winding. There is a large ____(6)____ in starting torque due to the addition of the capacitor during starting, while the torque produced is the same as the split phase motor _____(7)_____the switch has operated, which occurs at about_______(8)_____ percent of synchronous speed. As with any induction motor, the initial starting current of the capacitor start motor is______(9)_____and______(10)_____as the motor accelerates to its operating speed. In larger motors the centrifugal switch may be replaced with a current relay with it's coil in series with the______(11)_____winding.

The relay closes when the start current is______(12)_____and opens when motor speed______(13)_____and current______(14)_____.

In the capacitor start, capacitor run motor the run capacitor has a______(15)_____ value of capacitance than the start capacitor. The start capacitor is only connected in _____(16)_____with the_______(17)_____winding during starting, being open circuited by the______(18)_____switch at about_______(19)_____percent slip. The run capacitor is left connected in______(20)____with the_______(21)_____winding at all times the motor is running.

The______(22)_____motor has two identical windings displaced by_______(23)_____ electrical degrees around the stator. The______(24)_____may be connected in series with either winding depending on the desired_____ _(25)_____of rotation.

In the______(26)_____motor, a short circuited turn of copper, or "***shading coil***", is fitted around one tip of each pole of the motor. This causes flux changes in the shaded part o the pole to occur______(27)_____the same changes occur in the rest of the pole. As a result flux moves______(28)_____the shaded side of the pole, creating a small torque in that direction. To reverse a shaded pole motor the______(29)_____must be _____(30)_____in the stator.

SECTION C

1. A single phase 240 volt 50 hertz capacitor start induction motor has a run winding which takes 4 amperes at 0.6 lag power factor at start while the start winding/capacitor takes 3 amperes at 0.8 lead power factor. Determine:-
   a) the phase angle of each current and the angle between them; (53.1^{O}lag, 36.9^{O}lead, 90^{O})
   b) the total current taken by the motor at starting. (5A.)
   c) the voltage across the 35uF capacitor. (273V.)

SECTION D.

1. This question relates to the motor illustrated in Figure 1 below.
   a) Identify the type of motor illustrated in Figure 1.
   b) Identify the parts of the motor labelled A, B, C and D.
   c) Is the direction of rotation of the motor clockwise or anti-clockwise?

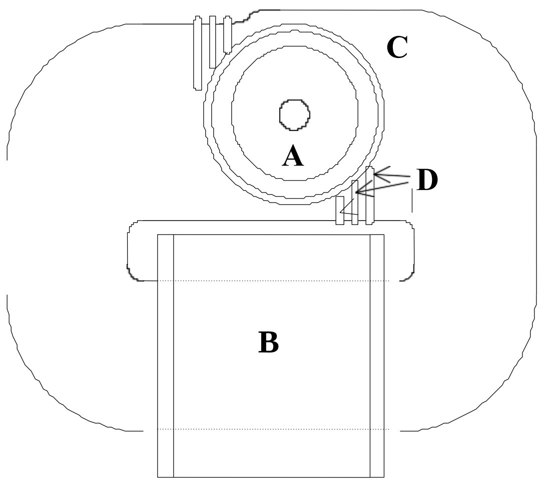


Figure 1

2. Figures 2(a) and (b) show the windings and capacitor for a permanent split capacitor motor. Complete each circuit for different directions of rotation.

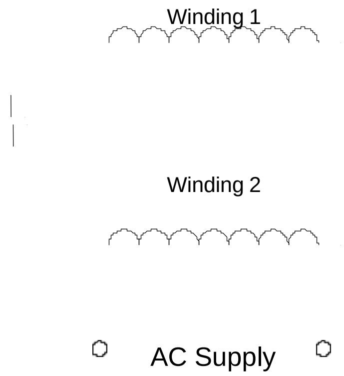


Figure 2(a)

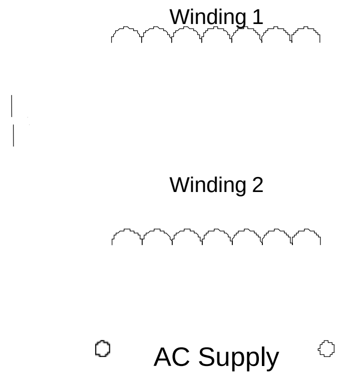


Figure 2(b)

SERIES UNIVERSAL MOTORS

PURPOSE:

This section introduces the series universal motor.

TO ACHIEVE THE PURPOSE OF THIS SECTION:

At the end of this section the student will be able to:

- Explain the principle of operation of the series universal motor.
- Identify by name and state the function of each of the basic parts of a series universal motor.
- List the operating characteristics and typical applications for the series universal motor.
- Connect, run and reverse the series universal motor.
- List common universal motor faults and their possible causes.

REFERENCES:

- Electrical Trade Principles 2nd Edition J Hampson & S Hanssen. Section 6
- Electrical Principles for the Electrical Trades. 4th Edition. Jenneson J.R. Pages 241-242.

1. INTRODUCTION

Universal motors are small, series wound motors which can be operated from either a DC or a single phase AC supply at approximately the same speed. The motor performance is the same in either application, hence the term "***universal***". Figure 1 shows a small universal motor.

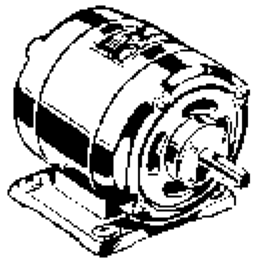


Figure 1

Since universal motors are series wound, their performance characteristics are very similar to those of the series wound DC motor.

Universal motors are usually manufactured in ratings from approximately -

- ______________________________.

The very low fractional horsepower universal motors, with ratings up to 5W are used in such equipment as -

- sewing machines
- fans
- electric shavers
- hair dryers.

The higher ratings, 5W to 560W, are found in -

- drills
- sanders
- circular saws
- vacuum cleaners
- food processors.

There are several types of universal motor in use today. The most popular type is a small, two pole series motor fitted with concentrated field poles, as shown in figure 2. Another type of universal motor has a field winding distributed in slots, much the same as the split phase motor.

Note, the treatment of the universal motor in this module will concentrate on the type of motor fitted with concentrated field poles. The same operation is equally applicable to the motor fitted with a distributed field winding.

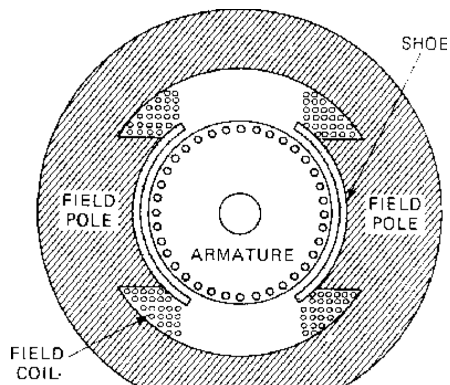


Figure 2

2. CONSTRUCTION

The main parts of the concentrated field universal motor are the -

- **frame** - is of rolled steel, aluminium or cast iron and large enough to hold the field core laminations snugly.

Very often the frame is constructed to form an integral part of the machine it supports.

- **field core** - is constructed of laminations that are tightly pressed together and held by rivets or bolts.

  As shown in figure 3, the laminations are designed to contain both field poles of a two pole motor.

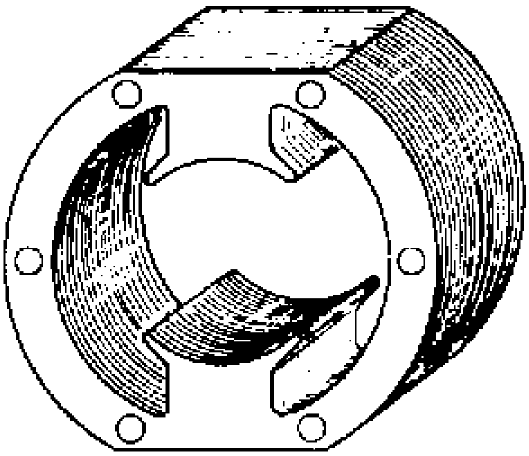


Figure 3

- **field coils** - nearly all universal motors are two pole machines and therefore have two field coils. See figure 4.

  Consist of relatively few turns of wire, generally several hundred turns, and are fitted into the field core as shown in figure 5.

  The field coils when fitted to the field core form field poles which are known as "***salient poles***".

  The field coils are connected in series with the armature winding.

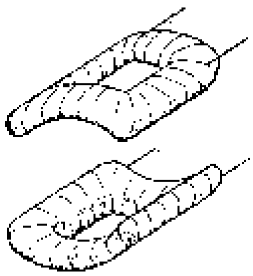


Figure 4

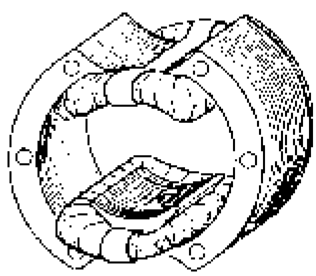


Figure 5

- **armature** - is similar to that of a small DC motor.

  It consists essentially of a laminated core having either straight or skewed slots and a commutator to which leads of the armature winding are connected.

  Both the core and commutator are pressed on the shaft. See figure 6.

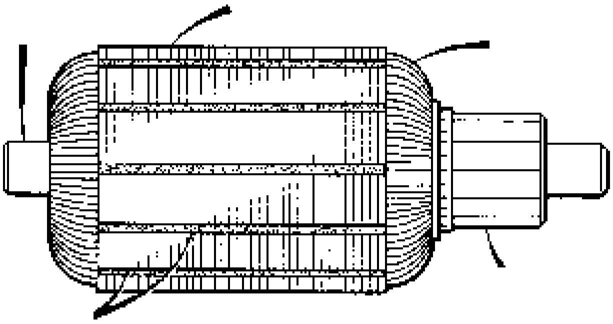


Figure 6

- **end plates** - as in other motors, the end plates are located on the ends of the frame and held in place by screws or bolts.

  The end plates house the bearings, usually of the ball or sleeve type, in which the armature shaft revolves.

  Many universal motors contain an end plate that is cast as part of the frame. Only one end plate can be removed from this type of motor.

  The other end plate has brush holders bolted to it and can be removed, see figures 7 and 8.

  Brush holders and brushes provide the sliding electrical contact between the field poles and the armature.

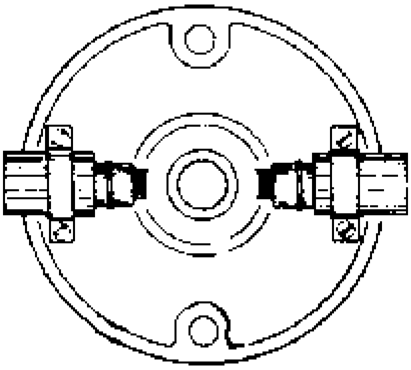


Figure 7

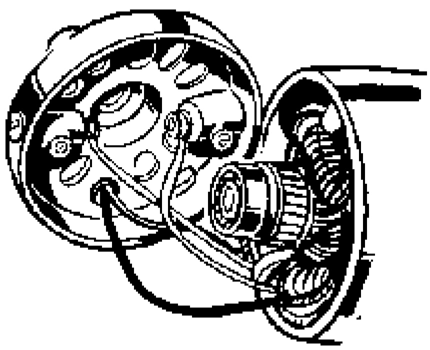


Figure 8

Figure 9 shows an exploded view of the construction of the universal motor.

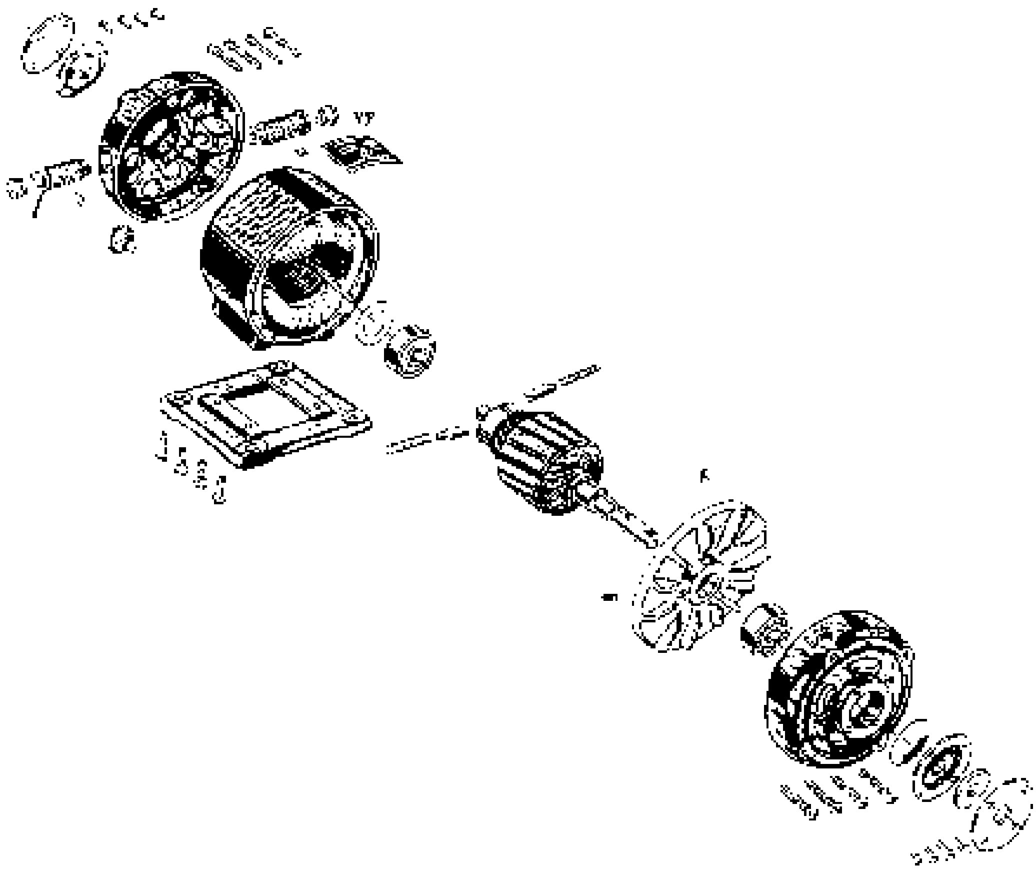


Figure 9

The series universal motor derives it name from the fact that the field windings are connected in series with the armature winding. The connection between the rotating armature winding and the stationary field windings is achieved via the commutator and brush gear. Figure 10 shows the circuit diagram for the universal motor.

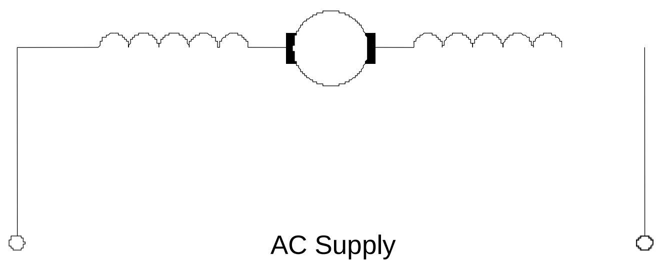


Figure 10

3. OPERATION

The universal motor is so constructed that when the armature and field coils are connected in series and an appropriate supply voltage applied, the magnetic lines of force created by the fields will react with the lines of force created by the armature and cause rotation. This is true regardless of whether the current is alternating or direct.

Assume that during the positive half cycle of the supply current flows through the motor as shown in figure 11.

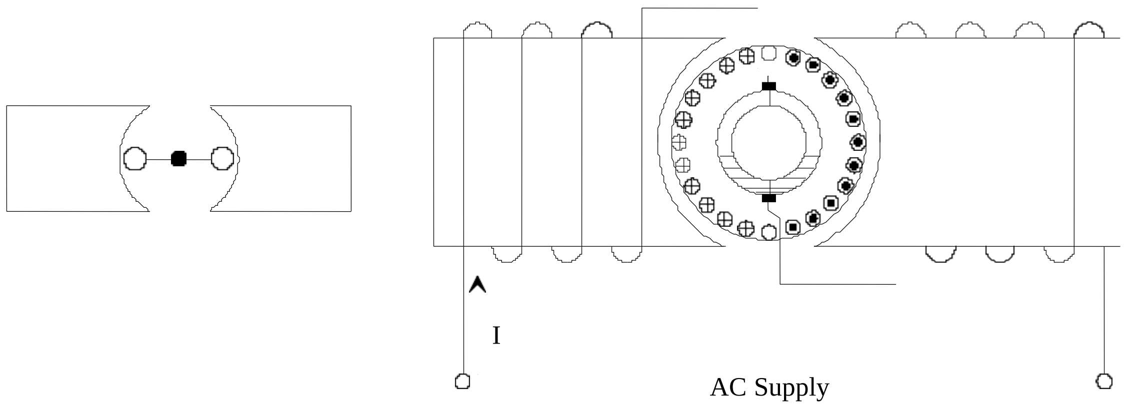


Figure 11

The current flowing through the two field poles will establish two magnetic poles, one north the other south. The same current flows through the armature winding, therefore the armature also establishes a magnetic field. The two magnetic fields interact causing a torque to be developed. As the armature is mounted on bearings, the developed torque will make the armature rotate. The direction of rotation of the armature can be determined by the application of Fleming's left hand rule.

When the supply current reverses, that is during the negative half cycle, the polarities of the field poles are reversed as shown in figure 12. The current through the armature also reverses, so reversing the armature flux. Again, by application of Fleming's left hand rule, it will be found that the torque developed will cause the armature to rotate in the same direction.

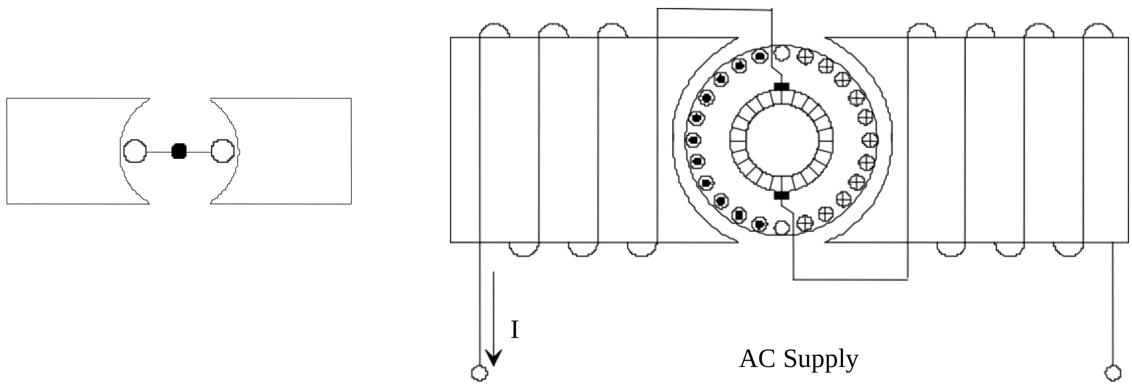


Figure 12

Therefore, in spite of the polarity reversal of motor current the torque developed is unidirectional, showing that a series machine will run as a motor when fed from an AC supply.

To keep the armature continuously turning in the one direction, a commutator is used. The purpose of the commutator is to -

- ____________________________________ of the current flowing in the armature coils as the coils move from the influence of one field pole to the other.

As soon as the armature begins to rotate, the armature conductors cut the magnetic lines of force established by the stator field poles. This causes a voltage to be induced in the armature conductors which opposes the supply voltage. This induced armature voltage is known as the motor -

- _____________________________.

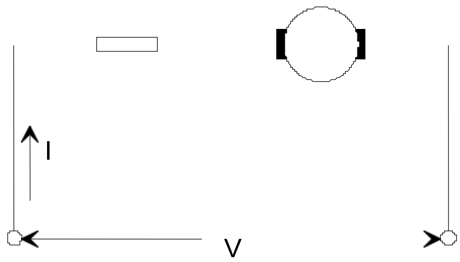
Figure 13 shows the equivalent circuit for the universal motor, in which -.

V = supply voltage

I = motor current

Z = motor impedance

Eg = armature back emf



By applying the laws of series circuits it is found that the supply voltage is given by the equation -

From the voltage equation the current taken by the motor can be determined -

The equation for the determination of motor current illustrates one of the important factors in the operation of the universal motor. That is, the generated back emf developed in the armature is the main current limiting factor as the motor impedance is a low value.

4. UNIVERSAL MOTOR CHARACTERISTICS

At the instant of starting the back emf developed by the motor is equal to___________. Under these conditions the current taken by the motor is given by-

Therefore the starting current is very_______________.

As a result of the very high starting current, the magnetic fields developed by the stator and the armature will be strong, resulting in a starting torque which is -

- _________________________.

As the motor accelerates the -

- back emf ____________________________
- motor current ____________________________
- stator and armature magnetic fields ____________________________
- torque developed____________________________.

The motor will continue to accelerate until it reaches a speed at which the developed torque equals the torque required by the load. The motor will then run at a constant speed unless there is a change in load.

If the load on the motor is increased the -

- motor speed ____________________________
- armature back emf ____________________________
- motor current ____________________________
- stator and armature magnetic fields ____________________________
- torque developed____________________________to drive the additional load.

If the load on the motor is decreased the -

- motor speed ____________________________
- armature back emf ____________________________
- motor current ____________________________
- stator and armature magnetic fields ____________________________
- torque developed__________________________to meet the requirements of the load.

From the previous examination of motor operation it should be seen that the universal motor has the torque-speed characteristics typical of series motors. That is -

- a very high speed on light load,
- rapidly falling speed when load is applied,
- reaching a very low value, or even zero, on overload.

Overall, the speed regulation of the universal motor is poor, that is, there are large variations in speed with changes in load. This is illustrated in figure 14 which shows the typical torque-speed characteristics for the universal motor.

