جامعة فلسطين التقنية
خضوري
Palestine Technical University
Kadoorei

Faculty of Engineering and Technology

Department of Electrical Engineering

Electrical Machines Lab
(12110335)
Second Edition

Student Manual

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Abstract

Electrical Machine laboratory is introduced for the undergraduate Electrical, Industrial Automation, and Mechatronics engineering students. The lab is designed to directly apply the theory learned in lectures to devices that will be studied in the laboratory. In this lab, students take all the information they need for all kinds of machines, such as the generators, motors, and transformers, students begin to link the theoretical material to the practical part and learns about its components, the Principle of work, characteristics, features, methods of testing, operation, diagnosis of faults and the necessary maintenance for each machine separately.

The creation of an Electrical Machines Lab at Palestine Technical University gives students the opportunity to gain some real-world experience in electrical machines. Moreover, a laboratory of this type facilitates educational opportunities. It also provides numerous additional benefits such as research.

Objectives

The laboratory course is intended to provide practical exposure to the student regarding the construction and operation of various electrical machines. The main objective is to enable students to apply and test the theoretical knowledge they mastered in previous years of studies. Students are allowed to conduct various experiments on all the machines for the validation of the performance characteristics of all the machines. From this lab course, the students will gain the skill to select the correct machine for a specific application.

The Laboratory covers all phases for the Electrical Machines specific of this field.
All electrical machines in the lab are exactly equal to those installed in the industrial units.

Course Intended Learning Outcomes (CILOs)

Knowledge and understanding

1. Understand the construction and principle of operation of Rotating and Stationary Machines;
2. Understand the performance of a Rotating and Stationary Machines by conducting various tests and to calculate the parameters of each machine;
3. Understand how to control the speed of different types of motors.
4. Understand the methods of starting motors safely.
5. Understand the Electrical Machines ratings.

Intellectual/Cognitive skills

1. Be able to perform experiments which are necessary to determine the parameters and the performance characteristics of the Electrical Machines;
2. Be able to recognize various types of Electrical Machines, detail of nameplate data of the machines and sketches the various connection diagrams involving these machines.

Subject specialization and practical skills

1. Identify and formulate engineering problems to solve problems in the field of electrical power engineering;
2. Specify and evaluate manufacturing of components and equipment related to electrical power and machines.

General and transferable skills

1. Work in a group and evaluate the results to prepare the report.
2. Find information independently

References

1- "**Electric Machinery Fundamentals**", Stephen Chapman, 4th Edition.
2- "**Electric Machinery**", A. E. Fitzgerald, C. Kingsley, S. D.Umans, 5th Edition. McGraw Hill, 1990.
3- "**Principles of Electric Machines and Power Electronics**", Sen, P. C, 3rd Edition. John Wiley & Sons.

Evaluation schemes

<table>
<tr><th colspan="3">Assessment Type</th><th>Weight</th><th>Date(s)</th></tr>
<tr><td rowspan="4">Course Work</td><td colspan="2">Reports</td><td>20</td><td rowspan="3">During Semester</td></tr>
<tr><td rowspan="2">Projects</td><td>Hardware:
DC Machines
(With Presentation)</td><td rowspan="2">30</td></tr>
<tr><td>Software:
AC Machines
(Matlab Simulink)</td></tr>
<tr><td colspan="2">Quiz</td><td>10</td><td></td></tr>
<tr><td colspan="2">Final Exam</td><td></td><td>40</td><td>Announced by Registrar</td></tr>
<tr><td colspan="2">Total</td><td></td><td>100%</td><td></td></tr>
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SAFETY RULES

1. Please don't touch any live parts.
2. Never use an electrical tool in a damp place.
3. Don't carry unnecessary belongings during performance of practicals (like water bottle, bags etc).
4. Before connecting any leads/wires, make sure power is switched off.
5. In case of an emergency, push the nearby red color emergency switch of the panel or immediately call for help.
6. In case of electric fire, never put water on it as it will further worsen the condition; use the class C fire extinguisher.

Fire is a chemical reaction involving rapid oxidation (combustion) of fuel. Three basic conditions when met, fire takes place. These are fuel, oxygen & heat, absence of any one of the component will extinguish the fire.

Figure: Fire Triangle

A(think ashes): paper, wood etc

B(think barrels): flammable liquids

C(think circuits): electrical fires

If there is a small electrical fire, be sure to use only a Class C or multipurpose (ABC) fire extinguisher, otherwise you might make the problem worsen.

The letters and symbols are explained in left figure. Easy to remember words are also shown.

***Don't** play with electricity, Treat electricity with respect, it deserve*

List of Experiments

Chapter 1

Introduction

Experiment (1)	Introduction to Electrical Machines Lab

Electrical Machines

An electrical machine is a device that can convert either mechanical energy to electrical energy or electrical energy to mechanical energy.

- ✓ When such a device is used to convert mechanical energy to electrical energy, it is called a generator.
- ✓ When it converts electrical energy to mechanical energy, it is called a motor.
- ✓ The transformer converts ac electrical energy at one voltage level to ac electrical energy at another voltage level.

Magnetic Field

Magnetic fields are the fundamental mechanism by which energy is converted from one form to another in motors, generators, and transformers. **Four basic principles** describe how magnetic fields are used in these devices:

1. A current-carrying wire produces a magnetic field in the area around it.
2. A time-changing magnetic field induces a voltage in a coil of wire if it passes through that coil. **(This is the basis of transformer action)**
3. A current-carrying wire in the presence of a magnetic field has a force induced on it. **(This is the basis of motor action)**
4. A moving wire in the presence of a magnetic field has a voltage induced in it. **(This is the basis of generator action)**

Types of Electrical Machines

Electrical machines are classified into two main types:

1. **Stationary/Static Electrical Machines**
   A stationary electrical machine is such kind of machine which **does not have any moving parts & they remain stationary throughout its operation. (Transformers)**

2. **Rotating/Dynamic Electrical Machines**
   Such type of machines **consists of moving parts as well as stationary parts**. There are two types of Dynamic electrical machines. **(Motors and Generators)**