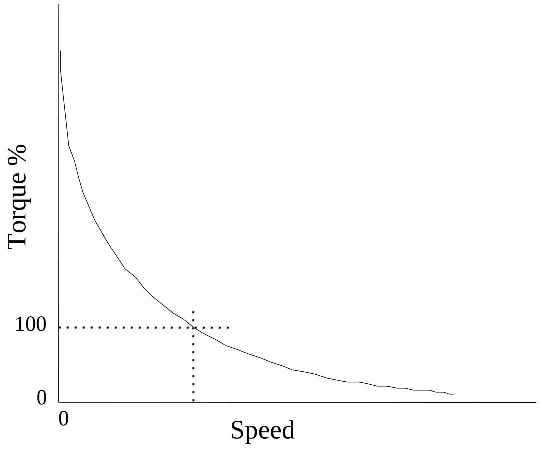


Figure 14

From the characteristic shown in figure 14 it can be seen that under no load conditions the armature can operate at extremely high speeds with the possibility of runaway. This is true for universal motors of higher power ratings and it is normal practice to couple these motors to the load via a built-in gear train so that the motor is always effectively loaded. In the case of motors with lower power ratings the problem does not occur, because the loading applied due to the fan, bearing and windage friction is sufficient to load the motor.

Overall, the universal motor is considered to be a motor which -

- operates at relatively high speed (up to 15000rpm in some appliances)
- has good starting torque characteristics
- has good running torque characteristics

} considering its small size

These characteristics make the series universal motor especially suitable for portable hand tools and appliances.

5. UNIVERSAL MOTOR REVERSAL

The direction of rotation is changed by reversing the flow of current through either the

- ___________________________

  or the

- ___________________________.

The usual method is to interchange the leads on the brush holders. See figures 15 and 16.

Forward rotation

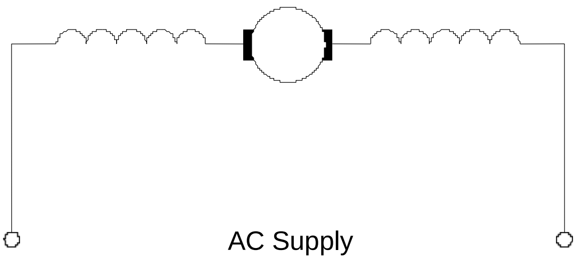


Figure 15

Reverse rotation

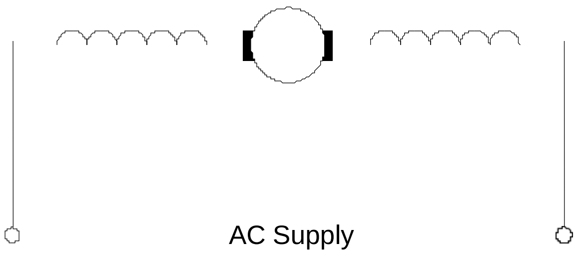


Figure 16

Some portable power tools are fitted with double pole reversing switches. Figure 17 illustrates the connection and operation of these switches.

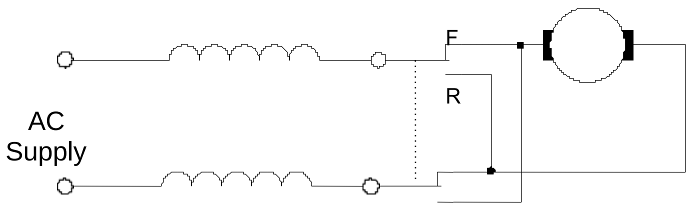


Figure 17

6. MOTOR FAULTS

The universal motor is not as robust or as simple in construction as the induction motor.

Table 1 lists common motor faults and the symptoms they produce

Table 1

Symptom	Possible Cause
	shorted field poles open circuit armature coils short circuited armature coils high mica between commutator segments worn bearings motor not designed for reversal
	worn bearings or excessive load dry bearings short circuited armature coils short circuited field coils
	short circuited armature short circuited field overload incorrect voltage
	short circuited armature coils short circuited field coils worn bearings
	worn brushes open circuit field coil open circuit armature coils faulty switch No supply

NOTES

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SERIES & SHADED POLE MOTORS

PURPOSE:

To observe the operation of single phase series and shaded pole motors.

TO ACHIEVE THE PURPOSE OF THIS SECTION:

At the end of this practical assignment the student will be able to:

- connect the single phase series motor to both AC and DC supplies for both forward and reverse directions of rotation.
- describe the effect of variation of load on the series motor.
- connect a the shaded pole motor.
- describe the effect of variation of load on the shaded pole motor.
- draw graphs of speed and current versus torque for both motors.

EQUIPMENT:

- 1 x 24 volt series motor + double machine bed
- 1 x 24 volt shaded pole motor
- 1 x dynamometer
- 1 x 24 volt single phase supply + 1 x variable DC power supply
- 1 x AC/DC current clamp
- 1 x rectifier panel
- 1 x optical tachometer
- 4mm connection leads

NOTE:

This practical segment is to be completed by students on an individual basis.

The time given per student is to be no longer than 40 minutes at the bench.

– REMEMBER –
– WORK SAFELY AT ALL TIMES –
Observe correct isolation procedures

Procedure:

1. SERIES MOTOR - DC OPERATION

1. Connect the series motor as shown in figure 1 and couple the dynamometer and motor shafts.

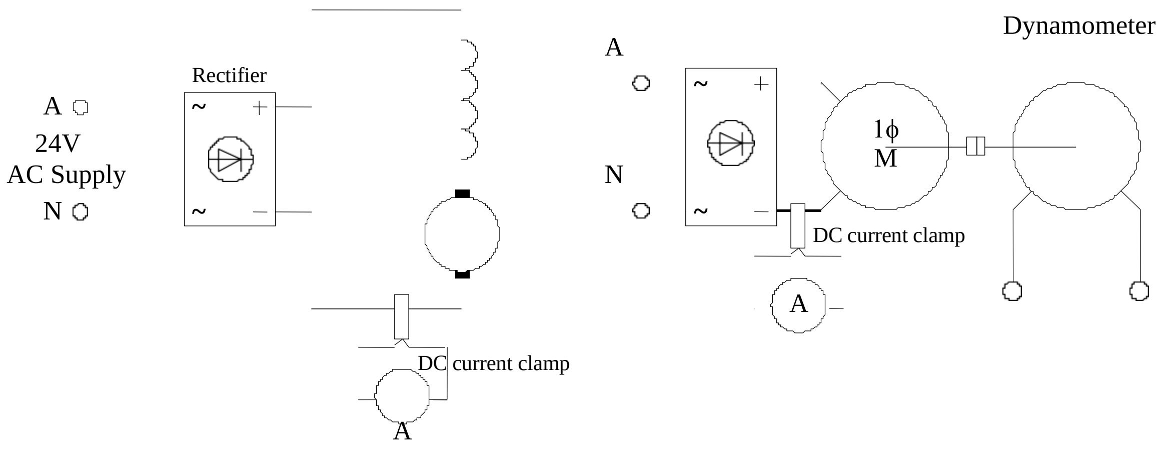

Figure 1

2. Switch on the AC supply and record the direction of rotation of the motor, looking at the drive end.

Drive end direction of rotation - ________________________

3. Switch off the supply.
4. Reverse the DC supply to the motor circuit terminals as in Figure 2.

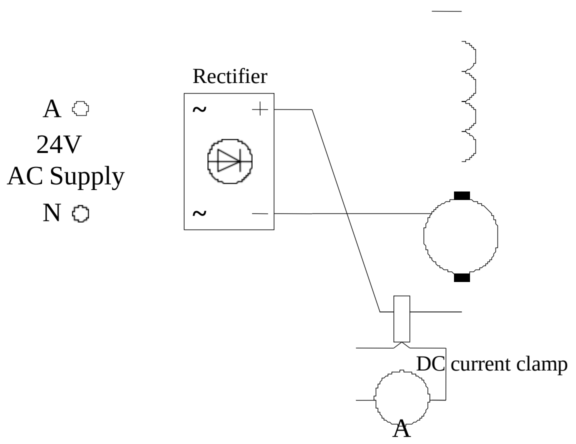

Figure 2

5. Switch on the supply and record the direction of rotation for this connection. Again, looking at the drive end.

Drive end direction of rotation - ________________________

6. **Do not proceed** until the teacher checks your results and completes the progress table.

Progress Table 1

attempt 1	attempt 2	attempt 3
5	2	0

7. Connect the dynamometer terminals to a DC power supply making sure that the power supply is off and its voltage control is at zero.
8. Switch on the AC supply but not the DC power supply - this will give the no load condition. Record speed and motor current in table 1 for this load.

Table 1

Motor Torque Nm	Motor Speed rpm	Motor Current A
No load		
0.1		
0.2		
0.3		
Breakdown torque =_______Nm	zero	

9. Adjust the DC power supply voltage to produce motor torque values as shown in table 1. For each of these values record the current and speed of the motor.
10. Breakdown torque will occur when the motor stalls.

> Read this value quickly and switch of the supply
> so the motor will not overheat

11. Switch off the AC supply, reduce the DC power supply voltage to zero and switch it off.
12. **Do not proceed** until the teacher checks your results and completes the progress table.

Progress Table 2

attempt 1	attempt 2	attempt 3
5	2	0

2. SERIES MOTOR - AC OPERATION

1. Reconnect the motor circuit directly to 24 volts AC supply as in figure 3.

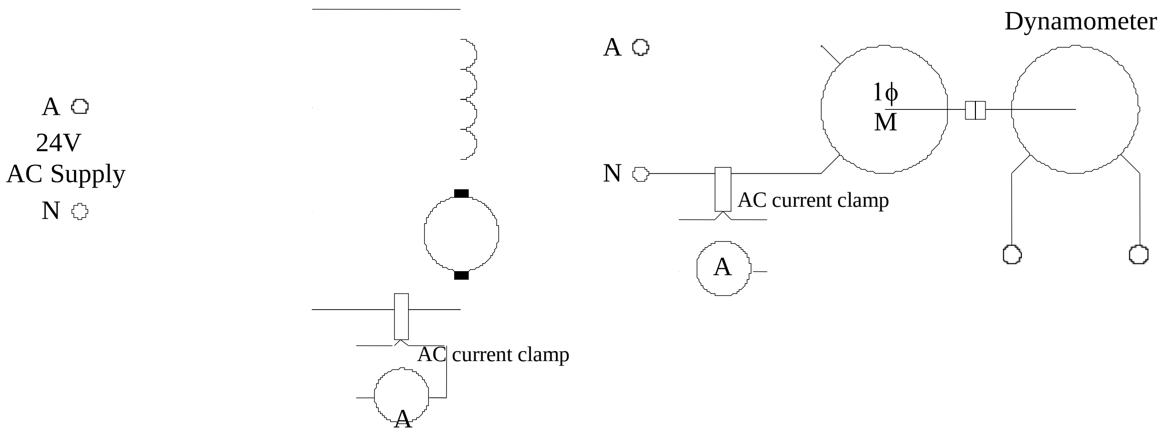

Figure 3

2. Switch on the AC supply and note the direction of rotation.

Drive end direction of rotation - ________________________

3. Step 3 is the no load condition, record current and speed for this load in table 2.

Table 2

Motor Torque Nm	Motor Speed rpm	Motor Current A
No load		
0.1		
0.2		
0.3		
Breakdown torque =_______Nm	zero	

4. Adjust the DC power supply voltage to the dynamometer to produce the motor torque values shown in table 2. For each of these values record the current and speed of the motor.

5. Breakdown torque will occur when the motor stalls.

> Read this value quickly and switch of the supply
> so the motor will not overheat

6. Switch off both the AC and DC power supplies.

7. **<u>Do not proceed</u>** until the teacher checks your results and completes the progress table.

Progress Table 2

attempt 1	attempt 2	attempt 3
5	2	0

3. SHADED POLE MOTOR

1. Connect the shaded pole motor directly to 24 volts AC supply as in figure 4.

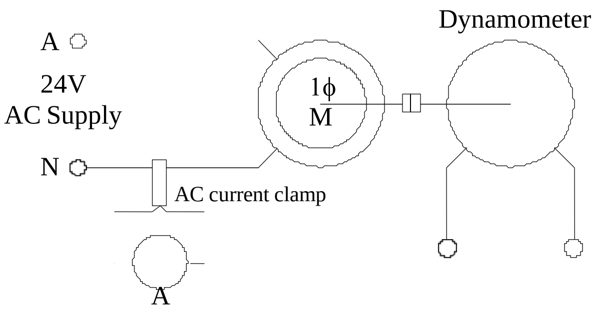

Figure 4

2. Switch on the AC supply and note the direction of rotation.

Drive end direction of rotation - ________________________

3. Step 3 is the no load condition, record current and speed for this load in table 3.

Table 3

Motor Torque Nm	Motor Speed rpm	Motor Current A
No load		
0.1		
0.2		
0.3		
Breakdown torque =_______Nm	zero	

4. Adjust the DC power supply voltage to the dynamometer to produce the motor torque values shown in table 2. For each of these values record the current and speed of the motor.

5. Breakdown torque will occur when the motor stalls.

> Read this value quickly and switch of the supply so the motor will not overheat

6. **<u>Do not proceed</u>** until the teacher checks your results and completes the progress table.

Progress Table 3

attempt 1	attempt 2	attempt 3
5	2	0

7. Switch off the AC supply, reduce the DC power supply voltage to zero and switch it off
8. Disconnect the circuit.
9. Please return all equipment to its proper place, safely and carefully.

4. OBSERVATIONS:

1. Use the information recorded in tables 1 and 2 to complete the graph of figure 5.

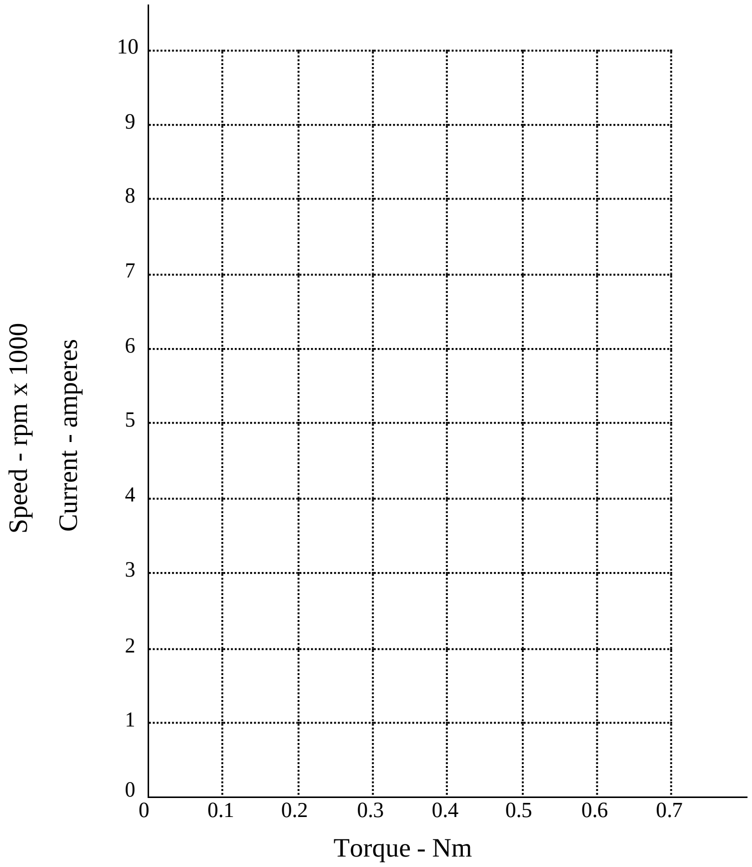

Figure 5

2. When operated as an AC motor, what effect does increasing the load have on:-
   - motor speed:

   ____

   ____

   - motor current:

   ____

   ____

3. How do the characteristics listed above compare with the operation of the squirrel cage motor?

   ____

   ____

4. From the curves drawn in figure 5, compare the AC and DC operation over the tested load range by commenting on:-
   - motor speed:

   ____

   ____

   - motor current:

   ____

   ____

   - breakdown torque:

   ____

   ____

5. What effect did changing the polarity of the DC supply have on the operation of the series motor?

   ____

   ____

6. What was the effect of changing the relative direction of currents through the field and armature of the series motor when operating on the AC supply?

   ____

   ____

7. In your opinion do the results show that the tested motor can be considered to be a universal motor? (that is, able to be operated on either AC or DC supply).

____

____

8. If the answer to question 7 is no, explain or give reasons for this. If the answer to 7 is yes, which supply will give the best operating characteristics, AC or DC. Use results to justify, this answer.

____

____

9. Use the information recorded in table 3 to complete the graph of figure 6 for the shaded pole motor.

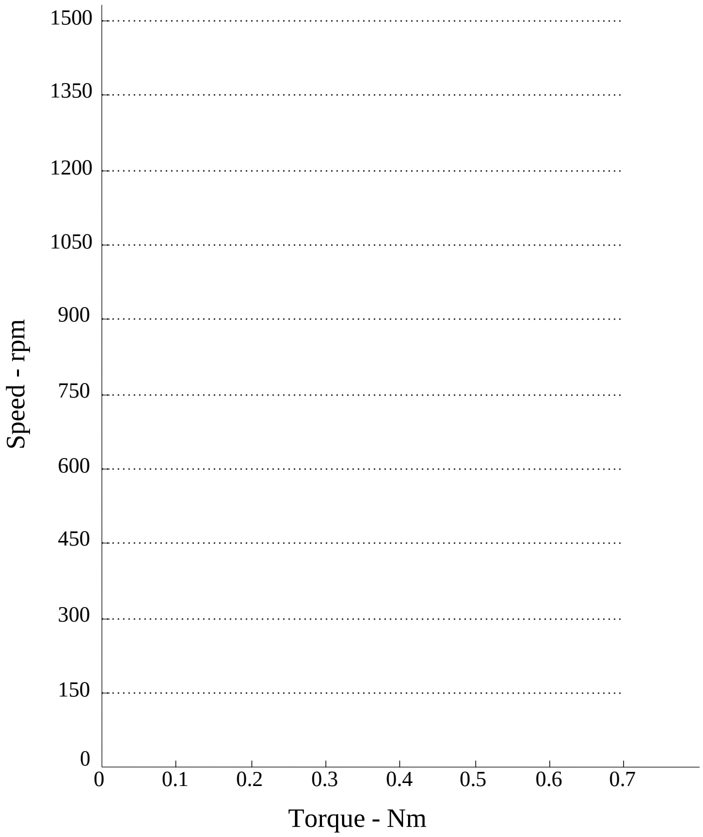

Figure 6

10. From the results obtained, comment on the advantages and disadvantages of the shaded pole motor.

____

____

____

11. What is the effect of the shading coil when used in starting induction motors?

____

____

____

12. Explain how the shaded-pole motor is reversed.

____

____

____

13. For what applications is the shaded-pole motor most suitable?

____

____

____

NOTES

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SERIES UNIVERSAL MOTORS

SECTION A

In the following statements one of the suggested answers is best. Place the identifying letter on your answer sheet.

1. A single phase motor rated at 240 volt, 500 watt, 6000 r.p.m., 3 amperes, 50 Hz would be:-
   a) a split phase motor;
   b) a shaded pole motor;
   c) a series universal motor;
   d) a permanent capacitor motor.

2. Voltage speed control of a constant torque load may be used with:-
   a) shaded pole motors;
   b) split phase motors;
   c) capacitor start motors;
   d) series universal motors.

3. The series universal motor is reversed by:-
   a) reversing the supply connections;
   b) reversing the armature and field connections;
   c) physically reversing the rotor in the field;
   d) reversing the armature connections.

4. A series universal motor driving a constant torque load has its armature voltage reduced from 200 volts to 100 volts using a series resistor. The result will be:-
   a) motor speed will remain unchanged;
   b) motor speed will double;
   c) motor speed will drop to half rated speed;
   d) motor current will decrease to half rated current.

5. The motor used in most mains powered portable hand tools is the:-
   a) shaded pole motor;
   b) split phase motor;
   c) capacitor start motor;
   d) series universal motor.

6. A series universal motor is identified by:-
   a) its universal
   b) its commutator
   c) its series winding
   d) its nameplate

7. The most commonly used motor for a 240 volt single-phase vacuum cleaner is:-
   a) split phase type;
   b) universal type;
   c) capacitor start type;
   d) shaded pole type.
8. A starting switch is not required in:-
   a) a capacitor start, capacitor run motor;
   b) a split phase motor;
   c) a capacitor start motor;
   d) a series universal motor.
9. A small shaded pole fan motor has new coils fitted to change the voltage rating of the motor. When re-assembled the fan rotation is reversed. This is most easily rectified by:-
   a) removing the new coils and turning them over;
   b) reversing the current in the motor winding;
   c) reversing the current in the shading coils;
   d) turning the rotor end for end.
10. For a given load the constant speed of a motor occurs when:-
    a) the input power is equal to the output power;
    b) the efficiency of the motor is at a maximum;
    c) the motor output torque equals the load input torque;
    d) the motor slip is at a maximum.

SECTION B

Blank spaces in the following statements represent omissions. Write the appropriate information on your answer sheet.

The series universal motor has a______(1)_____starting torque. As the motor accelerates the back emf______(2)_____causing the motor current to_______(3)_____ which______(4)_____the strength of the stator and armature magnetic fields _____(5)_____torque and_______(6)_____speed. The motor will continue to accelerate until it reaches a speed at which the developed______(7)_____equals that required by the load. If the load on the motor increases the motor speed _____(8)_____, back emf_______(9)_____, motor current_______(10)_____, producing______(11)_____ flux and______(12)_____ torque to meet the increase in

load. The speed of the series universal motor is______(13)_____on no load and very _____(14)_____on heavy loads.

In the universal series motor both the armature and field are laminated to reduce _____(15)_____loss and made from silicon steel to reduce_______(16)_____loss. The field windings and armature are connected in______(17)_____but as the armature has two parallel circuits between the brushes the armature conductors may be _____(18)_____than the field conductors. If an open circuit occurs in an armature coil this will cause_______(19)_____at the commutator as the brush shorts out the open circuited coil.

SECTION C

1. A 240 volt series universal motor has a total winding/armature impedance of 60 ohms. Determine:-
   a) the current taken by the motor at starting; (4A)
   b) the current taken by the motor when armature back emf is 120 volts. (2A.)
   c) the armature back emf when the motor takes rated current of 1.5 amperes; (150V)
   d) the starting torque as a percentage of rated torque if torque is proportional to current squared; (711%)

2. A 240 volt series universal motor drives a constant torque load at rated load and rated current of 7 amperes at 4 000 r.p.m. If speed is to be reduced to 2 500 r.p.m. determine:-
   a) the voltage required (hint: at constant torque, speed is proportional to voltage);(150V)
   b) the value of series resistance required to drop motor voltage to this value.(12.86Ω)

SECTION D

1. The performance curves for a 240V, 50Hz, 45 watt single phase motor are shown below in Figure 1. From these curves estimate the following:-

   a) starting torque;
   b) full load torque;
   c) full load current;
   d) full load speed;
   e) breakdown torque;
   f) number of poles;
   g) slip speed at full load.