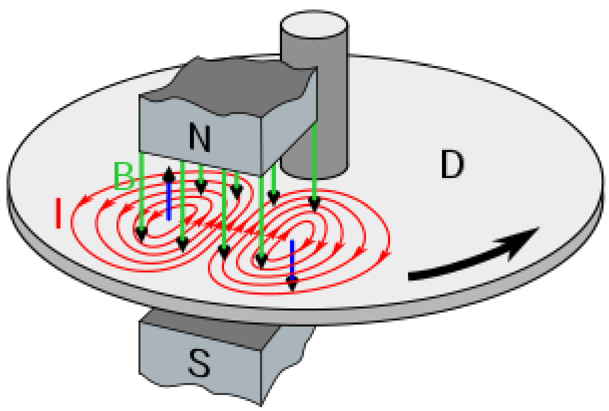
Electromagnetic Break

An electromagnetic brake is a device used to slow a moving object by dissipating its kinetic energy as heat. It allows to regulate with fine-tune the braking action, without any mechanical friction, therefore without any wear or consumption, therefore no need for any maintenance

The drag force that slow the moving object is an electromagnetic force between a magnet and a nearby conductive object in relative motion, due to currents induced in the conductor through electromagnetic induction.

A conductive surface moving past a stationary magnet will have circular electric currents induced in it by the magnetic field, as described by law of induction. The circulating currents will create their own magnetic field which opposes the field of the magnet. Thus the moving conductor will experience a drag force from the magnet that opposes its motion, proportional to its velocity. The kinetic energy of the moving object is dissipated as heat generated by the current flowing through the electrical resistance of the conductor.

The magnetic field is created by varying the electric current in the electromagnet's windings that create a north pole and a south pole. The braking force is proportional to the electric current and to the speed of the rotating brake.



The electromagnet exerts on the rotating disk a couple in the opposite direction of the motion, so with a floating system, with a dynamometer or with arms and weight, you can obtain the value of the braking couple.

When the motor to be tested is coupled with the brake, the braking torque is equivalent to the torque developed by the motor under test.

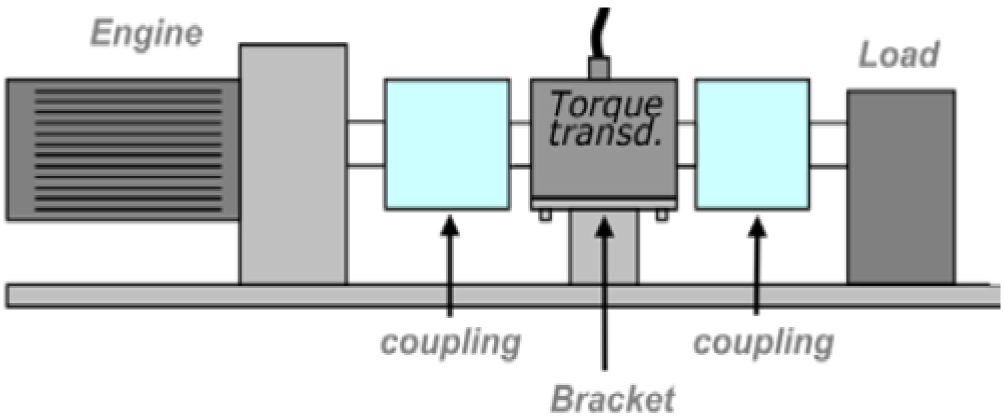
You have to put the measuring weight on the graduated arm, which will be put on the right, while the weight acting as a counterbalance will be put on the left arm. The disk has to be inserted on the testing motor shaft and locked with the suitable key. Lock very well both the brake and the testing machine and slip the thickness only after this operation. Verify that the disk rotates in a free way, without touch the brake magnet.

When the motor is lock, you have to put the measuring weight towards the brake and regulate the counterbalance till the brake is on balance. Now the counterbalance has to be locked and never more moved. Putting the motor in rotation, the balance is immediately changed and to brake the motor you have only to move the measuring weight along the arm according to the following ratio: **τ (N.m) = G x b** G = weight in Newton b = arm in meter

Torque Meter

This meter allows to measure the motor's torque during the test and to read the torque on the digital instrument display. For use with break generator, electromagnetic break or break generator, torque can be read in g.m or N.m.

The torque detection is made through the load cell placed under the brake that has the case oscillating on two ball bearings pleaced at the end of the shaft.



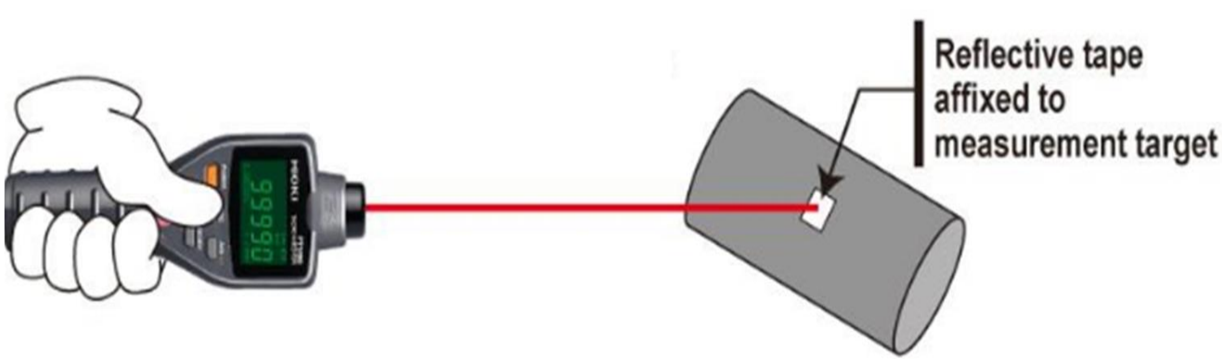
Tachometer

A tachometer refers to any device that produces a signal proportional to the speed of rotation of a joint. There are many different types of tachometers, some based on measuring the frequency, or the time between pulses generated by the rotating shaft.

A tachometer that does not need any physical contact with the rotating shaft is called a non-contact digital tachometer. In this type, a laser or an optical disk is attached to the rotating shaft, and it can be read by an IR beam or laser, which is directed by the tachometer.

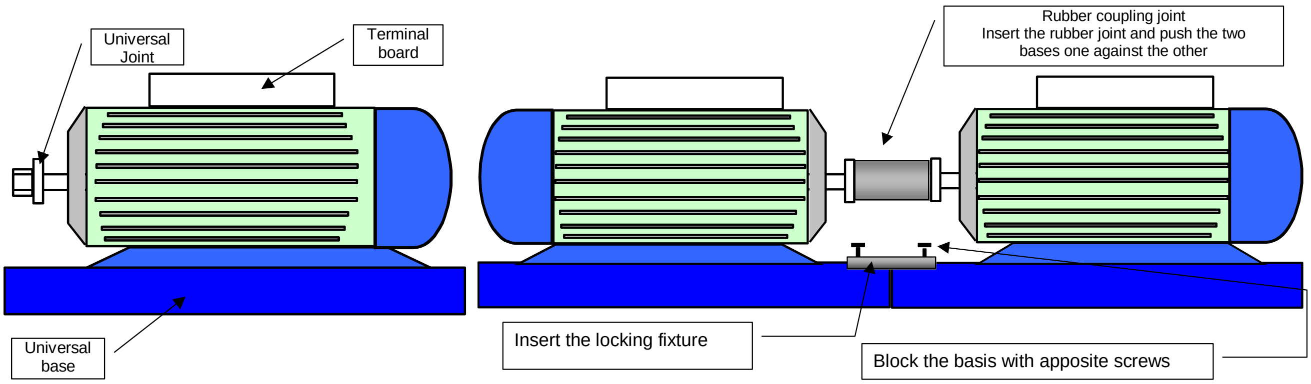
These types of tachometers are efficient, durable, accurate, and compact, and also visible from long distance.

Tachometer consists of an optical sensor which generates pulses proportional to the speed of rotation. It counts the number of pulses sensed by the sensor and number of pulses per second gives the rps and when multiplied by 60 gives rpm.

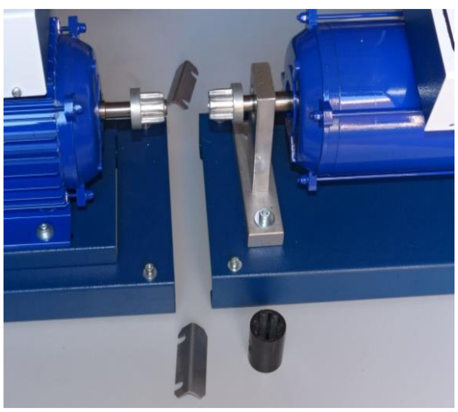


Machine Coupling

Coupling between two machines with base plate



Step (1)



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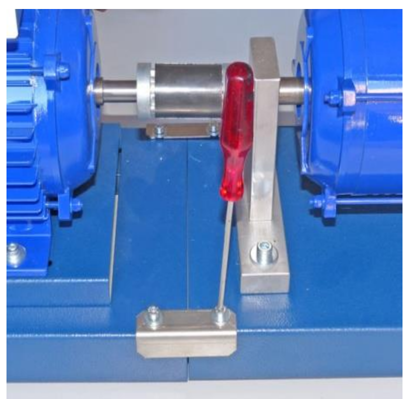

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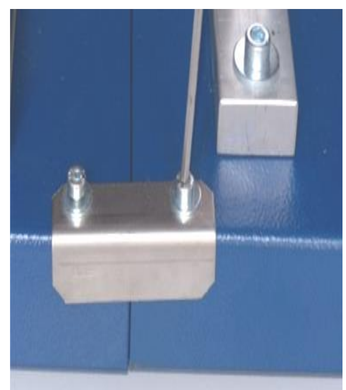

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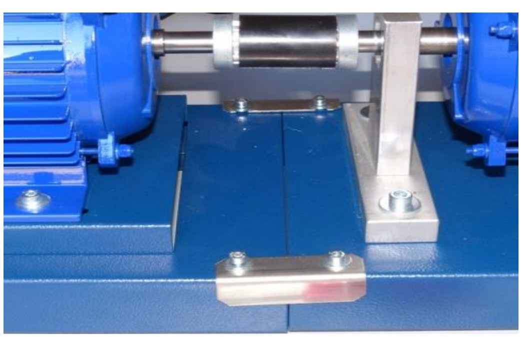
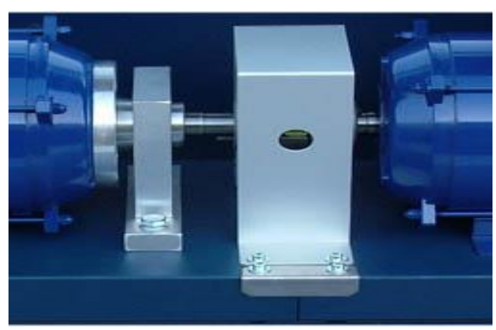


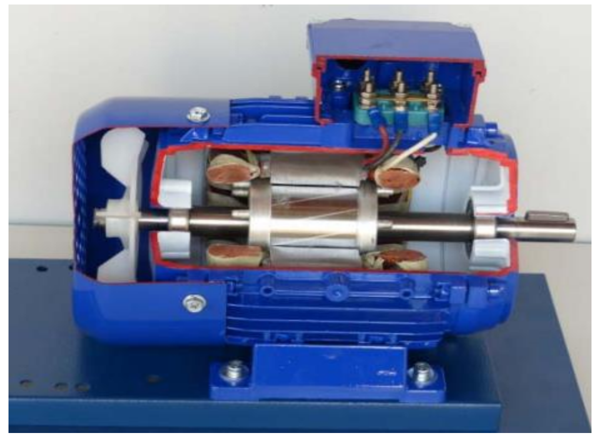
Step (5)



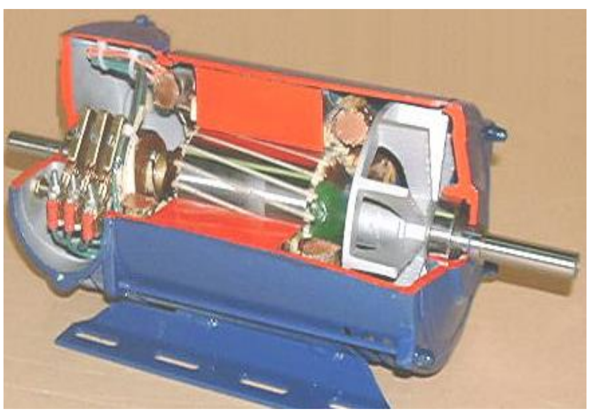
Cutaway diagram of the Machines in the lab