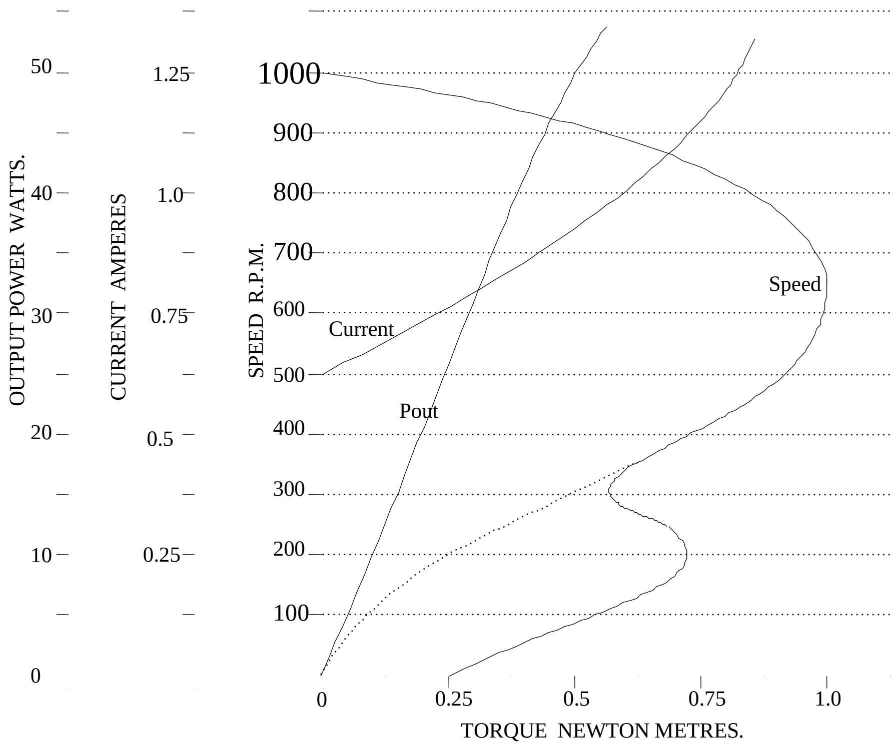


Figure 1.

2. For the current directions given in the series universal motor of Figure 2 determine and show:-

   a) the polarity of the field poles;
   b) the direction of the armature flux and pole location;
   c) the direction of rotation of the motor.

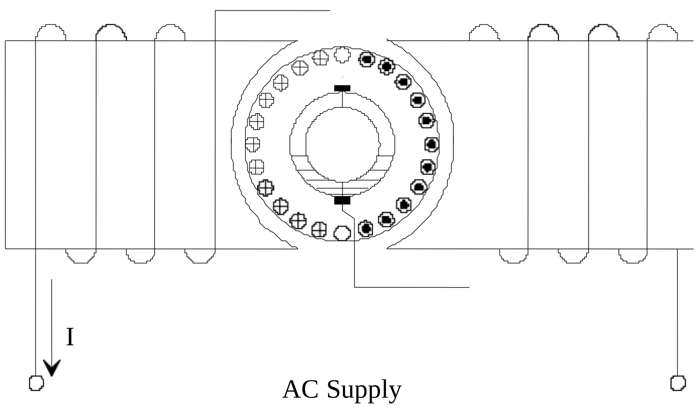


Figure 2.

ALTERNATORS – PART 1

PURPOSE:

In this section you will learn the construction operation and rating of single and three phase alternators.

TO ACHIEVE THE PURPOSE OF THIS SECTION:

At the end of this section the student will be able to:

- State the basic function of an alternator.
- Identify the main parts of an alternator.
- Describe the principles of operation of an alternator.
- List the methods used to provide dc excitation to alternators.
- Calculate the synchronous speed of an alternator given the number of poles and the required frequency.
- Draw the no-load (open circuit) characteristics of an alternator.
- State the factors to be considered when rating an alternator and calculate the apparent power output of an alternator.

REFERENCES:

Electrical Trade Principles, 2nd Edition J Hampson & S Hanssen. Section 6

Electrical Principles for the Electrical Trades, 5th Edition. Jenneson J.R.

Pages 250-253.

1. INTRODUCTION

The primary function of an alternator is to convert__________________energy to ____________ energy, see figure 1. When carrying out this energy conversion process the alternator generates an alternating voltage at a specific frequency, for example 240V at 50Hz.

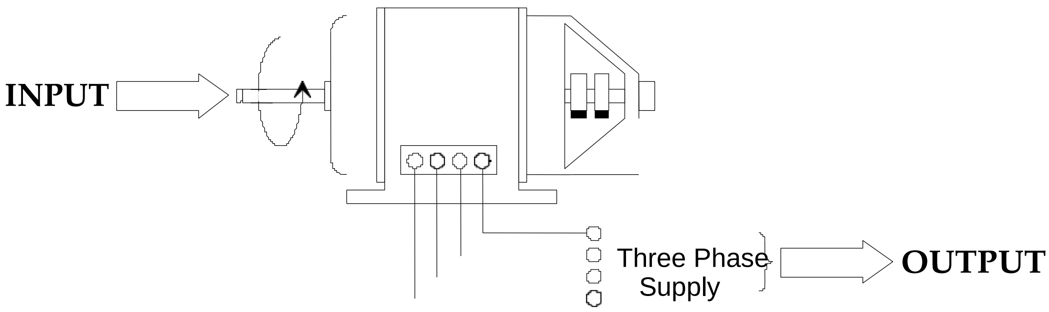


Figure 1

Commercial alternators are available in a wide range of output voltages and power ratings. In addition, there are many styles and there exists an enormous variation in physical size.

An example of a physically small alternator is that found in a motor car. An alternator of this type generates 14V and has a maximum rated output of approximately 500VA.

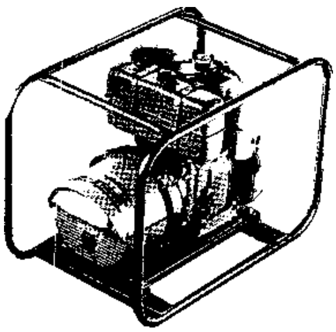


Figure 2

Single phase portable generating sets as used on building sites are designed to generate 240V, and are available in a range of power ratings. Figure 2 shows one type of portable generating set, in this case, the unit can deliver 3kVA at 240V and is driven by a small diesel engine.

Figure 3 shows a large scale generating set as used in a hydro-electric power station. In this case, the alternator generates a three phase line voltage of 11kV and can deliver 95MVA.

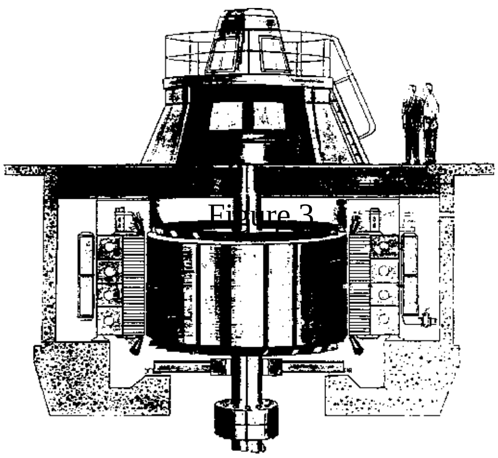


Figure 3

In thermal power stations, alternators having exceptionally high output power ratings can be found. For example, a generated line voltage of 17kV and a maximum power rating of 640MVA. An alternator of this rating can deliver a maximum current of 21,736A. Irrespective of the differences, all alternators use the same principle of operation - ____.

2. GENERATOR ACTION

The process of generation relies on the fact that if there is ________________________ between a conductor and a _________________________________ an emf will be induced in the conductor.

The direction in which the induced emf acts can be determined by the application of Fleming's right hand rule. See figure 4.

The magnitude of the induced emf is be governed by the -

- ______________________________________
- ______________________________________
- ______________________________________
- ______________________________________.

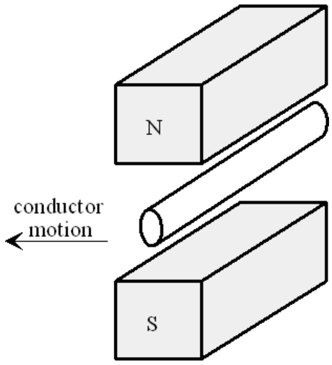
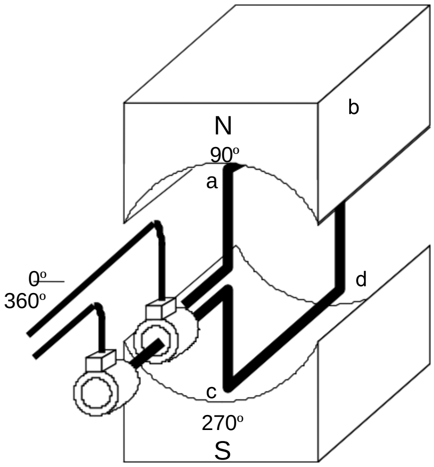


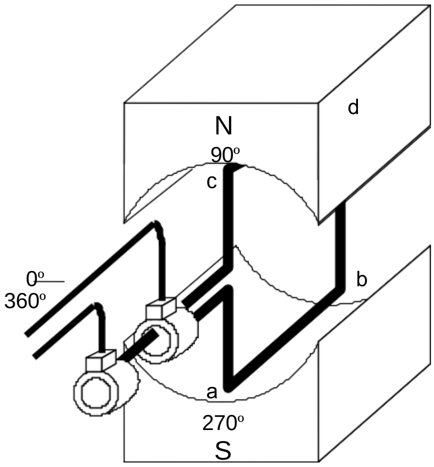
Figure 4

3. AC VOLTAGE GENERATION

Figure 5 shows a basic alternator. In this arrangement we have a simple loop of wire rotating in the magnetic field between two poles, one north the other south. The ends of the loop terminate in two metal slip-rings which are insulated from the driving shaft (not shown), and the conductors make rubbing contact with these rings through carbon brushes. Thus whatever the position of the loop, the conductor *ab* is always connected to the upper conductor of the external circuit, and similarly, the lower conductor of the circuit is, in effect, a continuation of the side *cd* of the loop.



conductor ab at an angle of 90º to the magnetic field



conductor ab at an angle of 270º to the magnetic field

Figure 5

If the emf induced in the loop is plotted for one complete revolution, the waveform shown in figure 6 would result. As shown, the emf within the loop has undergone a complete series of changes during the revolution. Such a waveform is termed an alternating emf.

If the circuit were closed, the resulting current would follow the variations of emf and an alternating current would flow in the loop and the external circuit.

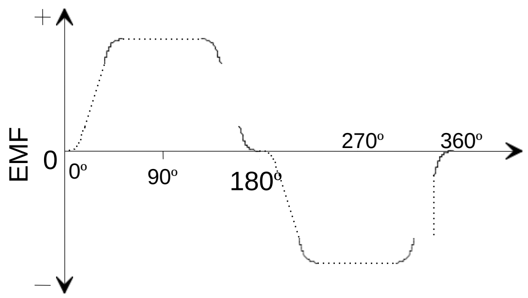


Figure 6

By the use of suitable construction methods, practical alternators can be manufactured to produce an output voltage that takes the form of a sinusoidal waveform. Some of the constructional methods used to obtain a sinusoidal waveform relate to the arrangement of the windings within the alternator and are beyond the scope of this module.

From the action previously described it should be seen that a single phase alternator consists essentially of two major parts -

- ________________ - normally carries the alternating current winding (called the armature)
- ________________ - carries the exciting current and produces the necessary magnetic field.

Figure 7 shows a simplified view of the construction of a single phase alternator.

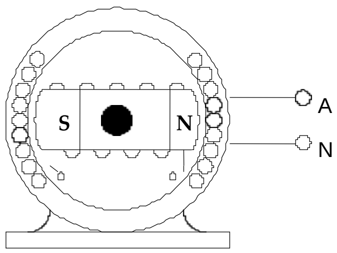
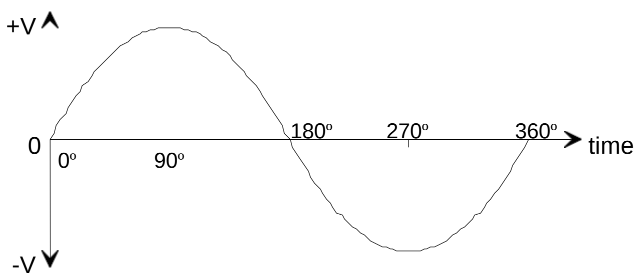


Figure 7

The output waveform of a single phase alternator would be a sinusoidal voltage as shown in figure 8. When a load is applied to the alternator output a sinusoidal current flows, the phase angle of this current being determined by the type of load, that is resistive, inductive or capacitive.



Consider three coils, or phase windings, spaced 120º apart as in the simple alternator shown in figure 9.

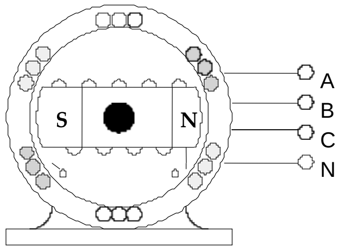


Figure 9

It should be seen from figure 9 that whatever occurs at a certain instant in phase A will occur 120º later in phase B and 240º later in phase C. Thus each of the three emfs produced in this alternator, has a phase difference of 120º between it and the other two, and the combination produces a "three phase system".

The emfs produced by the elementary three phase alternator of figure 9 are represented by the sinusoidal voltage waves shown in figure 10.

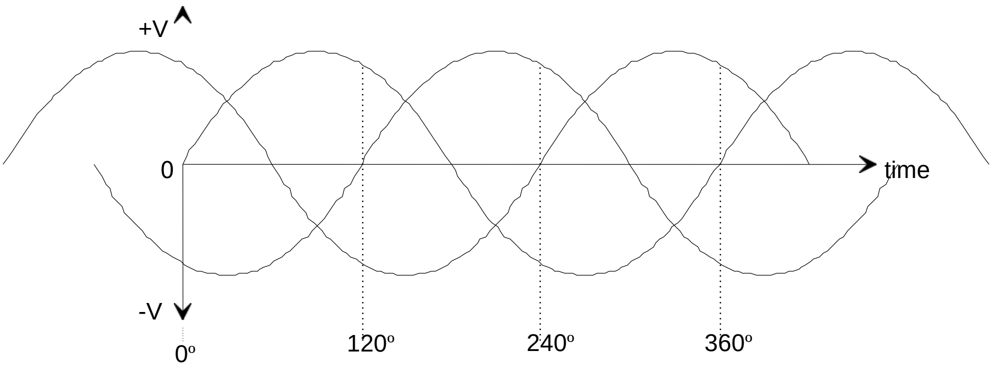


Figure 10

The same voltage waves may be represented by the phasor diagram shown in figure 11.

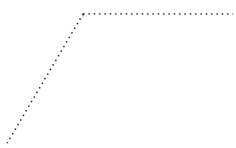


Figure 11

4. FREQUENCY AND NUMBER OF POLES

Alternators are designed to generate a specified voltage at a definite frequency. A definite relationship exists between the speed (n), the number of poles, and the frequency (f).

If an alternator has P poles on the field system then the emf goes through $\frac{P}{2}$ cycles per revolution or $\frac{n \times P}{2 \times 60}$ cycles per second.

Thus, the frequency of the generated emf can be determined using the equation -

where: f = frequency in hertz (Hz)
P = number of field poles
n = speed of rotation in revolutions per minute (rpm)

Alternately, if the desired generating frequency is known, the required speed of rotation can be determined -

Example: 1

An alternator used in a hydro-electric scheme has 48 field poles and rotates at a speed of 125rpm. Determine the frequency of the generated emf.

Example: 2

Determine the required speed of rotation for an alternator which has 2 field poles and generates at a frequency of 50Hz.

Therefore, in order for a given alternator to generate at a fixed frequency (eg. 50Hz), it must be driven at a____________________speed, known as the ____________________ speed.

5. ALTERNATOR CONSTRUCTION

The construction of all alternators, whether single or three phase, can be broken into two main parts, the -

- AC winding in which the induced emf will be generated, known as the ____________
- DC winding which establishes the magnetic field, known as the _________________.

From a theoretical point of view it does not matter whether the armature rotates between the field poles or whether the poles rotate inside a stationary armature. Consequently, there are two distinct types of alternator construction -

- _____________________________ type - the armature rotates between the field poles
- ____________________________ type - the poles rotate inside a stationary armature.

6. ROTATING ARMATURE TYPE OF ALTERNATOR

Some small alternators have the same type of construction as DC generators. The field system is fixed and the armature rotates. However, instead of the armature winding being connected to a commutator, it is connected to slip-rings. The construction of a small alternator armature is shown in figure 12.

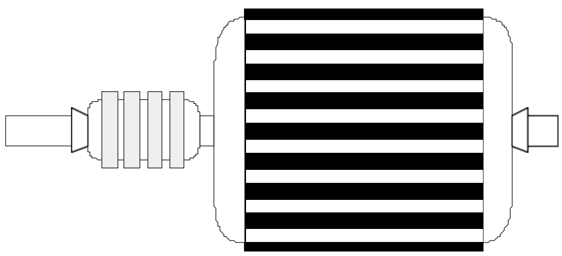


Figure 12

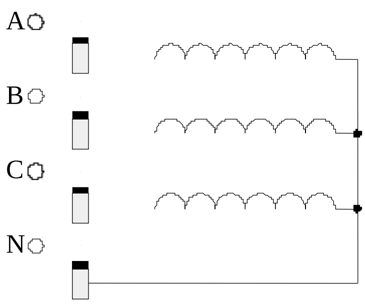


Figure 13

The armature coils are laid in slots in a laminated core. The slip-rings, usually made of bronze, are mounted on the shaft from which they are insulated. Carbon brushes make contact with the slip-rings and when a load is connected conduct current from them to the load.

The circuit diagram for the rotor shown in figure 12, would be as shown in figure 13.

The field system of the rotating armature type of alternator is shown in figure 14. The field poles are excited by means of current supplied to the field coils form a source of direct current.

Note, in one complete revolution of the field system, successive field poles are connected to produce poles of opposite magnetic polarity.

The DC supply used to establish the magnetic fields of the field system is generally known as the -

____________________________.

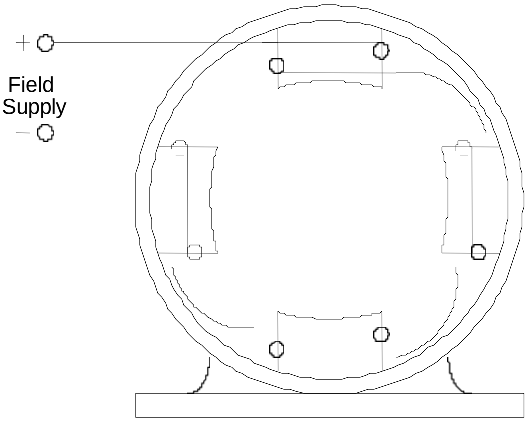


Figure 14

7. ROTATING FIELD TYPE OF ALTERNATOR

The rotating field type of alternator is now standard practice, except for some very small machines. An alternator of this type is arranged so that the field poles rotate inside a stationary armature.

The armature and rotating field poles are commonly referred to by alternative names -

- the armature is known as the _________________________
- the rotating field poles are known as the_________________________.

The principle of construction of the rotating field type of alternator is illustrated in figure 15.

In the diagram shown in figure 15, the field winding terminals A and B are connected to two slip-rings. Since the field poles are magnetised by direct current they are not usually laminated but are made of solid steel. The stator conductors have alternating emfs induced in them, consequently the stator core is made up of silicon steel laminations. The stator winding is carried in slots in the stator core.

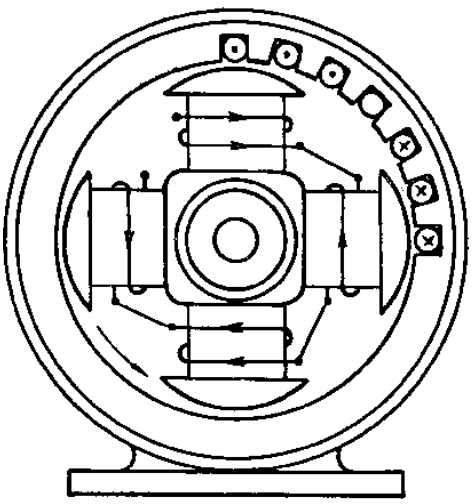


Figure 15

Rotor construction depends largely upon how the machine is to be ________________ and the________________at which it must run.

There are two types of rotor construction -

- ______________________________ rotors.
  - have projecting poles, with cores bolted to a heavy cast iron or steel ring of good magnetic quality. See figure 16.
  - used in alternators that operate at low and moderate speeds (up to 1500rpm)
  - used in small alternators and large low speed engine or water turbine driven alternators.

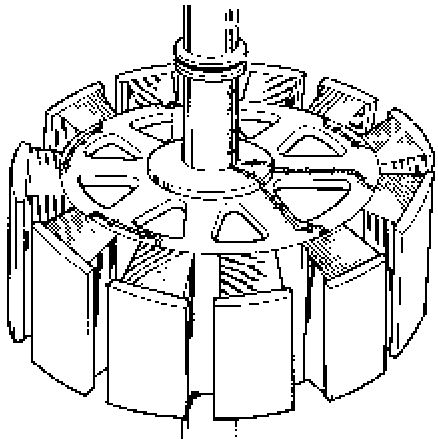


Figure 16

  - the pole faces of salient pole rotors are shaped so that the air gap is shorter at the pole centres than near the edges, as shown in figure 15. By this means the magnetic field is strongest at the pole centres and an approximately sinusoidal waveform of induced emf is produced.