Single Phase AC Motor (Capacitor Start/Run with centrifugal switch)

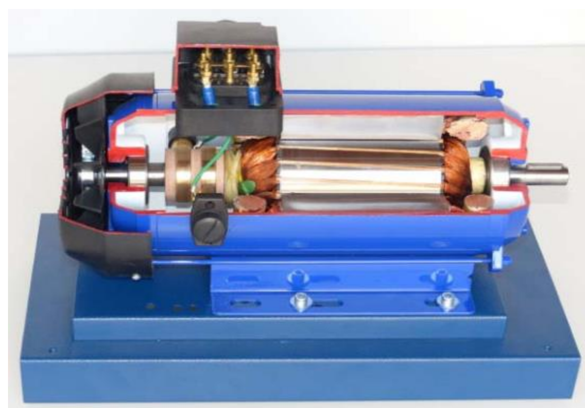
Three Phase Squirrel Cage Induction Motor



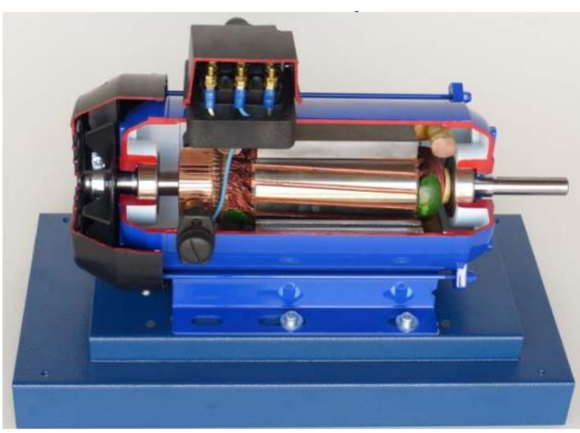
Three phase slip ring induction motor



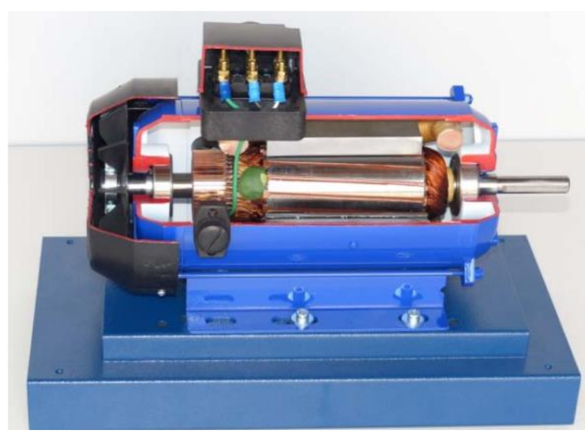
Three phase Synchronous Machine



Series/Shunt/Compound DC Machine



Universal Motor



Chapter 2

AC Machines

Contents

Part 1

Transformers

Experiment (1)	Single-Phase Transformers

Objectives:

1. To understand the basic working principle of a single-phase transformer.
2. To obtain the approximate equivalent circuit of single-phase transformer from open circuit and short circuit tests.
3. To make tests to confirm the specifications and performances of the transformer.
4. To determine polarities of transformer windings.

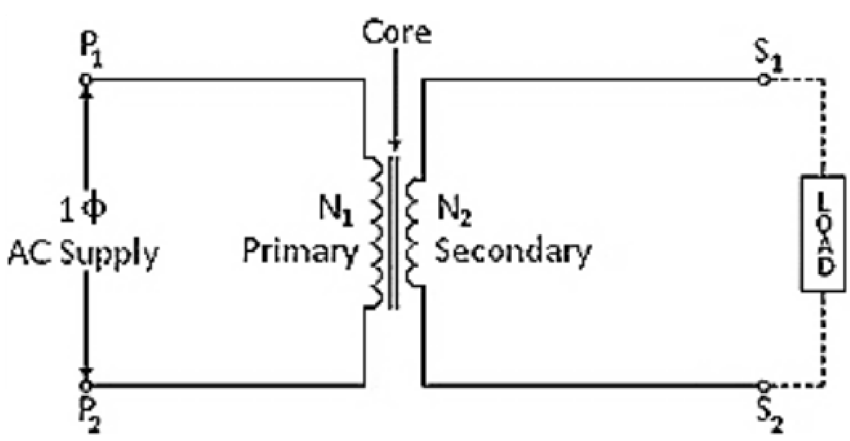
Theory and concepts:

Transformers are essential elements in any power system. They allow the relatively low voltages from generators to be raised to a very high level for efficient power transmission. At the user end of the system, transformers reduce the voltage to values most suitable for utilization. In modern utility systems, the energy may undergo four or five transformations between generator and ultimate user. As a result, a given system is likely to have about five times more kVA of installed capacity of transformers than of generators.

- The transformer is a static piece of device by means of which an electric power is transformed from one circuit to another circuit without change in the frequency.

- A transformer operates on the principle of mutual inductance between two inductively coupled coils. The winding in which electrical energy is fed is called Primary winding and the other from which energy is drawn out is called Secondary winding.

- The primary winding has number of turns N1, while the secondary winding has N2 number of turns.



- When an alternating voltage V1 is applied to primary winding, an alternating current I1 flows in it producing alternating flux in the core. According to **Faraday's law** of electromagnetic induction, an e.m.f. is induced in the primary winding which is given by,

$$e_1 = -N_1 \frac{d\phi}{dt}$$

where N1 is the number of turns in primary winding. The induced e.m.f. in the primary winding is nearly equal and opposite to the applied voltage V1.

- Assuming leakage flux to be negligible, almost whole flux produced in primary winding links with the secondary winding. Hence e.m.f. e2 is induced in the secondary winding.

$$e_2 = -N_2 \frac{d\phi}{dt}$$

where N1 is the number of turns in primary winding. If secondary circuit is closed through the load, a current I2 flows in the secondary winding.

- Thus energy is transformed from primary winding to secondary winding through magnetic field.

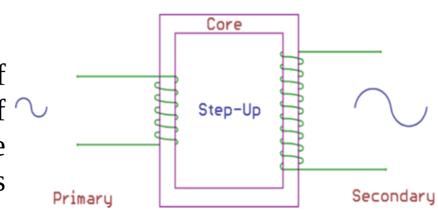
Types of Transformers:

According to Construction:

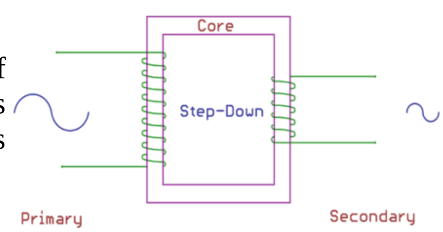
- ✓ Shell Type Transformer;
- ✓ Core Type Transformer;
- ✓ Berry Type Transformer.

According to their working:

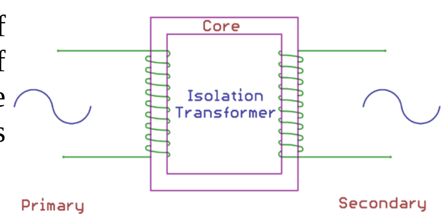
☑ **Step up Transformer:** When the number of turns of secondary winding (N2) are greater than number of turns of primary windings (N1), then voltage available across secondary is greater than the applied across primary.



☑ **Step down Transformer:** When the number of turns of secondary winding (N2) are less than number of turns of primary windings (N1), then voltage available across secondary is less than the applied across primary.



☑ **Isolation Transformer:** When the number of turns of secondary winding (N2) are equal to the number of turns of primary windings (N1), then voltage available across secondary is equal to voltage applied across primary.



- ☑ **Instrument transformer:** is an electrical device used to transform current as well as a voltage level. The most common use of instrument transformer is to safely isolate the secondary winding when the primary has high voltage and high current supply so that the measuring instrument, energy meters or relays which are connected to the secondary side of the transformer will not get damaged. The instrument transformer is further divided into two types Current Transformer (CT) Potential Transformer (PT).

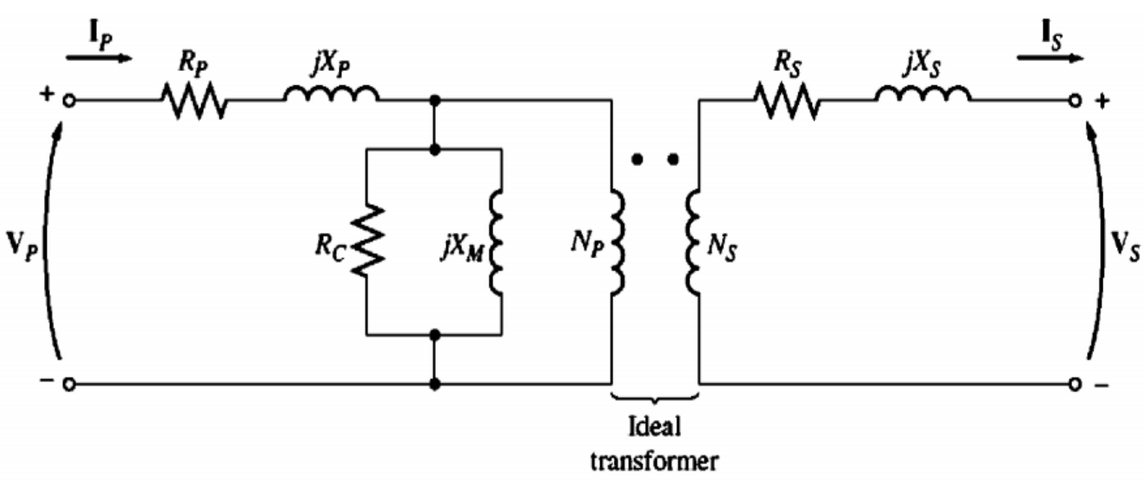
According to the number of phases:

- ☑ **Single-Phase Transformer:** With a constant level of voltage frequency and variation, this device transfers the AC power from one circuit to the other. The single-phase transformer consists of two types of windings; 1) Primary winding – to which the AC supply is transferred and 2) secondary winding – that connects the load.

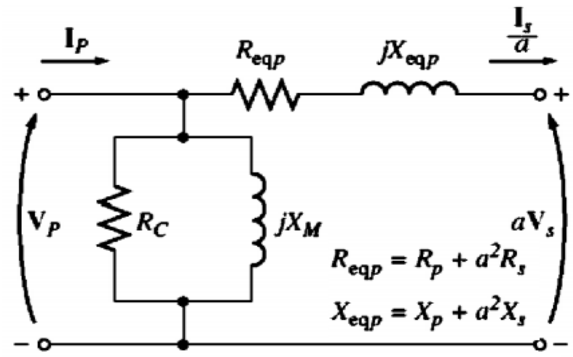
- ☑ **Three-Phase transformer:** Three single-phase transformers coupled together acts as a three-phase transformer. This device is mainly used for the industrial purpose to generate electric power, transmission, and distribution.

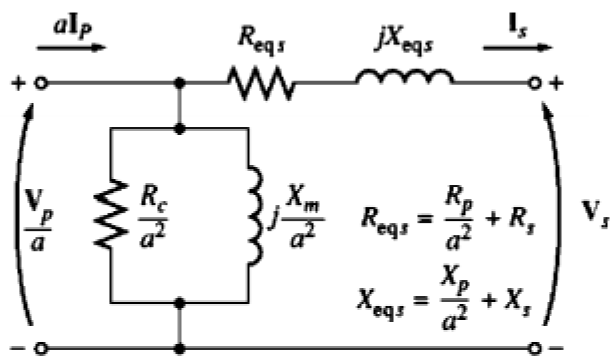
Equivalent Circuit of a Transformer:

- ✓ Copper losses are resistive losses in the primary and secondary windings of the transformer core. They are modeled by placing a resistor **Rp** in the primary circuit of the transformer and a resistor **Rs** in the secondary circuit.
- ✓ The magnetization current i_m is a current proportional to the voltage applied to the core and lagging the applied voltage by 90^0, so it can be modeled by a reactance $\mathbf{X_M}$ connected across the primary voltage source.
- ✓ The core-loss current i_{h+e} current proportional to the voltage applied to the core that is in phase with the applied voltage, so it can be modeled by a resistance **Rc** connected across the primary voltage source.
- ✓ Some leakage flux is present at both primary and secondary sides. This leakage gives rise to leakage reactances at both sides, which are denoted as $\mathbf{X_p}$ and $\mathbf{X_s}$ respectively.