- ______________________________ type rotors.
  - used in large, high speed (3000rpm), steam turbine driven alternators. See figure 17.
  - the cylindrical type rotor has slots machined in parts of the circumference.
  - the field coils are wound in the slots and the main part of the flux passes through the unslotted portion with considerable fringing of the magnetic field due to the spread of the winding. The effect of distributing the field winding in a cylindrical rotor is to produce a stronger field near the centre of the pole than near its edges. This assists in producing a sinusoidal waveform of induced emf.

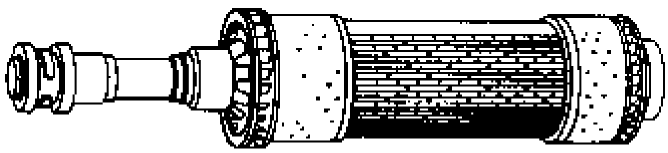


Figure 17

  - the cylindrical type rotor has several advantages over the salient pole type -
    - it can withstand the stresses set up by high speeds of rotation
    - mechanical balancing of the rotor is not as difficult
    - the smoother surface reduces running noise.

The stator of an the rotating field type of alternator, as shown in figure 18, consists of -

- a laminated silicon steel core formed with slots
- an armature winding which is laid in the stator slots
- phase windings made up of a number of series connected coils forming the same number of poles as the rotor
- in the case of three phase alternators the armature is always _____________ connected.

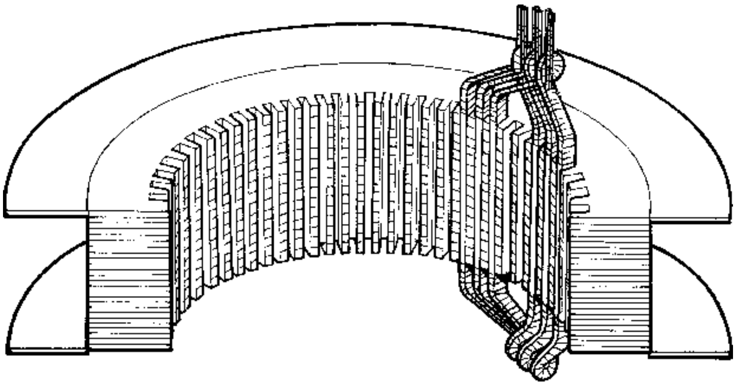


Figure 18

8. EXCITATION

Alternators have to be excited with direct current to provide the rotor field, they are not self exciting. The excitation current is often supplied by a DC generator called an _______________.

The exciter can be mounted on the end of the alternator shaft, see figure 19, or can be driven by a separate motor. The excitation current is fed to the rotor field winding via brushes and slip-rings.

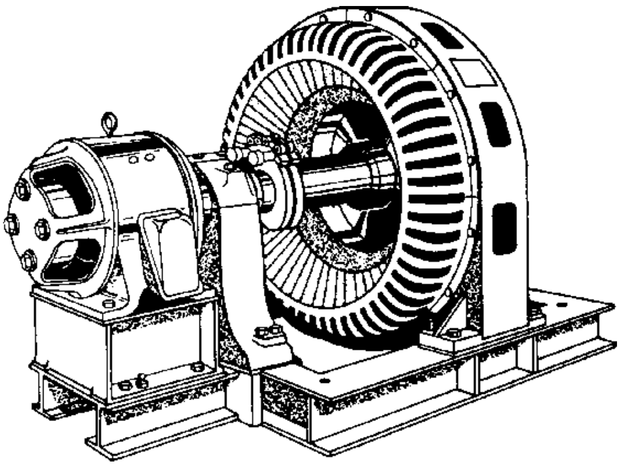


Figure 19

The circuit diagram of figure 20 shows the connections between the exciter and alternator. The exciter output is fed into the field windings of the alternator. By adjusting the rheostat in the exciter field circuit, the strength of the magnetic field in the rotor can be varied. Hence, the level of output voltage from the alternator may be controlled.

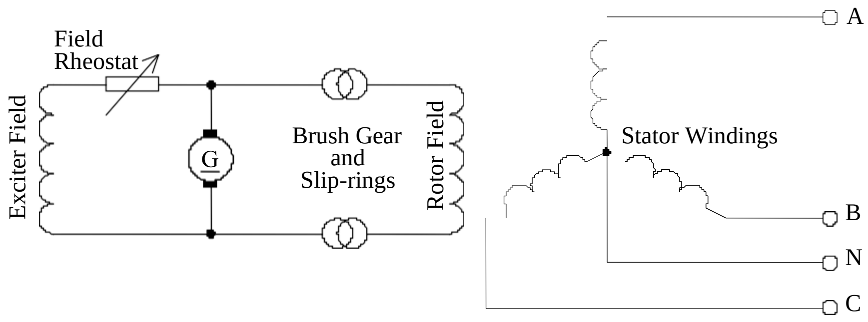


Figure 20

Another arrangement is the____________________exciter, where the excitation current is obtained from a separate AC winding placed on a separate rotor but connected to the main rotor. This system is shown in figure 21.

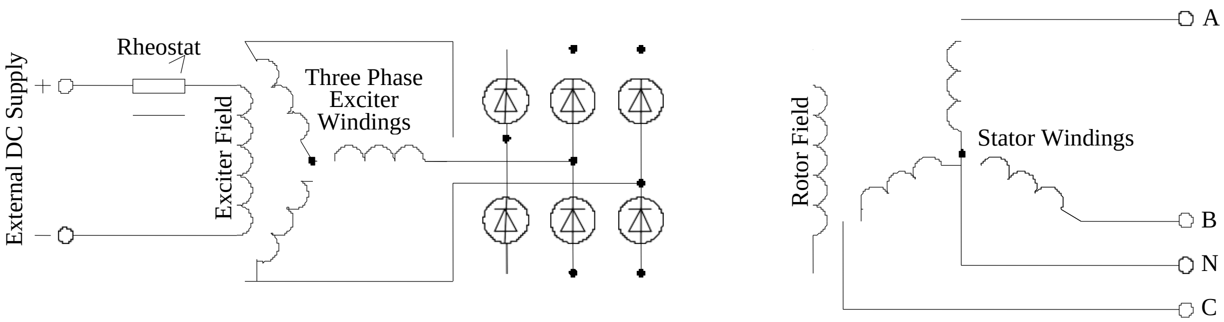


Figure 21

The AC voltage developed by the three phase exciter is fed through a three phase, full wave bridge rectifier mounted on the end of the exciter rotor, and converted to DC. The resulting DC voltage is in turn fed into the rotor windings of the alternator. By varying the current through the exciter field, the rotor field is varied and so controls the value of generated voltage produced by the alternator

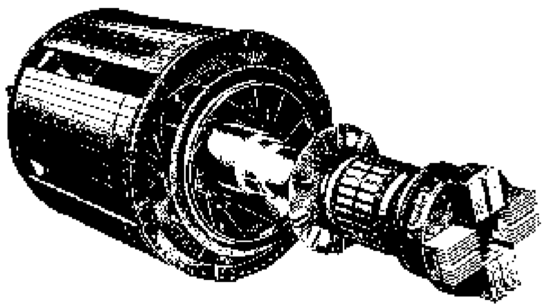


Figure 22

Figure 22 shows a salient pole rotor which incorporates brushless excitation.

The value of generated voltage developed by an alternator depends on the -

- strength of the ________________________________
- ________________ at which the field flux cuts the armature conductors.

Because the speed must be constant to maintain a fixed generating frequency, the level of generated emf is determined by the strength of the field flux.

The phase voltage developed by an alternator may be determined using the following equation -

where:	V	= phase voltage in volts
	ϕ	= magnetic flux per pole in webers
	f	= frequency of generated voltage in hertz
	N	= number of armature turns per phase
	k	= a constant related to the arrangement of the stator windings

Example: 3

A three phase star connected, 4 pole alternator is driven at 1500rpm. The alternator has 224 turns per phase and operates with a flux of 76.6mWb per pole. If the alternator has a winding constant of 1, determine the -

a) frequency of the generated voltage
b) generated phase voltage
c) alternator line voltage

____

____

____

____

____

____

____

____

____

____

Example: 4

If the field flux in the alternator of example 3 was reduced to 70mWb per pole, determine the -

a) frequency of the generated voltage
b) generated phase voltage
c) alternator line voltage

9. ALTERNATOR EQUIVALENT CIRCUIT

An alternator can be considered to consist of -

- an AC generating source
- a resistor - representing winding resistance, iron and copper losses
- an inductor - representing the inductance of the windings and magnetic leakage.

Any load placed on the alternator must be assumed to be in series with these components.

Figure 23 shows the equivalent circuit for a single phase alternator or one phase of a three phase alternator.

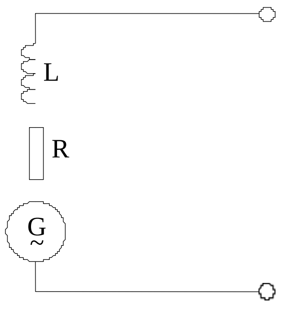


Figure 23

10. ALTERNATOR OPEN-CIRCUIT CHARACTERISTIC CURVE

The open-circuit characteristic curve of an alternator shows the relationship between the -

- ________________ current

  and

- ______________________________, when operated on open circuit, that is, no-load.

To obtain this curve the alternator is driven at -

- its rated speed
- while the field current is increased in steps from zero to its maximum value.

At each value of field current, the corresponding value of open-circuit terminal emf is measured, this being plotted against field current in the form of a curve as shown in figure 24. Under these conditions, the terminal voltage and the generated emf are the same because no voltage drop is incurred in the armature circuit.

The curve of figure 24 is called the "***open-circuit characteristic***" of the alternator. It is also called the magnetisation curve because it indicates the degree of magnetisation of the pole cores of the field system.

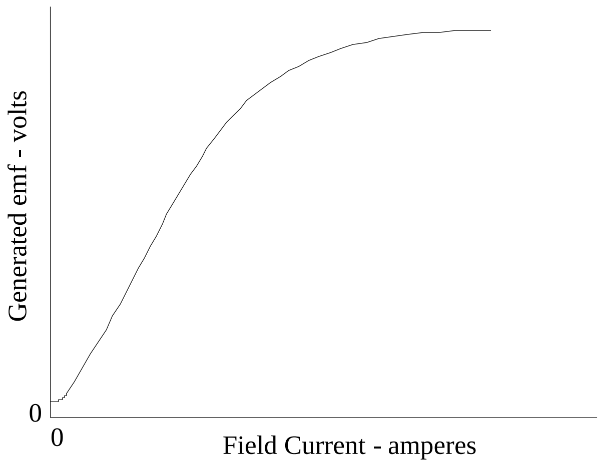


Figure 24

The straight (linear) part of the curve shows that over this range the generated emf is directly proportional to the field current. Beyond this the curve flattens out, showing that the field poles are becoming saturated. It should be noted from figure 24 that when the field current is zero, the generated emf is not zero, but is a small percentage of the normal voltage; this is due to the residual magnetism remaining in the magnetic circuit after the pole cores have once been magnetised.

The normal operating voltage of the machine is just below the knee of the curve.

11. RATING OF ALTERNATORS

The main factors to be specified in the rating of an alternator are -

- terminal voltage at full load
- VA output at full load (that is, the output in terms of apparent power)
- speed
- frequency
- the number of phases.

To determine the VA output for an alternator -

Single Phase	Three Phase

where: S = apparent power in volt-amps

V = terminal voltage in volts (line voltage for a three phase machine)

I = load current in amperes

Example: 5

At full-load a single phase alternator delivers 25A at 240V. What is the VA rating of the alternator?

___

___

Example: 6

At full-load, a three phase 11,000V alternator supplies a load current of 2,624.32A. Determine the rated output of the alternator.

___

___

Example: 7

What is the full-load current of a three phase 100kVA, 415V alternator?

___

___

Example: 8

A 240V single phase alternator is rated at 800VA. What is the full-load current?

Example: 9

A three phase 630MVA, 17kV, 50Hz alternator has two poles. Determine the alternators -

a) synchronous speed
b) rated current.

ALTERNATORS OPEN-CIRCUIT CHARACTERISTIC

PURPOSE:

This practical assignment will be used to plot and examine the open-circuit characteristic of an alternator.

TO ACHIEVE THE PURPOSE OF THIS SECTION:

At the end of this practical assignment the student will be able to:

- Connect an alternator and operate under no-load conditions with varying levels of field excitation.
- Measure values of generated voltage under varying levels of field excitation.
- Compare the levels of generated voltage produced
- Draw the open-circuit characteristic of an alternator.

EQUIPMENT:

- 1 x single phase dive unit
- 1 x Betts synchronous machine
- 1 x double machine bed
- 1 x AVO8 multimeter
- 2 x digital multimeters
- 4mm connection leads

– REMEMBER –
– WORK SAFELY AT ALL TIMES –
Observe correct isolation procedures

PROCEDURE:

1. NO-LOAD TEST

1. Couple the single phase drive unit to the alternator as shown in figure 1.

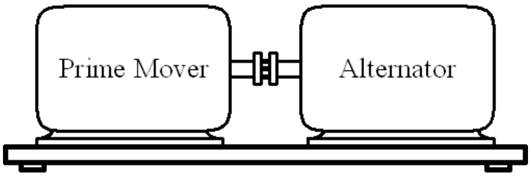


Figure 1

2. Connect the alternator as shown in figure 2.

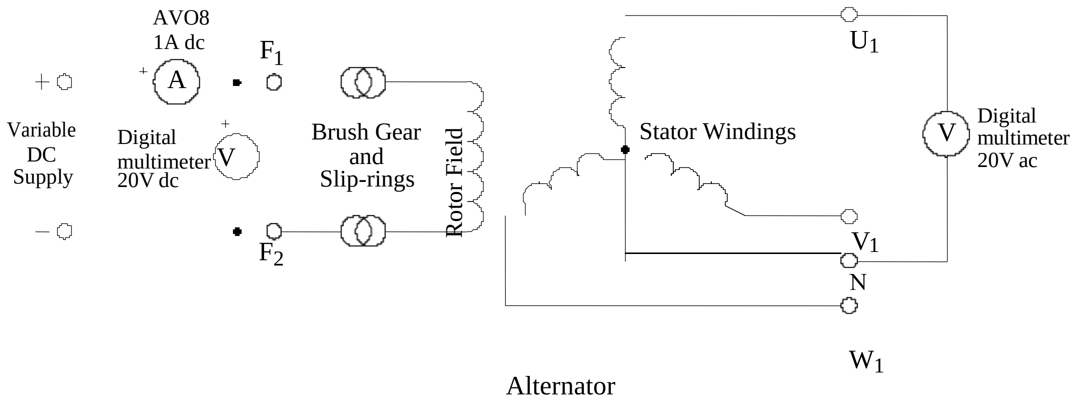


Figure 2

3. Ensure the dc power supply is set to minimum output and is switched off.
4. Switch on the single phase drive unit (prime mover).
5. Measure the alternator generated voltage. Record in table 1.

Table 1

Field Voltage volts	0	1	2	4	6	8	10	12	14	16	18	20	22	24
Field Current amperes	0													
Generated Voltage volts (Increasing Excitation)														
Generated Voltage volts (Decreasing Excitation)														

6. Slowly adjust the alternator field voltage to 1V, then measure and record the field current and the generated voltage. Record in table 1.

7. Repeat the procedure for each value of field voltage shown in table 1. Again, adjust the field voltage slowly till the required value is obtained.
8. **Do not proceed** until the teacher checks your results and completes the progress table.

Progress Table 1

attempt 1	attempt 2	attempt 3
5	2	0

9. Slowly reduce the field voltage from 24V to 22V, then record the value of field current and generated voltage. Record in table 1.
10. Repeat the procedure for each value of field voltage shown in table 1. Again, reduce the field voltage slowly till the required value is obtained.
11. **Do not proceed** until the teacher checks your results and completes the progress table.

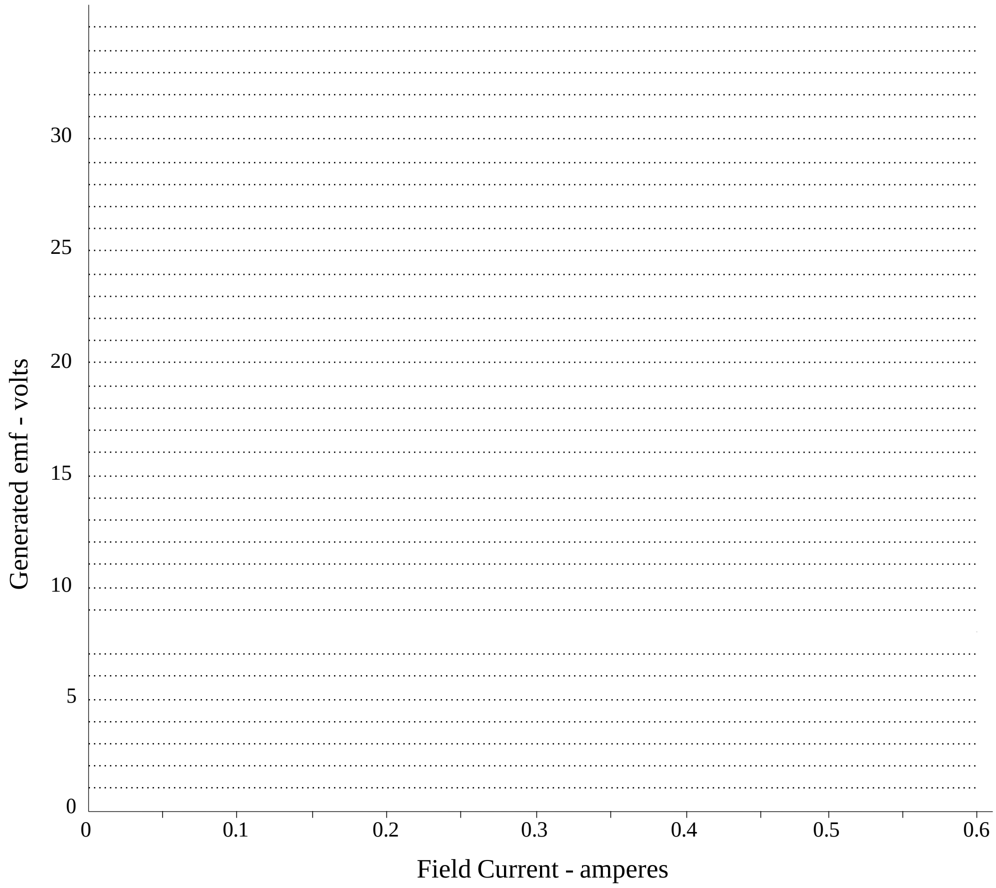
Progress Table 2

attempt 1	attempt 2	attempt 3
5	2	0

12. Switch of the single phase drive unit.
13. Switch off the supply, then disconnect the circuit.
14. Please return all equipment to its proper place, safely and carefully.

2. OBSERVATIONS:

1. Using the results from the alternator no-load test, plot the alternator open-circuit characteristic. Note, plot the characteristics for both increasing and decreasing excitation.



2. What was the effect on alternator generated voltage of increasing or decreasing field excitation?

____

____

____

3. How is it that the alternator could generate voltage when there was no field current?

____

____

____

4. The alternator in this practical was driven at a constant speed of 1500 rpm. Why is it necessary that an alternator be driven at constant speed?

5. For a given value of field current, the generated voltage was higher when the excitation was decreased compared to when the excitation was increased. Explain what causes this effect.

6. What would be the effect on alternator generated voltage if the excitation current was increased beyond 0.5A?

NOTES

****

Tutorial 14 **NAME:**

ALTERNATORS – PART 1

SECTION A

In the following statements one of the suggested answers is best. Place the identifying letter on your answer sheet.

1. Alternators are generally run at a constant speed to maintain:-
   a) a constant output voltage;
   b) a constant load current;
   c) maximum efficiency;
   d) a constant output frequency.

2. Low speed rotating field alternators use:-
   a) salient pole rotors with many poles;
   b) cylindrical rotors with many poles
   c) salient poles rotors with two poles
   d) cylindrical rotors with two poles

3. The armature winding in a rotating field alternator is placed:-
   a) in slots in the laminated stator core;
   b) in slots in the solid stator core;
   c) in slots in the laminated rotor core;
   d) around the poles on the solid rotor core.

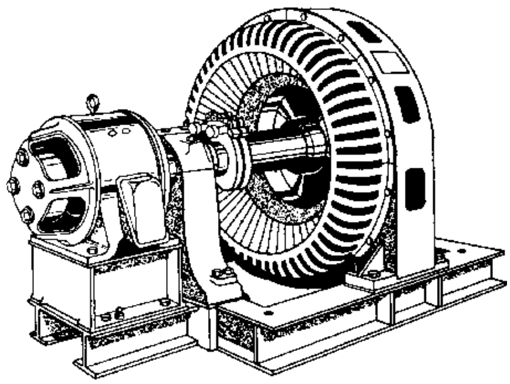
4. Most three phase alternators have their armature windings:-
   a) connected to a d.c. supply for excitation;
   b) connected to an a.c. supply for excitation.
   c) connected in star to allow earthing of the star point;
   d) connected in delta to increase the generated output voltage.

5. Cylindrical rotors are used in 50 Hz alternators with:-
   a) many poles driven at high speed;
   b) few poles driven at high speed;
   c) many poles driven at low speed;
   d) few poles driven at low speed.

6. A suitable rating for a 50 hertz three phase alternator required to deliver a balanced line current of 100 amperes to a 400 volt delta connected load at 0.8 lag power factor would be:-
   a) 40 kVA
   b) 32 kW
   c) 70 kVA
   d) 55 kW

7. The armature winding in an alternator is rewound with the number of turns in each coil increased by twenty percent. This will:-
   a) increase the output current by 20%;
   b) increase the output voltage by 20%;
   c) increase the kVA rating by 40%;
   d) all of the above.

8. An alternator, and it's excitation generator are shown in Figure 1. The output voltage of the alternator is adjusted by:-
   a) adjusting the field current in the d.c. generator;
   b) adjusting the speed of the d.c. generator;
   c) adjusting the three phase alternator supply voltage;
   d) adjusting the number of turns in the alternator field.



9. The open circuit characteristic of an alternator shows how:-
   a) generated voltage varies with field current;
   b) frequency varies with field current;
   c) generated voltage varies with frequency;
   d) speed varies with frequency.