Approximate Transformer Models



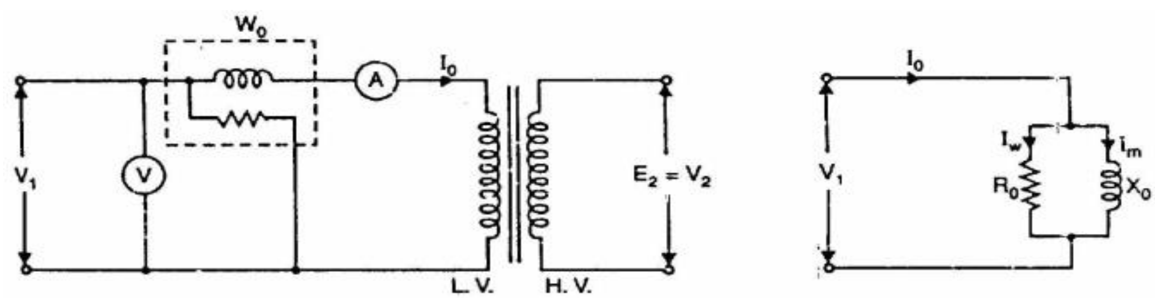


Refere to the **primary side** Refere to the **secondry side**

Determining the Values of Components in the Transformer Model

An adequate approximation of these values can be obtained with only two tests, the **open-circuit test** and the **short-circuit test**.

Open circuit test is conducted to determine the iron losses (or core losses) and parameters Rc and Xm of the transformer. In this test, the rated voltage is applied to the primary while the secondary is left open circuited. The applied primary voltage is measured by the voltmeter, the no load current by ammeter and no-load input power by wattmeter as shown in the following Figure.

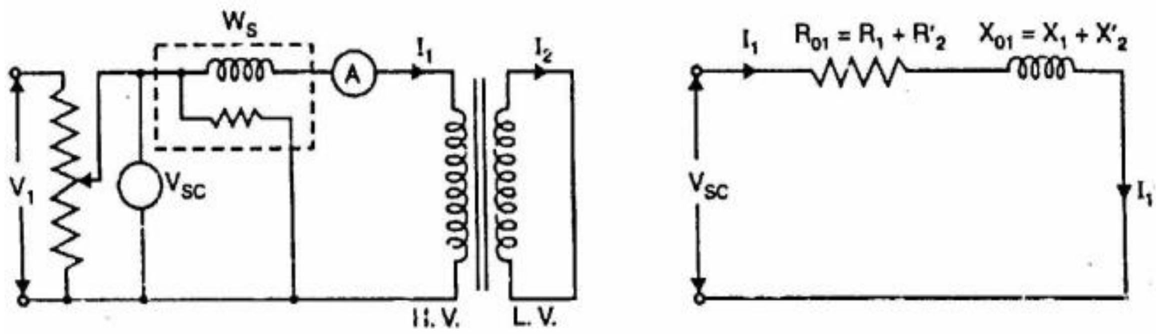


As the normal rated voltage is applied to the primary, therefore, normal iron losses will occur in the transformer core. Hence wattmeter will record the iron losses and small copper loss in the primary. Since no-load current is very small (usually 2-10% of rated current). Copper losses in the primary under no-load condition are negligible as compared with iron losses. Hence, wattmeter reading practically gives the iron losses in the transformer. It is reminded that iron losses are the same at all loads. The easiest way to calculate the values of **Rc and X_M** is to look first at the admittance of the excitation branch. The conductance of the core-loss resistor is given by

$$Y_E = \frac{I_{OC}}{V_{OC}} \angle -\cos^{-1} \text{PF} \qquad \theta = \cos^{-1} \frac{P_{OC}}{V_{OC} I_{OC}}$$

$$Y_E = G_C - jB_M = \frac{1}{R_C} - j\frac{1}{X_M}$$

Short-circuit test is conducted to determine Req, Xeq and full-load copper losses of the transformer. In this test, the secondary is short-circuited by a thick conductor and variable low voltage is applied to the primary as shown in the following Figure.



The low input voltage is gradually raised till at voltage V_{SC}, full-load current flows in the primary **(Be sure to keep the primary voltage at a save level, this voltage value is about 5-8% of the rated voltage**). The copper loss in the windings is the same as that on full load. There is no output from the transformer under short-circuit conditions. Therefore, input power is all loss and this loss is almost entirely copper loss. It is because iron loss in the core is negligibly small since the voltage V_{SC} is very small. Hence, the wattmeter will practically register the full-load copper losses in the transformer windings.

The series impedances referred to the primary side of the transformer is:

$$Z_{SE} = \frac{V_{SC}\angle 0^\circ}{I_{SC}\angle -\theta^\circ} = \frac{V_{SC}}{I_{SC}}\angle \theta^\circ \qquad PF = \cos\theta = \frac{P_{SC}}{V_{SC} I_{SC}}$$

$\mathbf{Z_{SE} = Req + jXeq}$

Turns Ratio (***a***) of a transformer is:

$$\frac{N_P}{N_S} = \frac{\mathbf{V}_P}{\mathbf{V}_S} = \frac{\mathbf{I}_S}{\mathbf{I}_P} = a$$

Efficiency from Transformer Tests

Full Load Iron loss = Pcore — from open-circuit test
Full Load Cupper loss = P_{Cu} — from short-circuit test
Total F.L. losses = Pcore + P_{Cu}

We can now find the full-load efficiency of the transformer at any p.f. without actually loading the transformer.

$$\text{F.L. efficiency, } \eta_{F.L.} = \frac{\text{Full - load VA} \times \text{p.f.}}{(\text{Full - load VA} \times \text{p.f.}) + \mathbf{P_{cu}} + \mathbf{P_{core}}}$$

Winding Resistance Test on a Single Phase Transformer

The two primary purposes of a resistance test on a transformer are:

1. **Winding identification** – how to identify the start and ends of the primary and secondary windings.
2. **Winding continuity** – are the windings intact, broken or shorted.