10. Large alternators place the high voltage a.c. armature winding on the stator. This is because -
    a) this winding is larger than the field winding and the stator has more room;
    b) high voltage windings are easier to insulate if they are not rotating/vibrating;
    c) this allows the use of two low current slip rings rather than four high current ones;
    d) all of the above.

SECTION B

Blank spaces in the following statements represent omissions. Write the appropriate information on your answer sheet.

The three phase armature windings in alternators are generally connected in _____(1)_____.

The windings of three phase alternators are spaced______(2)_____electrical degrees apart.

The field windings of an alternator are connected to a______(3)_____supply.

In a low speed rotating field type 50 Hz alternator the field system would have a _____(4)_____number of poles and the rotor would be of the______(5)_____type.

The open circuit characteristic of an alternator shows the change in______(6)_____ voltage when the______(7)_____current is changed.

Small alternators may be of the rotating______(8)_____type while large alternators are normally of the rotating______(9)_____type.

The frequency of the emfs produced by an alternator is directly proportional to _____(10)_____and_______(11)_____.

Cylindrical rotors are generally used in______(12)_____speed alternators and normally have a______(13)_____number of poles.

When the rotor in a 6 pole alternator has completed one revolution it will have generated______(14)_____complete cycles and passed through______(15)_____ electrical degrees.

If a star connected alternator in a power station is generating 15kV in each winding the output line voltage will be______(16)_____kV.

The winding in the alternator that generates the output voltage is termed the _____(17)_____winding, regardless of whether it is on the rotating or stationary part of the machine.

The generated voltage of an alternator may be increased by______(18)_____the _____(19)_____.

In a star connected alternator the phase angle between the phase and line voltages is _____(20)_____degrees.

SECTION C

1. At what speed must a 24 pole 50Hz alternator in a Hydro-electric power station be driven? (250 r.p.m.)
2. How many poles would be required on a 25Hz alternator running at 375r.p.m.? (8 poles)
3. Is it possible to design a 50Hz alternator that runs at 1200 r.p.m.?. Explain your answer.
4. A three phase star connected 50Hz alternator is to be used as an emergency supply with an output line voltage of 11kilovolts. What voltage must be generated in each phase winding? (5.6kV).
5. A 2 pole, 50 Hz, three phase, star connected alternator has a winding constant of 0.97, a flux per pole of 81.mWb and 364 turns in the windings of each phase. Determine:-
   a) the speed of rotation of the alternator; (3 000r.p.m.)
   b) the generated phase voltage; (6 350V.)
   c) the output line voltage. (11 000V.)

SECTION D

1. Name the curves shown in Figure 2.
2. Why are there two curves in the graph? What does each curve represent?.
3. Starting from zero amperes how far must field current be increased to give an output voltage of 250 volts?
4. Will generated voltage drop to zero volts when field current is reduced to zero amperes? Give reasons for your answer.

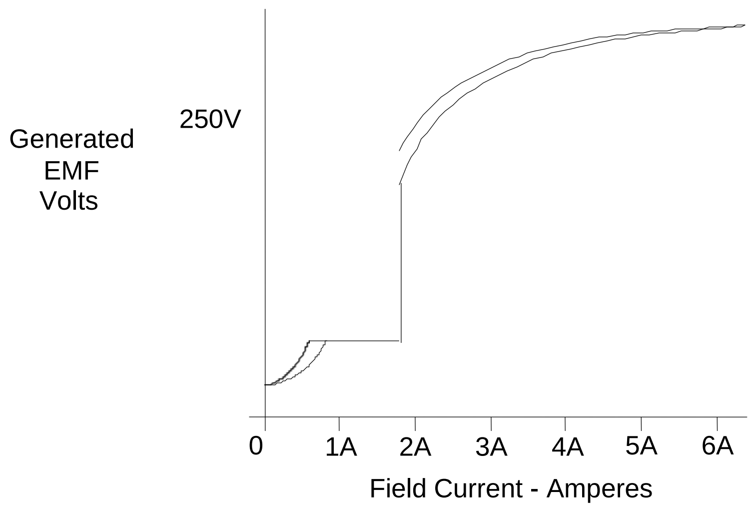


Figure 2

ALTERNATORS – PART 2

PURPOSE:

In this section you will learn about the alternator load characteristics, voltage regulation, efficiency and synchronising.

TO ACHIEVE THE PURPOSE OF THIS SECTION:

At the end of this section the student will be able to:

- Identify alternator load characteristics for resistive, inductive and capacitive loads.
- Describe why the terminal voltage of an alternator varies with load.
- Define alternator voltage regulation.
- Calculate the percentage voltage regulation of an alternator.
- Describe the losses that occur within and alternator and calculate alternator percentage efficiency.
- State the conditions necessary to allow satisfactory paralleling of alternators.
- Describe the process of synchronising alternators using either lamps or a synchroscope.
- Describe the effect of a change in excitation, when alternators are paralleled.
- State the purpose of armortisseur windings.

REFERENCES:

Electrical Trade Principles 2nd Edition J Hampson & S Hanssen. Section 6

Electrical Principles for the Electrical Trades. 5th Edition. Jenneson J.R.

Pages 253-258.

1. ALTERNATOR LOAD CHARACTERISTIC CURVE

The load characteristic of an alternator is obtained by determining the relationship between the -

- ______________________________
  and
- ______________________________.

the field current and speed being kept constant

The load increased in steps up to 125 percent of full load (i.e., 25 percent overload). At each step, the terminal voltage is measured and plotted against the armature or stator current as one of the points on a curve.

Figure 1 shows typical load characteristic curves for an alternator supplying the following loads:-

- unity power factor.
- power factor 0.8, lagging current.
- power factor 0.8, leading current.

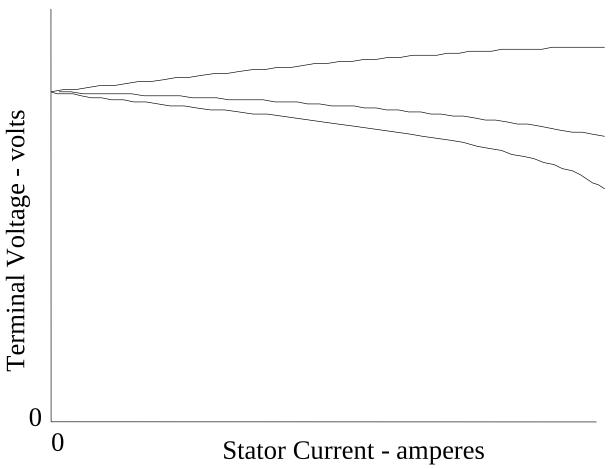


Figure 1

For a load of unity power factor the load characteristics is a slightly drooping curve. For a load of lagging current it droops considerably, whereas for a load of leading current the curve may rise, showing that the terminal voltage increases with in increase of load.

The change of terminal voltage with an increase in load is due to a number of causes, the chief of which are:-

- the impedance of the armature or stator windings
  and
- armature reaction.

2. WINDING IMPEDANCE

The stator winding of an alternator has resistance and reactance, and the joint effect of these two quantities produces the impedance. This causes a voltage drop equal to the product of the stator current and its impedance. See figure 2.

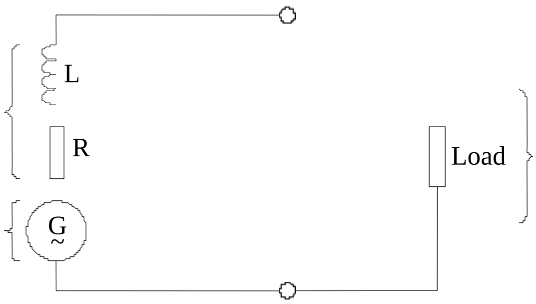


Figure 2

3. ARMATURE REACTION

Armature reaction is the effect of the magnetic field produced by the armature current on the main field and varies depending upon the type of load -

Unity Power Factor:

When the internal power factor of an alternator is unity the currents in the armature conductors are in phase with their respective generated emfs. The maximum values of both the currents and voltages of an alternator are then represented correctly by the circles containing dots and crosses opposite the rotor pole centres. See Figure 3. Note, a single-phase armature is shown, for simplicity.

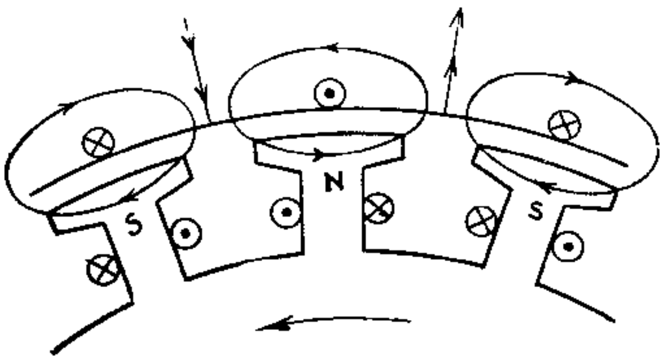


Figure 3

From this diagram it can be observed that the currents in the armature conductors establish mmfs tending to magnetise the rotor poles crosswise. The armature mmf, therefore, tends to distort the rotor field, reducing the flux under the leading pole tip and increasing it under the trailing tip. These two effects practically balance each other, and hence, at unity power factor, although the field distribution is altered by armature reaction, there is no appreciable change in the generated voltage.

Lagging Power Factor:

If the current lags the generated emf by 90 electrical degrees (a condition never actually obtained in practice), the rotor has advanced 90 electrical degrees beyond the position shown in figure 3 before the currents attain their maximum values in the conductors illustrated in that figure 4.

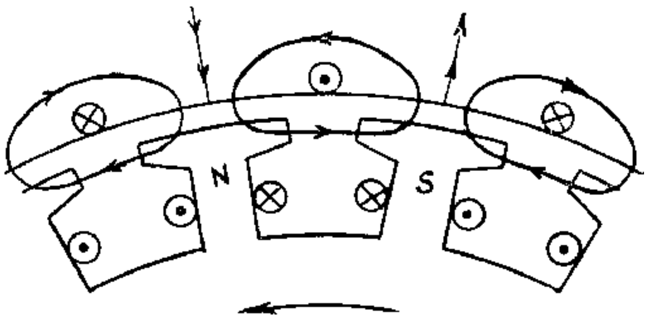


Figure 4

The armature mmfs now act along the centre line of each pole in the direction opposite to the rotor field mmf as shown in figure 4, thereby reducing the field flux and causing a drop in generated emf. This means that if the same value of voltage is required on inductive load as at unity power factor the dc field excitation current must be increased. For currents lagging by less than 90º, as in ordinary power loads, the effect of armature reaction is partly distortion and partly demagnetisation.

Leading Power Factor:

When the armature current leads the generated emf by 90 electrical degrees, the currents in the conductors illustrated in figure 5 reach their maximum values when the rotor is 90 electrical degrees behind the position shown in that figure 4. The armature mmfs now directly magnetise the rotor field poles and consequently increase the generated emf. If the same value of voltage is required as at unity power factor the field excitation must be reduced.

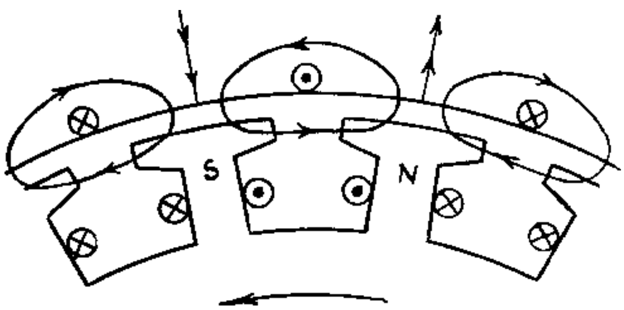


Figure 5

4. VOLTAGE REGULATION

When an alternator is required to supply a varying load, the terminal voltage varies with the load and the amount of this change determines the regulation of the alternator.

The regulation of an alternator is defined as -

"the percentage rise in voltage when full load is switched off, the excitation current being adjusted initially to give normal voltage".

To calculate the voltage regulation of an alternator -

where: VR% = percentage voltage regulation

V_{NL} = no-load voltage

V_{FL} = full-load voltage

The percentage regulation depends upon the -

- design of the machine
- the power factor of the load.

Practical values are of the order of 8 to 10% at unity power factor and at a power factor of 0.8 lag, 25 to 35% is quite normal.

It is usual to design an alternator with a considerable amount of internal reactance, because this limits the current if a short-circuit develops in the alternator or the load circuit. The high internal reactance causes a high voltage drop inside the machine or, in other words, a high value of regulation. For all normal loads, the terminal voltage of large power units can be maintained approximately constant by employing automatic voltage regulators.

Example: 1

An alternator has a TPD of 11,000V when delivering full-load, and the voltage rises to 13,200V when this load is suddenly removed. Determine the percentage regulation.

Example: 2

An alternator has a TPD of 415V when delivering full-load at unity power factor. If the voltage rises to 470V when full-load is suddenly removed, determine the percentage regulation of the alternator.

5. ALTERNATOR EFFICIENCY

By definition, the efficiency of an alternator is taken to be the ratio of the true power output to the true power input. Stated mathematically -

where: $\eta\%$ = alternator efficiency, expressed as a percentage
P_{OUT} = output power in watts
P_{IN} = input power in watts

An alternator has a number of areas within the machine which incur a loss -.

- rotational losses -
  - friction and windage
  - brush friction at the rotor slip-rings
  - power for driving ventilating fan.
- iron losses -
  - hysteresis loss
  - eddy current loss
- copper losses -
  - field coils and rheostat
  - stator winding.
- exciter losses -
  - losses in the exciter used for field excitation.
- stray load losses -
  - mainly due to non-uniform distribution of current over the cross-section of large conductors. This has the same effect as an increase of resistance.

It should be noted that because of the indeterminate nature of the stray-load losses it is usual to assume they are 1 per cent of the output of the alternator, if the alternator is rated above 150kVA.

Example: 3

A 415V, three-phase alternator supplies 82A at a power factor of 0.8483 lag. The prime mover supplies an input power to the alternator of 54.35kW. Determine the alternator -

a) output power
b) losses
c) percentage efficiency.

Example: 4

A 10MVA, 6.6kV, three-phase alternator operates at full load and a power factor of 0.9 lag. The alternator losses are as follows -

friction and windage loss	= 60kW
iron loss	= 160kW
copper loss	= 115kW
excitation loss	= 14kW
stray load loss	= 100kW

Determine the alternators -

a) full load current
b) total loss
c) input power
d) percentage efficiency

6. ALTERNATORS IN PARALLEL

Practically all modern power plants are designed for operation at constant voltage and usually employ several alternators which are operated singly or in several parallel combinations to supply a common load. There are many reasons for this practice, even though in some cases it might be more economical to install only one or two very large alternators to supply the system load. In the first instance, the efficiency of most electrical machinery is a maximum at, or near, full load. Now since the load of a power station varies widely throughout each twenty-four hour period, it is most economical to have, say, at least one small-sized machine delivering approximately rated output during the early hours of the morning when the load is light, substituting larger alternators as the load increases, and employing a number of machines connected in parallel when peak loads occur. Continuity of service is of extreme importance in the operation of a power distribution system, therefore in changing from one alternator to another, or connecting an alternator in parallel with others, operations are carried out in such a manner that no interruption of supply occurs.

In general, it is considered good power station practice to have the majority of the alternators of the same size and type, since relatively few spare parts need be kept in stock for repair purposes. Furthermore, if a number of similar machines are available, periodic inspections and overhauls may be given to each machine and its prime mover without interruption to supply. The number and size of alternators in a power station should be such that the station is able to supply its peak load when the largest machine is out of service.

In dealing with the parallel operation of alternators, there are four main factors to consider -

- the method of connecting an alternator to bus-bars that are already alive; the process being called "**synchronising**".
- the division of load between the alternators, that is, the sharing of load.
- the effect produced when the excitation of any given alternator is changed.
- the method of disconnecting an alternator from the line.

These factors will now be discussed in the order listed above.

7. SYNCHRONISING

Before a three-phase alternator is connected in parallel with another alternator, or with live bus-bars, the following conditions must be fulfilled -

- the two rms values of the voltage are approximately equal at the terminals being connected
- the two frequencies are the same
- the two voltages are directly opposite in phase
- the phase sequences of the two voltages are the same
- the two voltages have the same wave form.

The first three conditions can be adjusted satisfactorily by the operator, but the fourth depends upon the method of connection of the phase windings to the terminals of the machine, and the fifth to the design of the alternator. It has already been pointed out, however, that sinusoidal wave form is the standard wave form used in AC practice hence all alternators can be said to fulfil the latter requirement. The matter of determining the phase sequence of a machine was covered in the module Applied Electricity AC.

The operation of regulating the behaviour of an alternator to be placed in parallel with other machines to satisfy the first three conditions, and of closing the switch which connects it to the power station bus-bars, is known as synchronising.

The voltage of the incoming machine may be adjusted by varying the field excitation current, and the frequency by varying the speed of the prime mover. To ensure that the two voltages are exactly opposite in phase a synchronising device, for example, a bank of lamps or a synchroscope, may be used as described in the following sections.

8. SYNCHRONISING WITH LAMPS

The connections generally used for synchronising low voltage alternators by means of lamps are shown in figures 6 and 7.

The phase sequence is first checked by connecting a lamp across each phase of the paralleling switch as shown in figure 6.

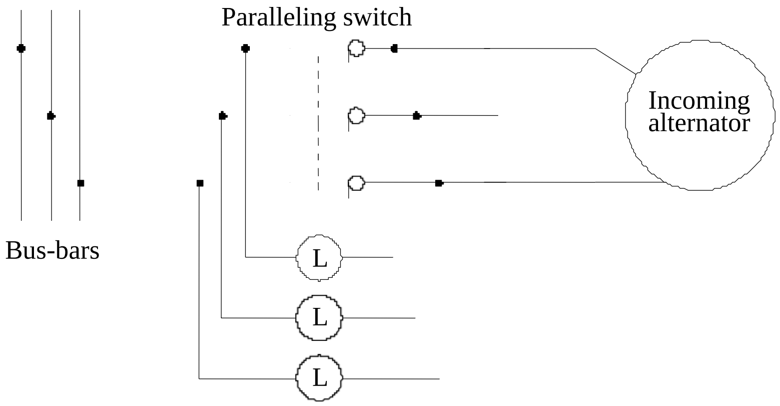


Figure 6

If the alternator is connected correctly, then the three lamps should all glow and darken simultaneously. If they glow and darken in sequence, it means that the phase sequence of the incoming alternator is opposite that of the bus-bars, consequently the connections to two of the phases of the alternator must be interchanged.

The lamps are then connected as shown in figure 7.

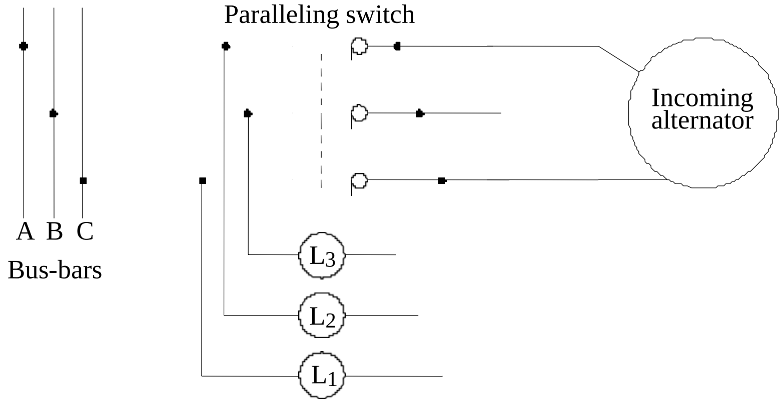


Figure 7

It can be seen from figure 7 that -

- lamp L1 is connected across C phase of the paralleling switch
- lamps L2 and L3 are cross-connected, L2 being connected between the switch terminals A and B, and L3 between B and A.

The three lamps provide the following indications -

- when the alternator is in synchronism with the bus-bars -
    - lamp L1 is dark
    - L2 and L3 glow with equal brightness.
- if the speed of the incoming alternator is too slow - the lamps glow in the order L3-L2-L1
- if the speed of the incoming alternator is too fast - the lamps glow in the order L1-L2-L3.

This means, that if the three lamps are placed in the form of a triangle, the light will travel around it in a direction depending upon whether the incoming alternator is fast or slow. See figure 8.

Figure 8

The paralleling switch is closed when the changes in light are very slow, and when the lamp L1 is dark, indicating that the incoming alternator is running at nearly synchronous speed. The voltage across lamp L1 is zero, and it can be proved that the voltage across the lamps L2 and L3 is $\sqrt{3}$ times the phase voltage. The maximum voltage occurring across the lamps during synchronising is $\sqrt{3}$ times the phase voltage, therefore the lamps should be capable of withstanding this voltage.

9. THE ROTARY SYNCHROSCOPE

Synchronising by means of lamps is not a very accurate method, as a considerable amount of experience and judgment are called for on the part of the operator, and in large machines even a small angle of phase displacement causes a certain amount of shock to the machines as well as causing line voltage disturbances. For this reason an instrument known as a "**rotary synchroscope**" is used.

Figure 9

One type of rotary synchroscope consists of a small motor which rotates when the alternator and bus-bar frequencies are different. The field winding of the motor is excited by a single-phase supply from the main bus-bars. The armature takes a single-phase supply from the incoming machine (usually through synchronising bus-bars) and this is converted into two-phase currents in the armature by a phase-splitting circuit. The speed of rotation depends on the difference in frequency between the incoming alternator and main bus-bar voltages, whereas the direction of rotation depends on whether the incoming alternator is running fast or slow.

The synchroscope is usually connected between two of the main bus-bars and two synchronising bus-bars, through potential transformers, as shown in figure 10.