Transformer Turns Ratio Test

We perform the Transformer turns ratio test to:

1. Determine the turn's ratio between the primary and secondary windings.
2. Calculate the error ratio between the design value and the actual value; this value shall not exceed the limit given in relevant standards, normally 0.5% at no load.

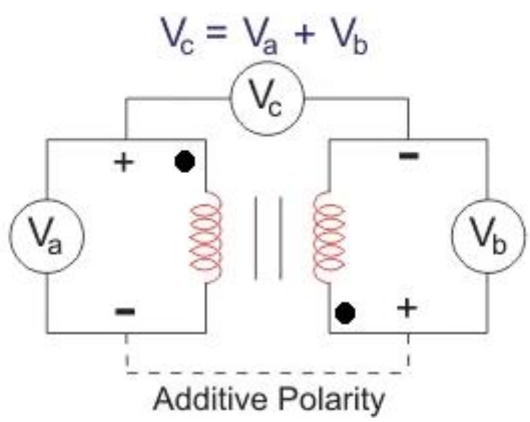
Polarity Test on a single phase transformer

Transformer polarity depends on which direction the coils are wound around the core (clockwise or counterclockwise) and how the leads are brought out from the winding ends to the terminals. The two coil windings have distinct orientation with respect to one another—each coil can be wound around the core clockwise or counterclockwise. If the primary and secondary coils are wound in opposite directions, the polarity is additive; if wound in the same direction, it's subtractive.

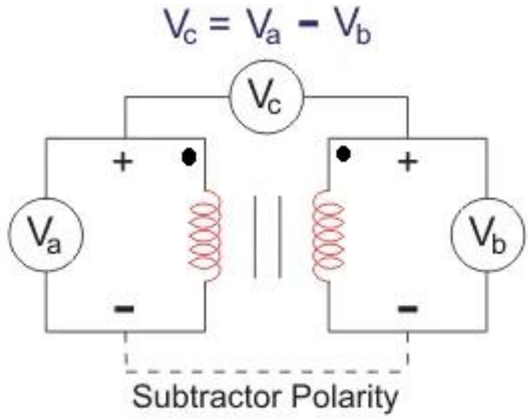
Polarity Test is carried out to check the positive and negative terminals of secondary windings to check whether input and output voltage of the transformer is in phase or 180 degree out of phase.

We use dot convention to identify the voltage polarity of the mutual inductance of two windings. If a current enters the dotted terminal of one winding, then the voltage induced on the other winding will be positive at the dotted terminal of the second winding.

In **additive polarity**, the voltage (Vc) between the primary side (Va) and the secondary side (Vb) will be the sum of both high voltage and the low voltage, i.e. we will get Vc = Va + Vb



In **subtractive polarity**, the voltage (V_c) between the primary side (V_a) and the secondary side (V_b) will be the difference of both high voltage and the low voltage, i.e. we will get $V_c = V_a - V_b$



In subtractive polarity, if Vc = Va – Vb, it is a **step-down transformer** and if Vc = Vb – Va, it is a **step-up transformer**.

We do polarity test on parallel transformers to ensure that we connect the same polarity windings and not the opposite ones. If we accidentally connect the opposite polarities of the windings, it will result in a short-circuit and eventually damage the machine.

If we require additive polarity, but we have subtractive polarity, we can simply change it by keeping any of the primary or secondary windings in the same fashion and reversing the winding connection of the other one.

Necessary Material:

1. **Mod.3000:** Universal Power Supply
2. **Mod.3190:** Single-Phase Transformer
3. **Mod.3209:** 1-ph and 3-ph multimeter

Experimental Procedures:

Part I: Specifications of the Single-Phase Transformer.

1. Read the nameplate of the Single-phase transformer then tabulate the rating values of the transformer in the following table, **Calculate the rated current and designed turns ratio of the transformer**.

<table>
<tr><th colspan="6">Name Plate of the Single-Phase Transformer Mod.3190</th></tr>
<tr><td>Input:</td><td colspan="2"></td><td>Output:</td><td colspan="2"></td></tr>
<tr><td>Power:</td><td colspan="2"></td><td>Frequency:</td><td colspan="2"></td></tr>
<tr><td>Insulation Class:</td><td colspan="2"></td><td>Ingress Protection:</td><td colspan="2"></td></tr>
<tr><td>Rated Current:</td><td>HV Side:</td><td></td><td>LV Side:</td><td colspan="2"></td></tr>
<tr><td colspan="2">Designed Turns Ratio</td><td>Step Up</td><td></td><td>Step Down</td><td></td></tr>
</table>

Part II: Winding Resistance Test of a Single Phase Transformer

1. Connect the circuit as shown in figure 1.
2. Measure the Resistance of the winding 1 and winding 2 respectively.
3. Tabulate your results in the following table and then specify which winding is the primary or secondary winding if this transformer is to be used as a **step-down transformer**.