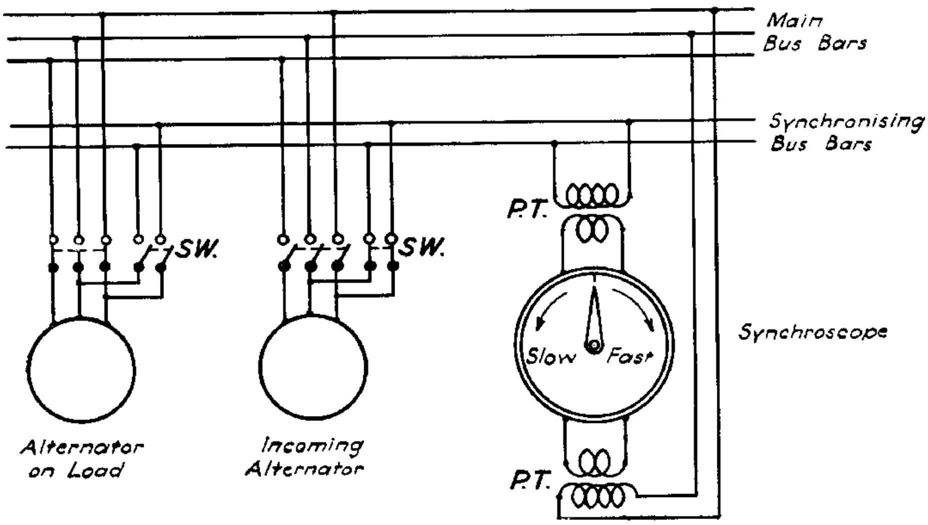


Figure 10

The incoming alternator is synchronised by closing the synchronising switch Sw., this connects the synchroscope between two terminals of the alternator and the main bus-bars. If the frequency of the alternator voltage is not the same as that of the bus-bars, the pointer of the synchroscope rotates. The speed of the incoming alternator is varied until the synchroscope pointer remains stationary in a vertically upward position. This indicates that the incoming alternator is in synchronism with the bus-bars; the main switch is now closed and the synchronising switch opened.

By the use of synchronising bus-bars, any one of a group of alternators may be synchronised by means of one synchroscope.

Before synchronising newly installed machines, however, the phase sequence must first be checked by either lamps or a phase sequence indicator. The synchroscope does not check the phase sequence since it operates only on single-phase supply.

10. DIVISION OF LOAD BETWEEN TWO OR MORE ALTERNATORS

The prime movers of alternators are usually fitted with governors that can be adjusted while the machines are in normal operation.

If an alternator is required to carry more load, the governor is adjusted slightly causing it to admit more input power. This will tend to cause the machine to increase in speed, and it is found that only a very slight increase in speed is required to cause one alternator to take a greater share of the load when operating in parallel with others.

If it is desired to reduce the load on a given machine, the governor is adjusted to admit less input power to the prime mover.

11. EFFECT OF CHANGE OF EXCITATION

Assume that two alternators operating in parallel are exactly in phase, but that the generated emf of, say, alternator No. 2 is, momentarily, slightly less than that of alternator No.1. Now with respect to the local circuit, their voltages must be in exact phase opposition as shown in the phasor diagram of figure 11, but they set up a resultant voltage E_R in phase with E_1.

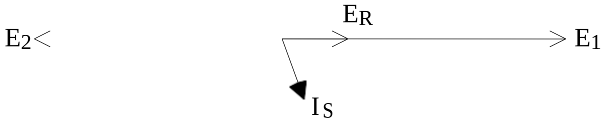


Figure 11

This resultant voltage establishes a synchronising current I_S between the two machines, lagging behind E_1 by nearly 90º.

As described earlier, a lagging current must exert a demagnetising effect upon the mmf of the rotor field of alternator No. 1, thus causing the generated emf of that machine to fall.

On the other hand, the synchronising current I_S leads the voltage of alternator No. 2 by approximately 90º and tends to strengthen the rotor field in that machine, consequently its generated emf is increased.

The two effects therefore combine to lessen the inequality in the two voltages and thereby tend towards producing stability between them.

If the bus-bar voltage is low, the field currents of ALL the alternators must be increased. Increasing the excitation of one machine only causes it to acquire reactive load.

If the frequency of the system is low, the power input to all the prime movers must be increased.

12. DISCONNECTING AN ALTERNATOR FROM THE LINE

When it is desired to remove an alternator from the line, the load should first of all be removed gradually from the machine by reducing the power input to the prime mover after which the circulating current can be removed by reducing the field excitation current until the alternator is merely floating on the bus-bars. The main switch controlling the alternator may now be opened, thus disconnecting the machine from the line, after which the prime mover may be shut down.

13. HUNTING

It has already been shown that when two alternators are operating in parallel, their rotors maintain the same relative position, and the voltages of the two machines are in direct opposition as far as their local circuits are concerned. Any variation of the driving torque exerted by the prime mover of either machine tends to disturb this condition of stability and establishes a synchronising current tending to pull the two alternators back to the correct phase position.

In reciprocating engines, the turning torque varies during each stroke, and this variation is only partly corrected by the use of fly-wheels. The varying torque gives rise to a regular motion of the rotor of the alternator on either side of the normal position, thus producing a synchronising current. This phenomenon is referred to as "**hunting**."

The oscillations produced by hunting, particularly if reciprocating engines are used as prime movers, may become large enough to produce excessive synchronising current and even to cause the machines to fall out of step.

The rotor pole faces can therefore be considered to be situated in a magnetic field which oscillates back and forth and consequently have emfs induced in them. Now these emfs will produce currents in any closed circuit in which they are able to act and thus tend to damp out the motion which produces them (Lenz's law) and so the pole face eddy currents result in smoother running.

To increase the damping effect of eddy currents, special windings are sometimes placed in slots in the pole shoes. These windings are known as damping grids or "**amortisseur windings**", and consist of a number of heavy copper bars or rods, one in each slot, securely joined at the ends to a common connecting bar to form a short-circuited grid arrangement, as shown in 12.

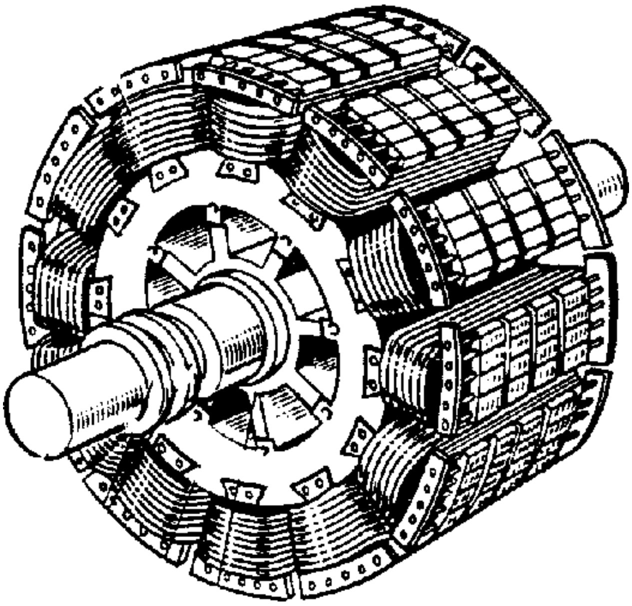


Figure 12

ALTERNATOR LOAD CHARACTERISTICS

PURPOSE:

This practical assignment will be used to plot and examine the load characteristic of an alternator.

TO ACHIEVE THE PURPOSE OF THIS SECTION:

At the end of this practical assignment the student will be able to:

- Connect an alternator and operate under variable load conditions with fixed field excitation.
- Measure values of generated voltage under varying load conditions.
- Describe the effect of load on the terminal voltage of an alternator for resistive and capacitive loads.
- Draw the load characteristic of an alternator for resistive and capacitive loads.

EQUIPMENT:

- 1 x single phase dive unit
- 1 x Betts synchronous machine
- 1 x double machine bed
- 1 x variable dc power supply
- 1 x alternator lamp load panel
- 1 x alternator capacitor load panel
- 1 x ac current clamp
- 2 x digital multimeters
- 4mm connection leads

– REMEMBER –
– WORK SAFELY AT ALL TIMES –
Observe correct isolation procedures

PROCEDURE:

1. RESISTIVE LOAD

1. Couple the single phase drive unit to the alternator as shown in figure 1.

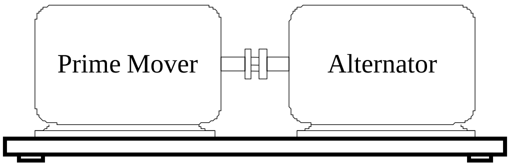


Figure 6

2. Connect the alternator as shown in figure 2.

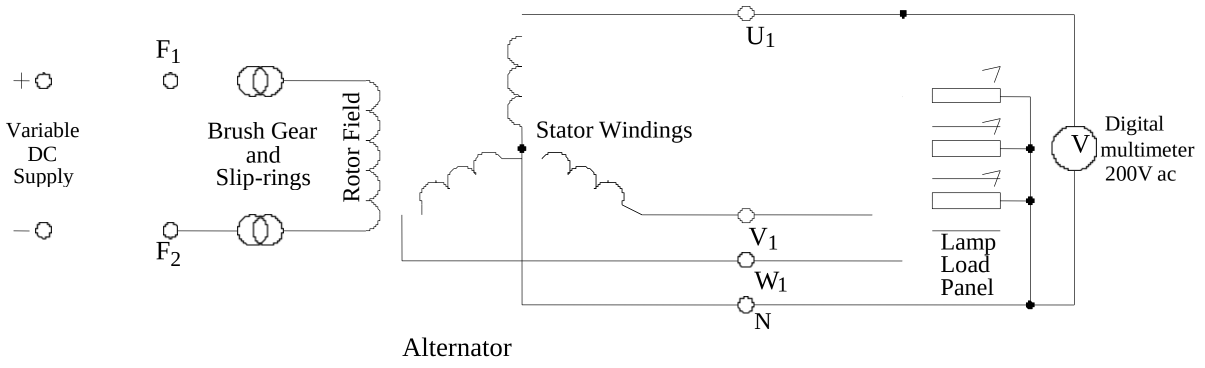


Figure 2

3. Ensure the load panel switch is in the OFF position.
4. Switch on the single phase drive unit (prime mover).
5. Switch on the dc power supply and adjust the field voltage to 24V.
6. Measure the alternator phase voltage. Record in table 1.

Table 1

	Lamp Load Panel Switch Position				
	OFF	1	2	3	4
Phase Voltage volts					
Load Current amperes	0				

7. Apply load to the alternator by moving the load panel switch to position 1, then measure and record the phase voltage and load current. Record in table 1.
8. Repeat the procedure for positions 2, 3 and 4 of the load panel switch.

9. **<u>Do not proceed</u>** until the teacher checks your results and completes the progress table.

Progress Table 1

attempt 1	attempt 2	attempt 3
5	2	0

10. Set the load panel switch to the OFF position.
11. Reduce the field voltage to 0V and turn off the single phase drive unit.

2. CAPACITIVE LOAD

1. Connect the alternator as shown in figure 3. That is, replace the lamp load panel with the capacitive load panel.

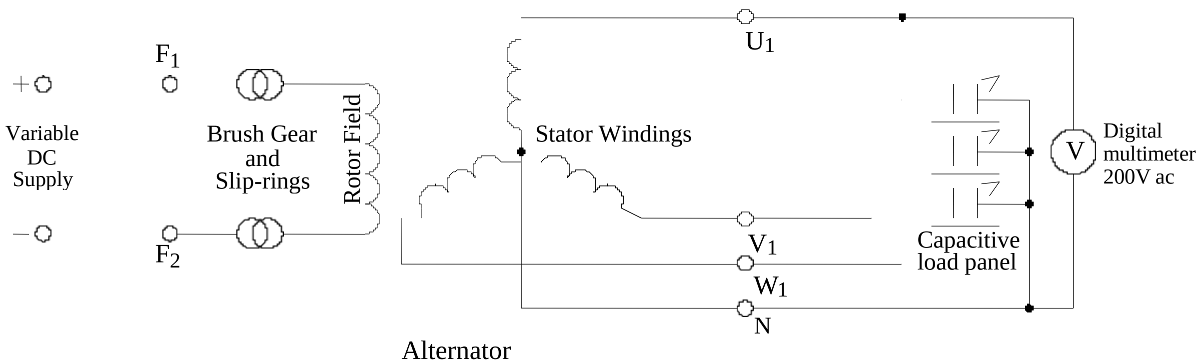


Figure 3

2. Ensure the load panel switch is in the OFF position.
3. Switch on the single phase drive unit (prime mover).
4. Switch on the dc power supply and adjust the field voltage to 24V.
5. Measure the alternator phase voltage. Record in table 2.

Table 2

	Capacitive Load Panel Switch Position				
	OFF	1	2	3	4
Phase Voltage volts					
Load Current amperes	0				

6. Apply load to the alternator by moving the load panel switch to position 1, then measure and record the phase voltage and load current. Record in table 1.
7. Repeat the procedure for positions 2, 3 and 4 of the load panel switch.
8. **Do not proceed** until the teacher checks your results and completes the progress table.

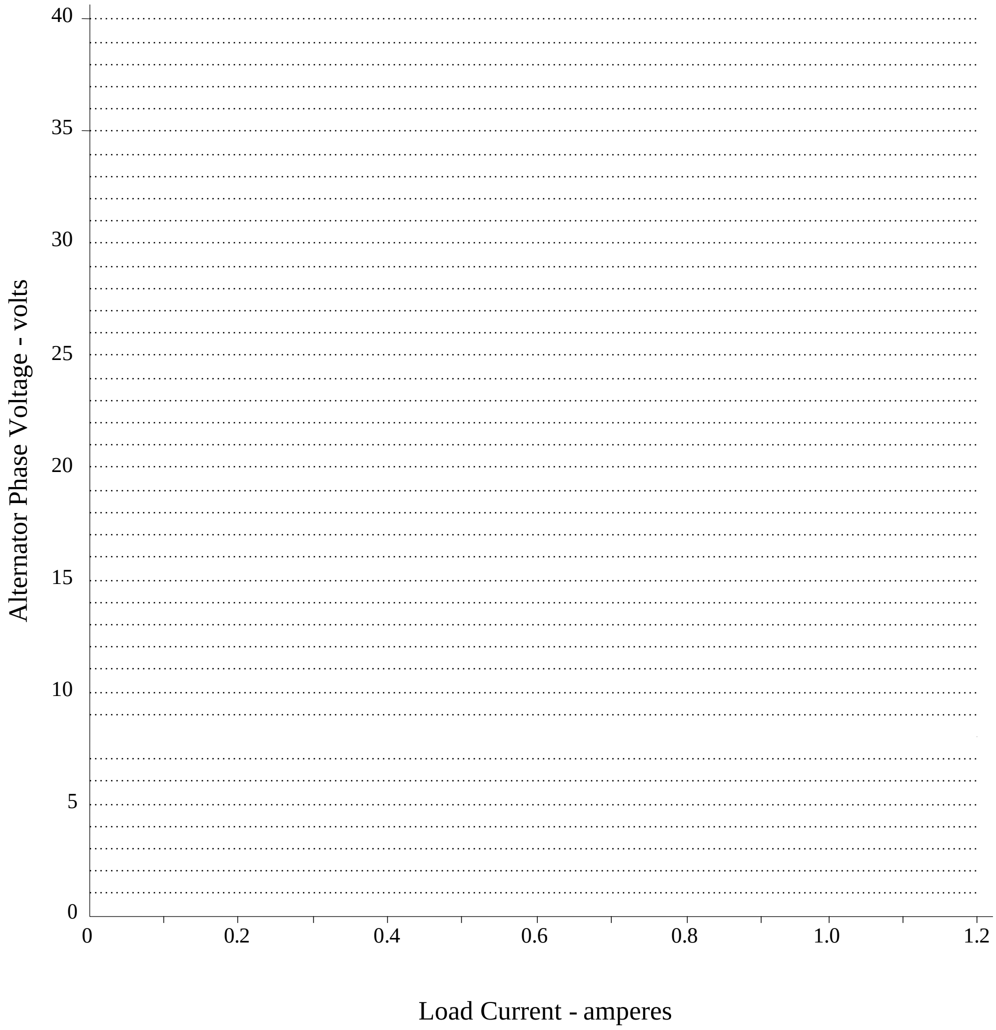
Progress Table 1

attempt 1	attempt 2	attempt 3
5	2	0

9. Set the load panel switch to the OFF position.
10. Reduce the field voltage to 0V and turn off the single phase drive unit.
11. Switch off the dc power supply, then disconnect the circuit.
12. Please return all equipment to its proper place, safely and carefully.

3. OBSERVATIONS:

1. Using the results from the alternator load tests, plot the alternator load characteristic for both resistive and capacitive loads.



2. What was the effect on alternator terminal voltage of increasing the resistive load applied?

____

____

____

3. What was the effect on alternator terminal voltage of increasing the capacitive load applied?

____

____

____

4. What causes variation of alternator terminal voltage with variation of load?

5. What would be the effect on alternator terminal voltage of applying a variable inductive load?

6. Why did you apply 24V to the alternator field? Note, check the alternator nameplate.

Tutorial 15 **NAME:**

ALTERNATORS – PART 2

SECTION A

In the following statements one of the suggested answers is best. Place the identifying letter on your answer sheet.

1. The efficiency of an alternator is the ratio of:-
   e) kVA output to kVA input;
   f) kW output to kW input;
   g) kVA output to kW input;
   h) kW output to kVA input;
2. The terminal potential difference of a three phase 50 hertz alternator is adjusted to the required value by means of:-
   a) altering the field excitation;
   b) changing the speed
   c) using a tapped winding;
   d) adjusting the number of poles.
3. Modern large alternators use hydrogen cooling. This is done to:-
   e) prevent the windings from oxidising;
   f) reduce the rotational losses in the machine;
   g) reduce the load on the alternator bearings;
   h) reduce air pollution caused by arcing.
4. Alternators are connected in parallel to:-
   a) increase the output voltage supplied to the load;
   b) increase the output current supplied to the load;
   c) allow two alternators to be driven by one prime mover;
   d) because two small alternators are more efficient than one large one.
5. As the power factor of a constant current load with a lagging power factor is improved towards unity power factor the t.p.d. of the alternator will:-
   a) increase;
   b) decrease;
   c) remain unchanged;
   d) depend on load frequency.
6. Alternators are rated in terms of:-
   a) speed and voltage;
   b) current and voltage;
   c) voltage and kVA;
   d) voltage and kW.

7. An alternator normally designed with a high voltage regulation to:-
   a) control output voltage;
   b) limit short circuit current;
   c) reduce losses in windings;
   d) limit open circuit speed.
8. If the terminal voltage on an alternator increases as load increases the type of load is a:-
   a) modern highly efficient load;
   b) lagging power factor load;
   c) unity power factor load;
   d) leading power factor load.
9. The load characteristic of an alternator shows the manner in which the:-
   a) excitation varies with load;
   b) speed varies with excitation;
   c) t.p.d. varies with load;
   d) t.p.d. varies with excitation.
10. Armature reaction in an alternator causes:-
   a) a reduction in torque due to load current;
   b) a change in field flux as load power factor changes;
   c) an increase in armature speed as load increases;
   d) a decrease in armature speed as load increases.

SECTION B

Blank spaces in the following statements represent omissions. Write the appropriate information on your answer sheet.

The percentage rise in terminal voltage of an alternator when full load is removed is called it's______(1)_____.

The load characteristic of an alternator is a graph showing the variation in terminal voltage when a change occurs in the______(2)_____current.

The effect of armature reaction in an alternator supplying a lagging power factor load is to______(3)_____the t.p.d. compared to an equivalent unity power factor load.

Variations in t.p.d. which may occur due to changes in load on an alternator are minimised by the use of______(4)_____.

Voltage regulation of an alternator is the difference between no-load voltage and full-load voltage expressed as a percentage of______(5)_____voltage.

When operating alternators in parallel the load share of one alternator may be increased by increasing the______(6)_____on the_______(7)_____.

When the rotor in a 6 pole alternator has passed through one complete revolution it has completed______(8)_____electrical degrees.

Alternators are rated in kVA rather than kW because the voltage and kVA rating can be used to determine the maximum______(9)_____ that the______(10)_____can withstand..

The output voltage of an alternator is maintained constant as load current changes by using a______(11)_____to monitor output voltage and adjust______(12)_____.

SECTION C

1. An alternator has a t.p.d. of 415 volts when delivering full load at unity power factor. Calculate the no load t.p.d. if the alternator has a voltage regulation of 13 percent. (468.95V)
2. A three phase 6 600 volt alternator supplies a current of 2 200 amperes at full load. Determine:-
   a) the rated kVA output; (25.15MVA or 25 150kVA)
   b) the output power at 0.8 lagging power factor. (20.1MW or 20 100kW)
3. An alternator with a full load t.p.d. of 415 volts has the terminal voltage increase to 499 volts on no load. Determine the percentage voltage regulation for the alternator. (20.24%)
4. The terminal voltage of a 70MVA, three phase, 50 hertz, star connected alternator is 11.7kV. If the armature winding has a breadth factor (k) of 0.956 and the armature winding has 16 turns per phase determine:-
   a) the maximum flux per pole; (1.98Wb)
   b) the full load current rating of the alternator. (3 454A.)
5. The 70MVA alternator in the previous question has an efficiency of 92 percent when operating at full load and 0.8 power factor. Determine the power output of the prime mover at this load. (60.87MW)

SECTION D

1. For the alternator load characteristic curves shown in Figure 1:-

a) indicate whether curve A, B and C are lagging, leading or unity power factor;

A:-__________________________power factor;

B:-__________________________power factor;

C:-__________________________power factor;

b) for the rated current shown, determine the open circuit and full load voltage and then calculate the voltage regulation of the alternator for the leading, lagging and unity power factors shown.

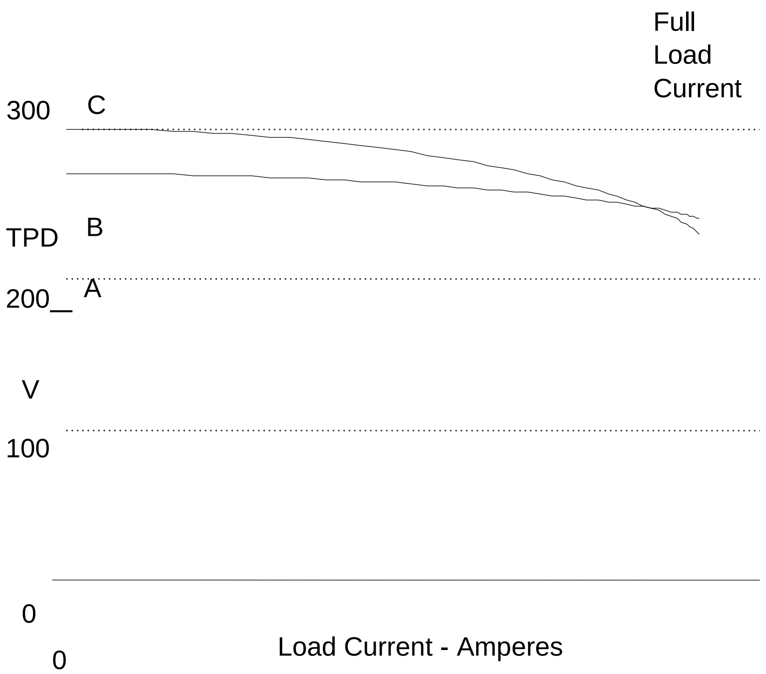


Figure 1

SYNCHRONOUS MOTORS

PURPOSE:

In this section you will learn about the construction and operation of three phase synchronous motors.

TO ACHIEVE THE PURPOSE OF THIS SECTION:

At the end of this section the student will be able to:

- Describe the construction of three phase synchronous motors.
- Describe the operation of the three phase synchronous motor.
- List methods used to start three phase synchronous motors.
- Calculate the synchronous speed of a three phase synchronous motor, given the supply frequency and number of poles.
- Describe the effect of varying the dc excitation on the operation of a three phase synchronous motor.
- Identify and interpret the V-curves of a three phase synchronous motor.
- List practical applications of three phase synchronous motors.

REFERENCES:

- Electrical Trade Principles 2nd Edition J Hampson & S Hanssen. Section 6
- Electrical Principles for the Electrical Trades. 5th Edition. Jenneson J.R. Pages 259-262.

1. INTRODUCTION

An alternator, when supplied with electrical energy at rated voltage and frequency, will operate satisfactorily as a motor. If a synchronous machine operates as a motor, it is called a "**synchronous motor**". As the name implies, synchronous motors run in synchronism with a rotating magnetic field. The speed of rotation is therefore tied to the frequency of the supply. Because the frequency is fixed, the motor speed

- _______________________________, irrespective of the load.

However, synchronous motors are used not so much because they run at constant speed, but because they possess other unique electrical properties. These properties will be dealt with in this section.

Most synchronous motors are rated between -

- ____________________________

  and operate at speeds ranging from

- _____.

Consequently these machines are mainly used in heavy industry

At the other end of the power spectrum, you will find tiny single phase synchronous motors used in control devices and electric clocks. The operation of these smaller synchronous motors will be treated at the end of this module.

2. TYPES OF SYNCHRONOUS MOTORS

There are three types of synchronous motors in common use. All three motors have the same type of construction for their stators and they differ in their rotor construction.

Reluctance Synchronous Motor: The rotor of this type of motor is supplied with DC excitation through 2 slip rings mounted on the shaft. This motor will be discussed further in this topic.

Hysteresis Synchronous Motor: The rotor of this motor is constructed of a very hard, highly permeable permanent magnet alloy material supported on a non-magnetic shaft. This rotor is smooth without windings or slots and this design causes the motor to develop a constant torque through every revolution of the rotor. These motors are generally rated at less than 1kW.

Permanent Magnet Synchronous Motor: The rotor of this motor is a permanent magnet without any external excitation required. The number of poles on the rotor must equal the number of poles on the stator. The amount of torque developed by these motors varies according to the machines construction parameters.

3. CONSTRUCTION

As with alternators and induction motors, synchronous motors may be single, two or three phase. The constructional details of a three phase synchronous motor are essentially the same as that of a three phase alternator, as discussed in section 1. Therefore, depending upon the required application the synchronous machine maybe used to convert -

- mechanical energy to electrical energy - ___________________ operation
- electrical energy to mechanical energy - ___________________ operation.

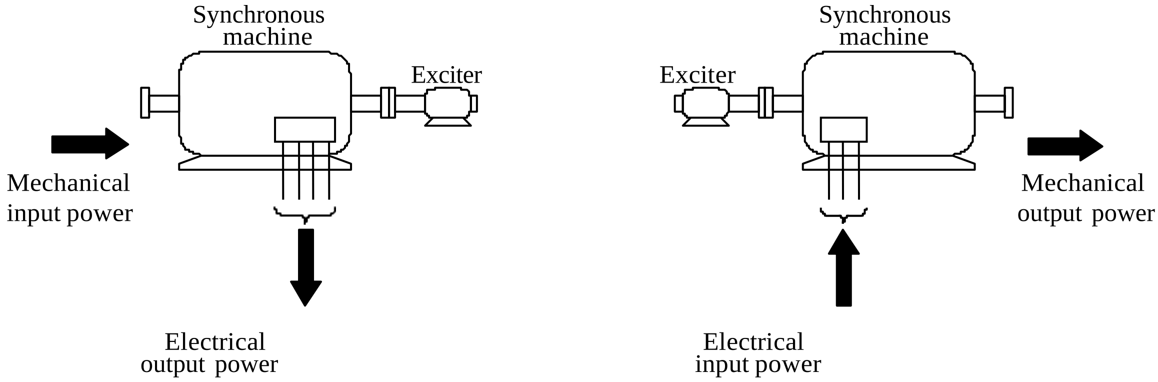


Figure 1

In construction, the synchronous motor is almost identical with the alternator. However, better synchronous motor characteristics can be obtained if slight modifications are made, for example, in length of air-gap and number of field ampere-turns. In general, synchronous motors are of the salient pole type, since this type gives greater stability of operation.

As shown in figure 2, the "**stator**" is composed of a slotted magnetic core which carries a three phase winding. The winding is identical to that of a three phase induction motor.

The stator is supplied with electrical energy from a three phase source.

The combination of three phase windings displaced by 120^0E and supplied with three phase currents which are also displaced by 120^0E results in the production of a -

- ___________________________________

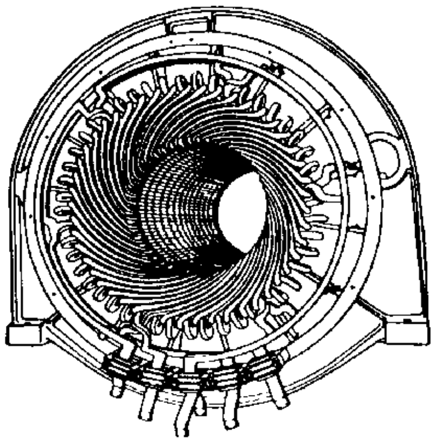


Figure 2

Figure 2

The "**rotor**" has a set of salient poles that are excited by DC current, see figure 3. The exciting coils are connected in series to two slip rings, and the DC current is fed into the winding from an external source, usually an exciter.

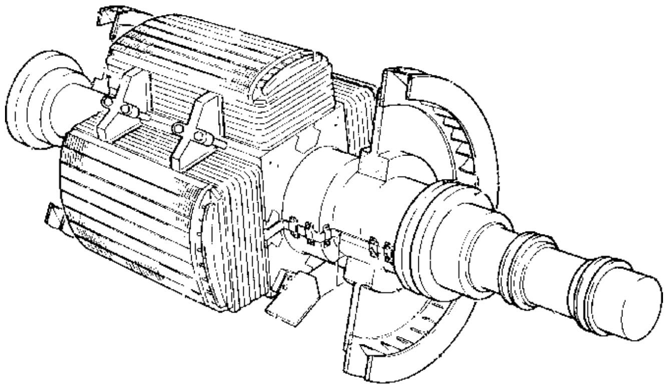


Figure 3

Slots are punched out along the circumference of the salient poles. They carry a squirrel cage winding similar to that in a three phase induction motor, see figure 4. This so called **damper winding** serves to start the motor and improve operating stability.

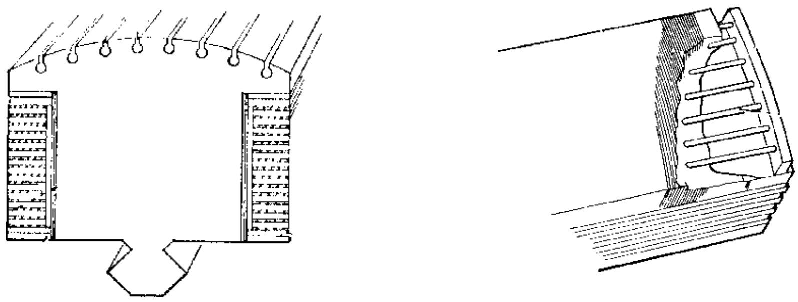


Figure 4

The general arrangement of the three phase synchronous motor is shown in figure 5.

The stator winding is supplied from a three phase source.

The rotor winding is supplied with direct current from an external source, usually an exciter.

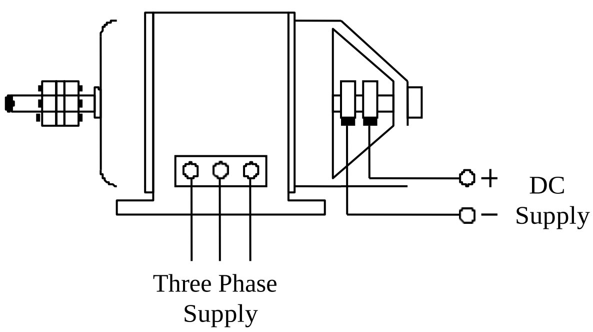


Figure 5

4. PRINCIPLE OF OPERATION

The stator of the synchronous motor is similar to the stator of the alternator and the induction motor.

Consequently, if polyphase currents are supplied to the stator, a rotating magnetic field is produced. This field travels at synchronous speed. The speed is determined by the same factors that govern the synchronous speed of induction motors. The synchronous speed is found using the equation -

where: n_S = synchronous speed in rpm

f = supply frequency in hertz

P = number of poles

Figure 6 illustrates such a rotating magnetic field and the four pole field produced is assumed to be rotating in a clockwise direction.

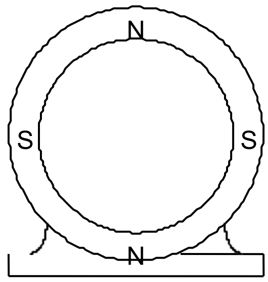


Figure 6

If a stationary salient pole rotor having four poles is placed in this field, figure 7, it will be found that the rotor

- ____.

However, if the rotor is run up to nearly synchronous speed, the south poles of the rotor will be attracted to the north poles of the stator and the north poles of the rotor attracted to the south poles of the stator. The rotating field of the stator, thus being locked with the rotor poles, will drag the rotor round at

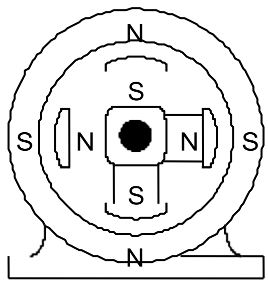


Figure 7

- ______________________________.

5. METHODS OF FIELD EXCITATION

The rotor field windings are supplied with low voltage DC through slip rings, in the following ways -

- from a small DC generator, called an exciter, direct coupled to the shaft of the synchronous motor.
- from an independent DC supply.

6. LOAD ON A SYNCHRONOUS MOTOR

When load is applied to the shaft of a synchronous motor, its average speed cannot decrease because the motor must operate at constant average speed, that is, synchronous speed.

In figure 8 it is assumed that a synchronous motor is rotating in a clockwise direction on no load.

The line OC, drawn through the centre of a north pole of the stator, therefore can be considered as rotating synchronously with the stator rotating magnetic field. The centre line of each south pole of the rotor coincides with the centre line of the stator north pole opposite to it.

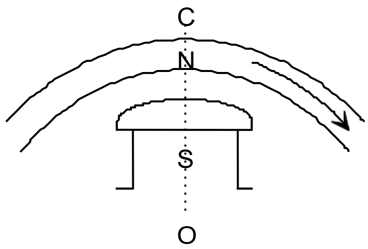


Figure 8

In figure 9 it is considered that load has been applied to the motor shaft.

Now the position of the line OC is not changed by this load because its position is determined by the north pole produced by the stator rotating magnetic field.

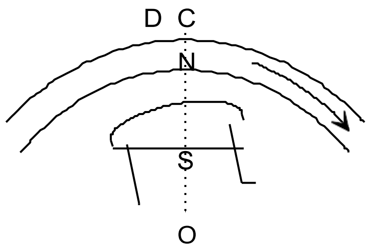


Figure 9

However, the rotor is pulled back through an angle θ, usually referred to as the

- ___________________________,

from the line OC, that is, from the position it would occupy on no load into a new position OD. The stretching of the magnetic field in the air gap tends to pull the rotor back into its no load position. The rotor will still continue to run steadily at synchronous speed, but the position of the rotor lags continuously behind the position which it would occupy on no load. This means there is an

- ____

between the rotor and the stator rotating magnetic field.

The synchronous motor, therefore, does not operate at reduced speed when load is applied to its shaft, but the phase position of the rotor is moved backwards.

7. STATOR COUNTER EMF

The stator winding of a synchronous motor is acted upon by two separate voltages -

- ______________________________________
- ______________________________________.

If the motor is operating unloaded the counter or induced emf (ε_O), which is produced in the stator winding by the motion of the rotor field poles, is practically equal and opposite to the applied voltage. Therefore the stator current is

- _____________________________________. See figure 10.

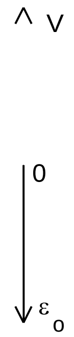


Figure 10

When load is applied to the shaft of the motor the rotor drops back by the load angle θ from the position it occupies at no load. Consequently, the induced or counter emf (ε_L) will now lag behind its former value (ε_O) by an angle θ. The resultant emf (V_R) acting on the stator winding is therefore the phasor sum of V and ε_L, see figure 11.

It should be noted that the ratio of stator reactance to stator

resistance (X/R) is so large that the current lags behind V_R by an angle which is approximately 90^0.

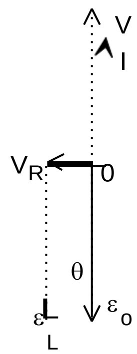


Figure 11

If the load is further increased -

- the angle θ____________________,
- which in turn_____________________the resultant voltage V_R
- and the current taken by the stator____________________.

The result is a____________________power input to the stator winding.

Notice particularly, that the power input to the stator depends, not upon any change in the counter emf, but upon the value of the load angle θ. The effect of a variation in the counter emf by variation of the exciting current will be considered in the following section.

8. EFFECT OF VARYING EXCITATION

The direct effect of varying the field excitation of a synchronous motor is to vary the counter emf, that is, the emf induced in the stator windings by the rotor field.

The most suitable excitation is that which requires the stator current to be a minimum for a particular load. Any increase or decrease in the exciting current from this normal value will result in an increase in stator current. But as the power supplied to the motor depends primarily on the load angle and not on the excitation current (except for I^2R losses) an increase in stator current must be accompanied by a reduction in the power factor.

Figure 12 is the phasor diagram of a synchronous motor operating on its rated full load and at a value of field excitation below normal. Notice that the supply current **lags** behind the applied voltage.

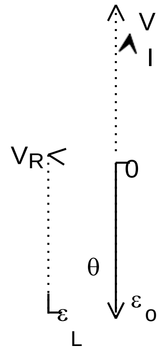


Figure 12

If the field excitation is brought up to normal value while the load remains constant. This will cause

- the air gap flux to________________,
- the counter emf________________,
- the load angle to________________.

This results in a

- ________________ of the resultant voltage
- ________________ of the stator current
- ________________ of the stator phase angle ϕ.

For the case under consideration, figure 13, it is assumed that the increased excitation is such as to bring the stator current in phase with the applied voltage, that is, the motor in this case operating at **unity** power factor.

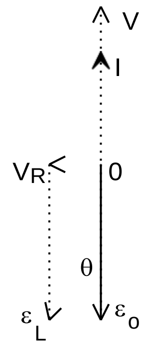


Figure 13

An increase in excitation beyond normal results in a further increase of the counter emf and a further reduction in the load angle θ, as shown in figure 14. The stator current is increased but it now **leads** the applied voltage.

The characteristic behaviour of a synchronous motor taking a leading current when over excited is frequently utilised to **improve the power factor** of installations containing inductive loads.

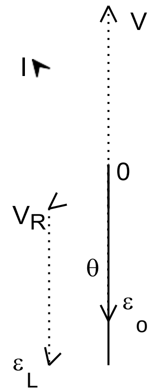


Figure 14

9. V-CURVES

V-curves are curves showing the relationship between the stator current and the field excitation current of a synchronous motor, for various loads.

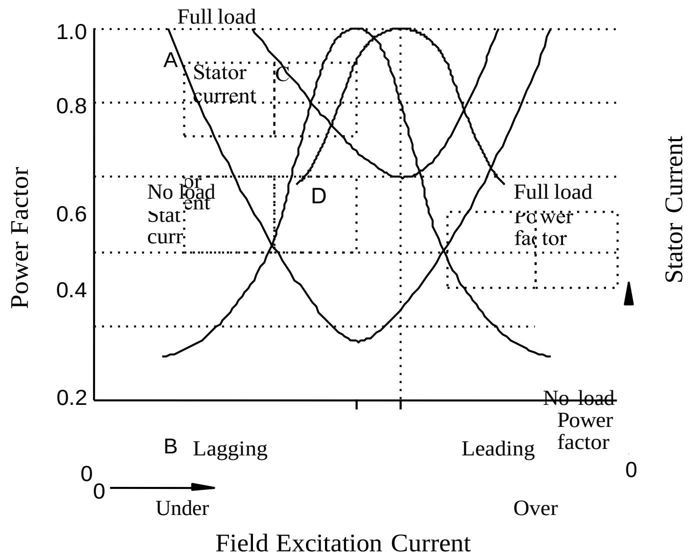


Figure 15

If the power input to a synchronous motor is held constant and the excitation current varied, it is found that -

- for small values of excitation current the takes a large **lagging** stator current and the power factor is low. This is shown by curves A and B in figure 15, which represents stator current and power factor, respectively, for a synchronous motor on no load.
- as the excitation current is increased, the stator current falls until a minimum value is reached with a power factor of **unity**.
- further increases in excitation current cause the stator current to increase and become **leading** while the power factor falls.

The excitation current that gives the minimum stator current and unity power factor is termed -

____ for the particular load considered.

If power factor improvement is not required, then normal excitation is the best excitation to use.

If the excitation is less than normal, the motor is said to be________________________.

If the excitation is greater than normal, the motor is said to_______________________.

If the power output is increased to its full load value and kept constant, the stator current (curve C) and the power factor (curve D) are obtained. Notice that the normal excitation is increased by an increase in load.

It should be kept in mind that when under excited the motor acts as an inductance, in that it takes a lagging current. With over excitation it takes a leading current and behaves as a capacitor. Over excitation is desirable for the following reasons -

- it provides a stronger working field and so increases the pull out torque.
- it reduces the liability to fall out of step through hunting.
- the motor works with a leading stator current and so compensates for lagging currents in other parts of the system.

10. HUNTING

Hunting, or phase swinging, is an effect produced in alternators and synchronous motors which interferes with their smooth working.

It is the oscillation of the rotor above and below normal synchronous speed, that is, a swinging movement on each side of the true synchronous position. The hunting effect can be detected by ear, in some cases, because of the pulsating sound set up by the pendulum motion. In all cases, the hunting effect is shown on instruments connected in the stator circuit, unless the meters are very highly damped. The pointers of analogue instruments sway to and fro in time with the oscillations of the machine.

Hunting in a synchronous motor is caused in the following ways -

- sudden change of load on the motor.
- sudden change of supply frequency.
- periodic pulsation of the load on the motor, usually when reciprocating machinery is being driven.
- sudden changes in the excitation current caused by loose connections or chattering brushes.

It is possible for hunting to cause such an amount of oscillation that the magnetic coupling stretches beyond the limit of its elasticity and the motor stops.

Hunting is prevented or reduced in the following ways -

- by running the motor with strong excitation.
- by using "**amortisseur windings**" or "**damping windings**" on the pole shoes.

The swaying to and fro of the flux across the pole face cuts the conductors of the amortisseur winding, inducing emf's in them and as the circuit is closed a current is produced, which by Lenz's Law, will tend to damp out the motion which causes it and thus produce smoother running. If the rotation of the rotor is perfectly uniform there is no relative movement between the flux and amortisseur windings and so no currents are set up in them.

11. STARTING SYNCHRONOUS MOTORS

Since the ordinary synchronous motor is not self starting, it is necessary to start it by auxiliary means and bring it up to about synchronous speed. The stator and the field poles are then energised and the motor falls into step and continues to rotate at synchronous speed.

The following methods are commonly employed to start synchronous motors -

- using the exciter as a motor -

  The exciter is sometimes used as a motor to bring the synchronous motor up to synchronous speed, if a suitable DC supply is available. The motor is then synchronised by connecting its stator winding to the AC supply and its field to the DC supply. After synchronisation, the motor has its field supplied from the exciter.

- using a pony motor -

  An alternative method of starting a synchronous motor is to use a small auxiliary direct coupled induction motor called a pony motor. If a pony motor is connected in parallel with the main motor it is designed with two poles less to enable it to reach the synchronous speed of the synchronous motor.

- using the damping winding -

  Three phase synchronous motors can be started by the addition of a special damping winding on the field system. The stator currents set up a rotating magnetic field which cuts the damping winding and establishes currents in the short circuited bars or grids. A torque is developed and the machine runs up as an induction motor to a speed slightly less than synchronous speed. A gradually increasing direct current is then supplied to the field winding until the two sets of poles lock together with a magnetic coupling between them.

  Because of the large starting current required by this method it is usual to start on a reduced voltage, as with the squirrel cage induction motor. This reduced voltage may be obtained from tappings on an auto transformer. The DC field circuit should be disconnected in several places during the earlier part of the starting period, because of the high voltages induced in it by transformer action when the speed is low. For the same reason also, it is usual to insulate the field windings for a voltage much higher than the excitation voltage, when this method of starting is used.

- using a variable frequency drive -

  A variable frequency supply may be used to reduce the supply frequency to allow the rotor field to lock onto the stator rotating magnetic field. Once started the supply frequency is increased to accelerate the motor to rated speed. The supply voltage is reduced when frequency is reduced to compensate for the reduction in stator winding inductive reactance at the lower frequency.

12. THE SYNCHRONOUS INDUCTION MOTOR

The "**synchronous induction motor**" is similar in construction to the slip ring induction motor and is sometimes referred to as an "**auto synchronous motor**".

Since the stator of a synchronous motor is the same as the stator of an induction motor, the machine simply consists of a slip ring induction motor with a direct coupled DC exciter. The motor is started with the usual rotor resistances, these being disconnected and replaced by the DC exciter as synchronous speed is approached. An elementary diagram of connections for a synchronous induction motor is shown in figure 16.

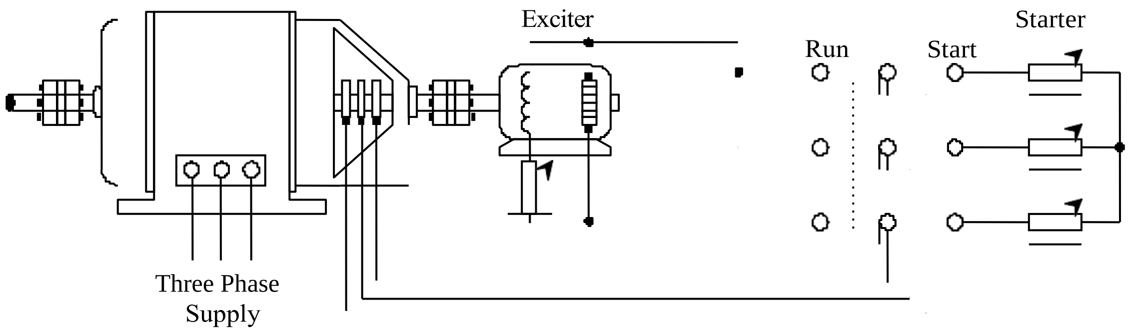


Figure 16

A synchronous induction motor can be designed to pull into synchronism against full load torque, and by suitably regulating the excitation current can be made to operate on a leading current, if required.

This type of motor operates as a plain induction motor if the breakdown torque is exceeded and the motor falls out of step. However when the load is reduced, the machine pulls into step again and continues to operate as a synchronous motor.

One disadvantage of the synchronous induction motor is that its breakdown torque is much less than that of the equivalent synchronous motor of the normal type. If the motor falls out of step and operates as an induction motor, the low frequency alternating currents set up in the rotor are superimposed on the direct currents from the exciter, which causes considerable fluctuations in -

______________________ and______________________.

Another disadvantage is that it is not very well adapted for power factor improvement as the plain synchronous motor.

13. APPLICATIONS OF SYNCHRONOUS MOTORS

Synchronous motors have three important characteristics which dictate their application -

- ________________________ for all loads (zero speed regulations)
- ________________________ power factor
- ________________________ operating efficiency (85% to 96%).

Applications for synchronous motors include -

- power factor correction
- transmission line voltage control
- constant speed drives, such as fans, air compressors, pumps, rock crushers and mill rolls
- variable speed drives, such as extruder and mill drives, the advantage being higher efficiency at slower speeds than an induction motor.

Notes

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SYNCHRONOUS MOTORS

PURPOSE:

This practical assignment will be used to plot and examine the characteristics, known as the V-curves, of a three phase synchronous motor.

TO ACHIEVE THE PURPOSE OF THIS SECTION:

At the end of this practical assignment the student will be able to:

- Connect an asynchronous motor and operate under variable load conditions and variable field excitation.
- Describe the effect of variation of field excitation on motor line current.
- Describe the effect of variation of field excitation on motor power factor.
- Draw the V-curves for a synchronous motor operating under no-load and full-load conditions.

EQUIPMENT:

- 1 x Betts synchronous machine
- 1 x Betts dynamometer
- 1 x double machine bed
- 1 x dual variable dc power supply
- 1 x digital multimeter
- 1 x ac current clamp
- 1 x dc ammeter (0 - 1A)
- 1 x tachometer
- 4mm connection leads

– REMEMBER –
– WORK SAFELY AT ALL TIMES –
Observe correct isolation procedures

PROCEDURE:

1. NO-LOAD OPERATION

1. Mount the synchronous motor on the double machine bed as shown in figure 1.

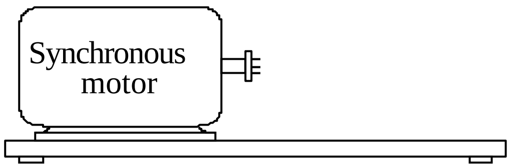

Figure 1

2. Connect the synchronous motor as shown in figure 2.

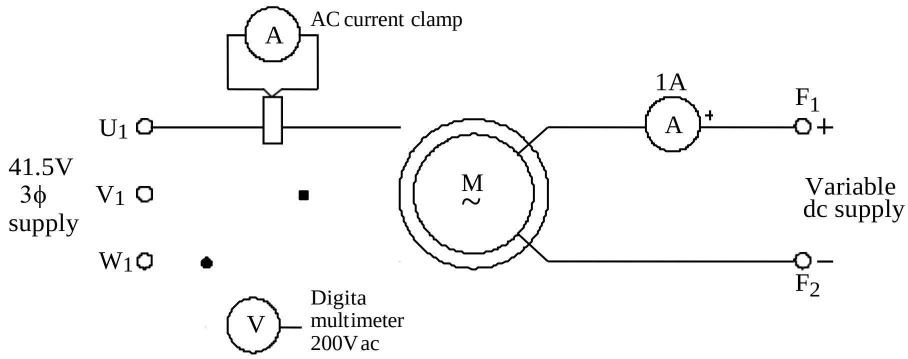

Figure 2

3. Adjust the dc power supply for a motor field excitation of 0.4A.
4. Switch on the 41.5V three phase supply. The motor will start and accelerate to synchronous speed.
5. Adjust the motor field excitation until the motor draws minimum ac line current. Record the value of dc excitation and the ac line current in table 1.

Table 1

DC Excitation		Motor Line Current amperes	Motor Speed rpm	Motor Power Factor
%	Amperes			
25%				
50%				
75%				
Normal		**I_{MIN} =**		
125%				
150%				
175%				

6. Using the hand held tachometer, measure the motor speed of rotation. Record in the appropriate column of table 1.
7. Determine the values for 25%, 50%, 75%, 125%, 150% and 175% of normal excitation. Record the values in table 1.
8. Vary the dc excitation in steps of 25% above and below normal excitation. At each step measure and record the motor line current and speed. Record in table 1.
9. Calculate the motor power input for normal excitation -

$P_{IN} = \sqrt{3} \times V_L \times I_L \times \lambda$ (Note: Assume unity power factor at normal excitation)

10. Determine the motor power factor for each value of field excitation -

$$\lambda = \frac{\mathbf{P_{IN}}}{\mathbf{\sqrt{3} \times V_L \times I_L}}$$

11. **Do not proceed** until the teacher checks your results and completes the progress table.

Progress Table 1

attempt 1	attempt 2	attempt 3
5	2	0

12. Reduce the field excitation to 0A.
13. Switch off the three phase supply.

2. FULL LOAD OPERATION

1. Couple the synchronous motor to the dynamometer as shown in figure 3.

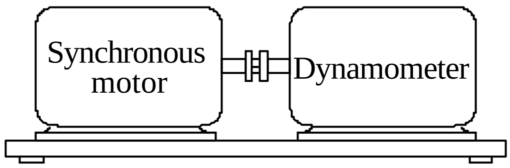

Figure 3

2. Connect the circuit as shown in figure 4.

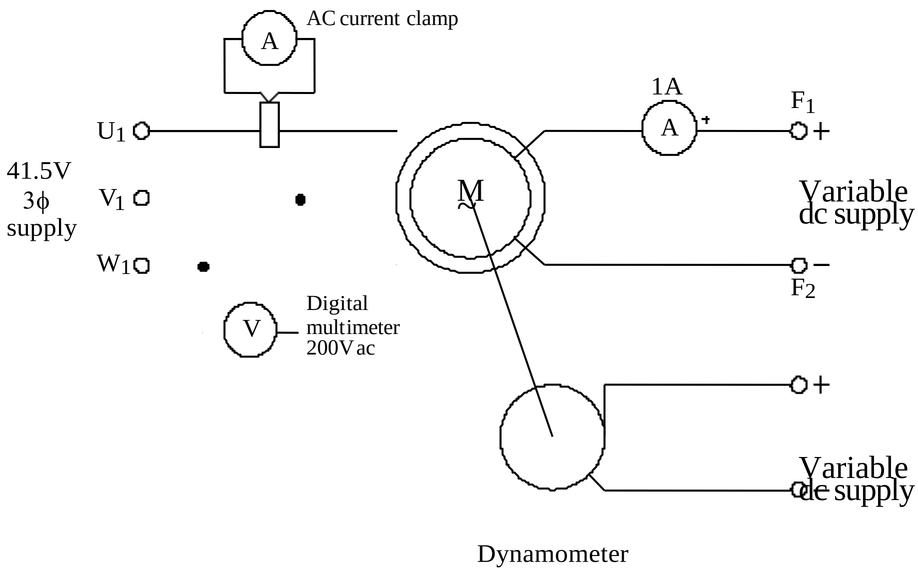

Figure 4

3. Adjust the dc power supply for a motor field excitation of 0.4A.
4. Switch on the 41.5V three phase supply. The motor will start and accelerate to synchronous speed.
5. Adjust the dynamometer dc supply for a load torque of 0.3Nm.
6. Adjust the motor field excitation until the motor draws minimum ac line current. Record the value of dc excitation and the ac line current in table 2.
7. Using the hand held tachometer, measure the motor speed of rotation. Record in the appropriate column of table 2.
8. Determine the values for 25%, 50%, 75%, 125%, 150% and 175% of normal excitation. Record the values in table 2.
9. Vary the dc excitation in steps of 25% above and below normal excitation. At each step measure and record the motor line current and speed. Record in table 2.

Table 2

DC Excitation		Motor Line Current amperes	Motor Speed rpm	Motor Power Factor
%	Amperes			
25%				
50%				
75%				
Normal		I_{MIN} =		
125%				
150%				
175%				

10. Calculate the motor power input for normal excitation -

$P_{IN} = \sqrt{3} \text{ x } V_L \text{x } I_L \text{ x } \lambda$ (Note: Assume unity power factor at normal excitation)

____

____

11. Determine the motor power factor for each value of field excitation -

$$\lambda = \frac{\mathbf{P_{IN}}}{\sqrt{\mathbf{3}} \textbf{ x } \mathbf{V_L} \textbf{ x } \mathbf{I_L}}$$

____

____

____

____

____

____

____

____

____

12. **Do not proceed** until the teacher checks your results and completes the progress table.

Progress Table 2

attempt 1	attempt 2	attempt 3
5	2	0

13. Reduce the dynamometer current to 0A.
14. Reduce the field excitation to 0A.
15. Switch off the three phase, then disconnect the circuit.
16. Please return all equipment to its proper place, safely and carefully.

3. OBSERVATIONS:

1. Using the results from table 1, plot the V-curves for the motor operating on no-load. Use the axis shown in figure 5.

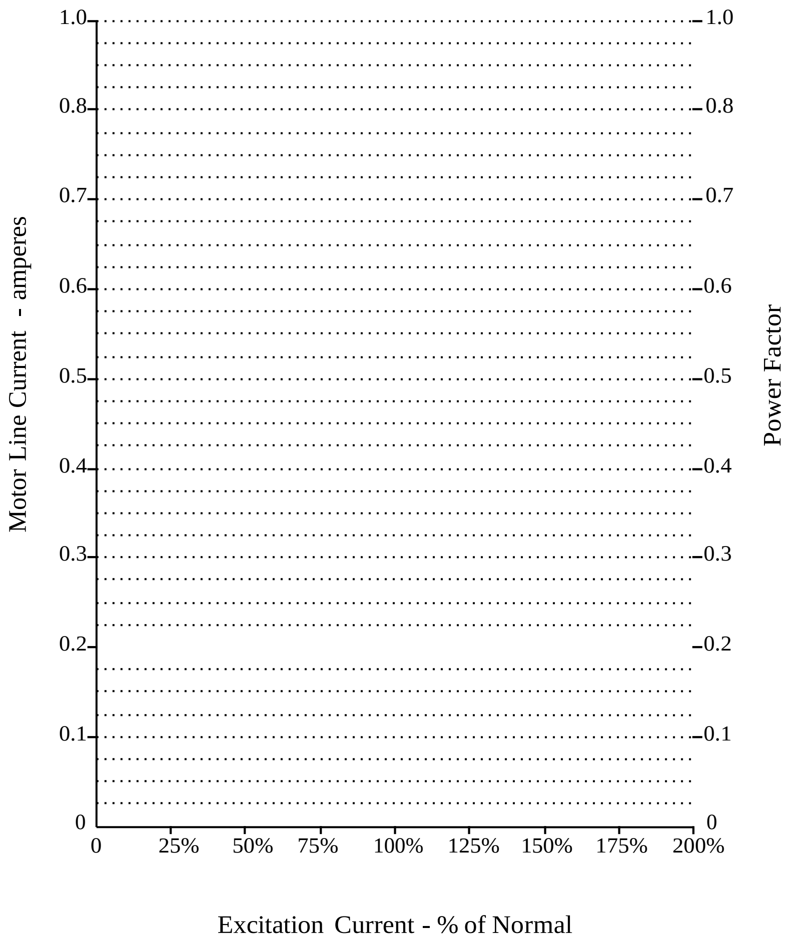

Figure 5

2. Using the results from table 2, plot the V-curves for the motor operating on full-load. Use the axis shown in figure 6.

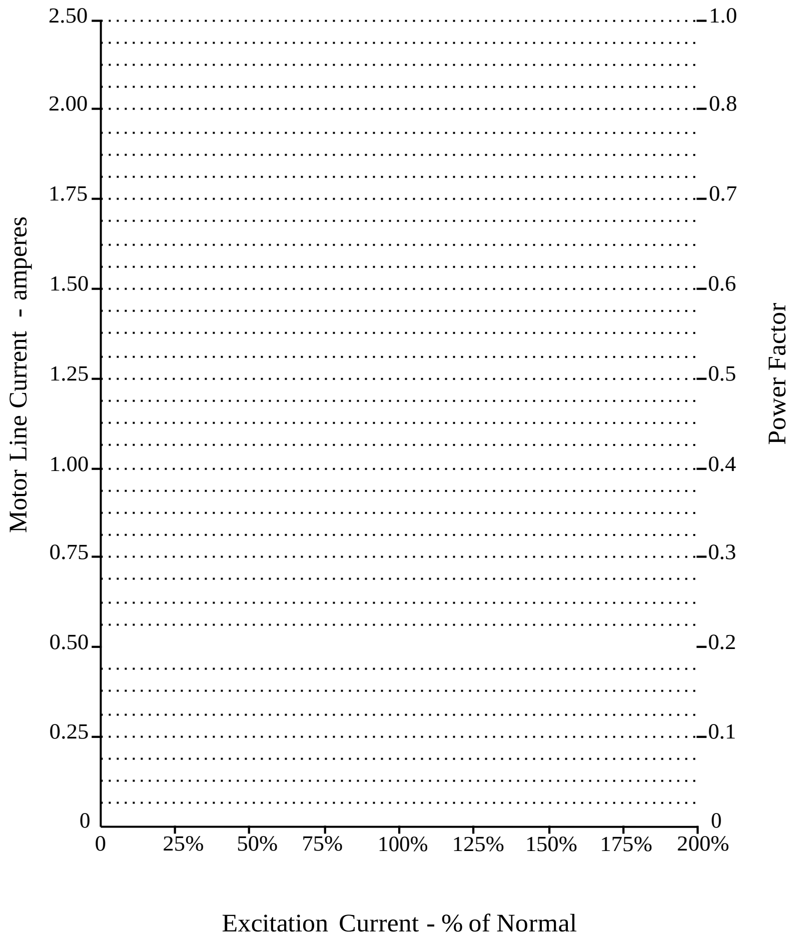

Figure 2

3. Compare the motor current taken from the supply at normal excitation on no-load and full-load. If they are different, give reasons for the difference.

4. Compare the values of normal field excitation for the no-load and full- load conditions. If they are different, give reasons for the difference.

5. Determine the efficiency of the motor at full-load.

6. What are the two benefits of operating the synchronous motor with an overexcited field?

Tutorial 16 **NAME:**

SYNCHRONOUS MOTORS

SECTION A

In the following statements one of the suggested answers is best. Place the identifying letter on your answer sheet.

1. The speed of a synchronous motor:-
   a) depends on supply frequency;
   b) depends on the size of load;
   c) depends on both frequency and load;
   d) is constant regardless of frequency and load;

2. The operating power factor of a synchronous motor:-
   a) is affected by phase sequence of the supply:
   b) is affected by field excitation;
   c) is constant regardless of any changes;
   d) improves as load increases.

3. "Normal excitation" of a synchronous motor at full load:-
   a) is the rated field current on the nameplate;
   b) gives minimum power factor and maximum current;
   c) gives minimum power factor and minimum current;
   d) gives unity power factor and minimum current.

4. Synchronous motors develop a torque by:-
   a) electromagnetic induction between stator and rotor;
   b) mutual induction between stator and rotor;
   c) attraction between stator and rotor fields;
   d) stator field hunting the rotor field.

5. The advantages of operating a synchronous motor with "over excitation" are:-
   a) increased pull out torque and increased power factor;
   b) decreased line current and a leading motor power factor;
   c) decreased line current and a leading motor power factor;
   d) increased pull out torque and a leading motor power factor.

6. The "V Curves" of a synchronous motor show how:-
   a) line current and speed vary with excitation;
   b) line current and power factor vary with excitation;
   c) speed and power factor vary with load;
   d) line current and power factor vary with load.

7. "Pull out torque" of a synchronous motor:-

a) may be increased by increasing excitation current in the field;
b) is the maximum torque produced during starting;
c) varies with variations in load;
d) decreases as motor speed increases.

8. An "under excited" synchronous motor would operate with:-

a) a leading power factor at more than synchronous speed;
b) a leading power factor at synchronous speed;
c) a lagging power factor at synchronous speed;
d) a lagging power factor at less than synchronous speed.

9. Synchronous motors are:-

a) all self starting and produce high starting torque;
b) started as induction motors or with a pony motor;
c) started as a d.c. motor by connecting d.c. to the stator;
d) started as a slip ring motor by connecting a.c. to the rotor.

10. Damper windings or amortisseur windings are used in synchronous motors to:-

a) start the motor and reduce hunting on reciprocating loads;
b) reduce the amount of direct current required in the field windings;
c) reduce the amount of current taken from the supply during starting;
d) bring the motor to a stop quickly after being turned off.

SECTION B

Blank spaces in the following statements represent omissions. Write the appropriate information on your answer sheet.

As load on a synchronous motor increases the load or torque angle will _____(1)_____. This angle is the angle between the centres of_____(2)_____and _____(3)_____poles.

The term "synchronous capacitor" is used to describe a_____(4)_____motor which has been_____(5)_____excited.

If the exciter is used to bring the synchronous motor up to speed it is necessary to have a separate_____(6)_____supply.

A three phase synchronous motor may be started as an induction motor if the motor is fitted with_____(7)_____windings.

If a pony motor is used to bring a synchronous motor up to speed it is necessary to start the motor on_____(8)_____load or have a_____(9)_____between the motor and load.

The synchronous induction motor uses a rotor similar to a _____(10)_____motor, is started with_____(11) connected in the rotor circuit, which is disconnected and reconnected to a_____(12)_____when close to synchronous speed.

The stator winding of the synchronous motor, when connected to a three phase supply, produces a_____(13)_____magnetic field at_____(14)_____speed.

A three phase synchronous motor with a four pole salient pole rotor would have _____(15)_____slip rings, and a stator winding which produces a_____(16)_____ pole field.

SECTION C

1. A four pole synchronous motor is connected to a 60Hz supply. Determine the speed of the motor. (1 800 r.p.m.)
2. A three phase four pole 415 volt synchronous motor takes a current of 75 amperes at full load with normal excitation while driving a 50kW load. Determine:-
   a) the input power to the motor; (53.91kW)
   b) the efficiency of the motor under these conditions; (92.75%)
   c) the speed of the motor; (1 500r.p.m.)
   d) the torque delivered to the load at normal excitation; (318.3Nm)
   e) the current taken if excitation is reduced until power factor is 0.8 lagging. (93.75A)

SECTION D

1. For the curves drawn for a three phase synchronous motor shown in Figure 1:-

a) What do we call this family of curves?

b) Use the labels on the curves (A, B, C, and D) to indicate which curve is:-

i. the curve of power factor vs field current for no load;

ii. the curve of power factor vs field current for full load;

iii. the curve of stator current vs field current for no load;

iv. the curve of stator current vs field current for full load.

c) What is the value of field current for the motor at normal excitation on full load?

d) What is the value of stator current taken by the motor at normal excitation on no load?

e) If the field current is 4 amperes while the motor is driving full load:-

i. What is the stator current taken?

ii. What is the power factor?

iii. Is the power factor leading, lagging or unity?

iv. Is the motor under, over or normally excited?

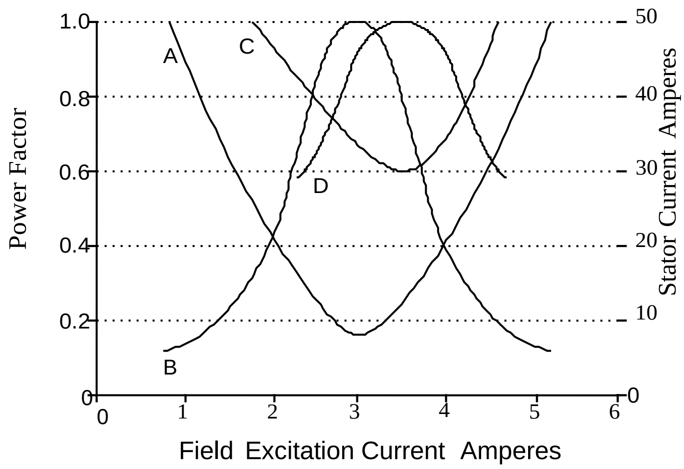

Figure 1