Winding	Winding Resistance	Primary/Secondary Winding
Winding 1		
Winding 2		

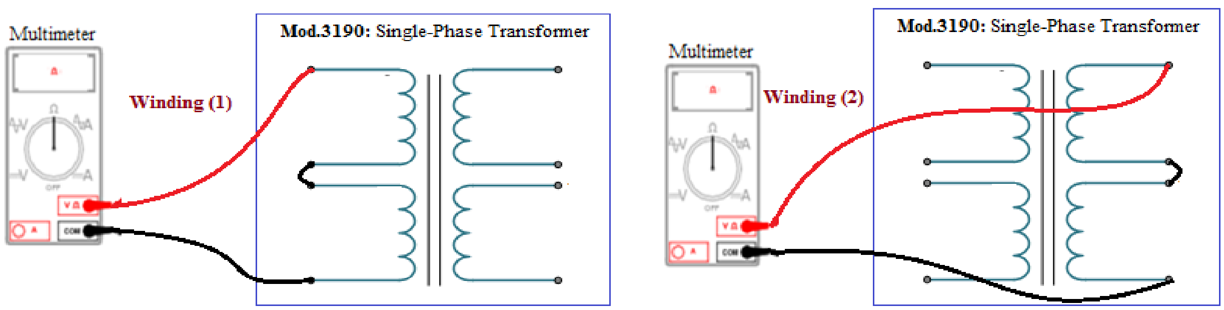


Figure (1)

Part III: Turns Ratio Test of a Single-Phase Transformer

1. Connect the circuit as shown in figure 2.
2. Apply the full-rated line voltage (230-V) at the primary windings of the transformer.
3. Measure the Secondry Voltage and then calculate the actual turns ratio of the transformer.
4. Calculate the error in turns ratio of the transformer using the following relation:

$$\%Error = \frac{|Measured - Designed|}{Designed} * 100$$

Primary Voltage	Secondary Voltage	Actual Turns Ratio	Error in Turns Ratio
230			

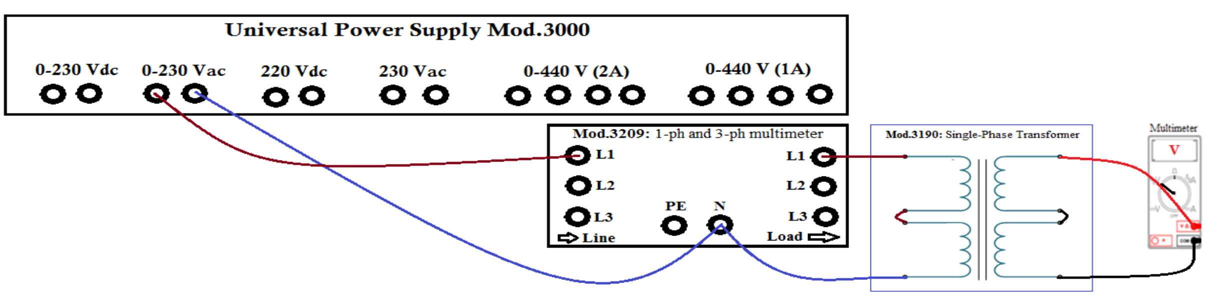


Figure (2)

Part IV: Polarity Test of a Single-Phase Transformer

1. Connect the circuit as shown in figure 3.
2. Apply a low voltage (around 100 volts) to the primary terminals; this will result in a voltage of about 50 volts across the secondary winding (provided the turns ratio is 2:1).
3. Measure the secondary voltage Vb and Voltage across two windings Vc.
4. Tabulate your results in the following table.
5. Use the oscilloscope to display the primary and secondary waveforms.
6. Draw the displayed waveforms taking into consideration the amplitudes and the phase-shift.

Primary Voltage	Secondary Voltage (Vb)	Voltage (Vc)	Additive or subtractive
100			

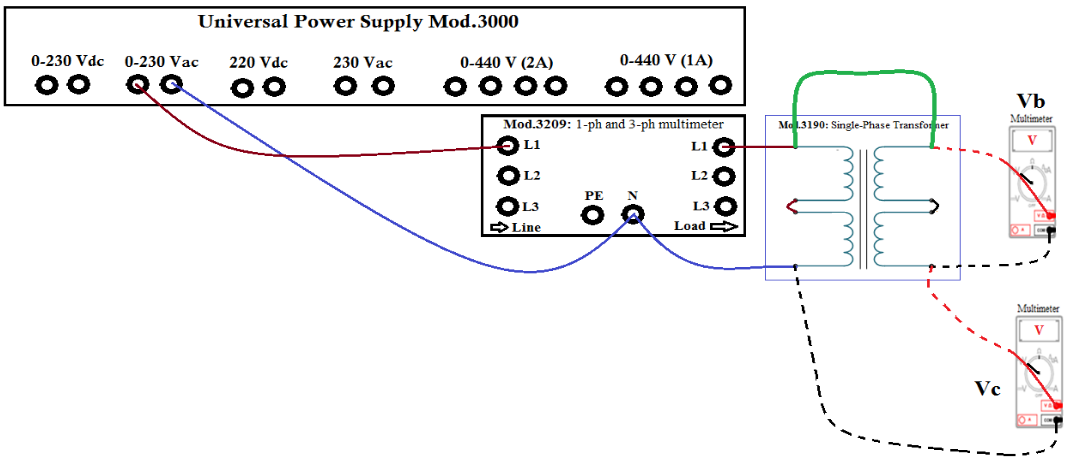


Figure (3)

Part V: Open-Circuit Test of a Single-Phase Transformer (HV-Side)

1. Keep the connection of the transformer as shown in figure 2.
2. Start to increase the input (primary) voltage in steps to match the requirements of the following table.
3. In each step measure the input current, input power and input power factor, **use ItelTec software**.
4. Tabulate your results in the following table.

Input Voltage	Input Current	Input Power	Input PF
100			
150			
200			
230			
235			
240			

5. Plot and explain the **no-load characteristics** of the transformer:
   (a) Sketch the relation between no load power and no load voltage **P = f (V).**
   (b) Sketch the relation between no load current and no load voltage **I = f (V).**
   (c) Sketch the relation between no load PF and no load voltage **PF = f (V).**
6. At the **rated vaules** of the transformer, calculate the value of Rc and Xm.

Rc	
Xm	

Part VI: Short-Circuit Test of a Single-Phase Transformer (HV-Side)

1. Connect the circuit as shown in the Figure 3.
2. Increase the input voltage **very carefully and slowly** so that the current in pimary winding reaches **rated value**, measure the input voltage, input power and input PF.
3. Reduce the voltage slowly, in each step measure the input voltage, input power and input PF, **use IteITec software**.
4. Tabulate your results in the following table.

Input Voltage	Input Current	Input Power	Input PF
	1.35		
	1.20		
	1.00		
	0.80		
	0.60		
	0.40		

5. Plot and explain the **Short-circuit characteristics** of the transformer:
   (a) Sketch the relation between short circuit voltage and short circuit current **V = f (I).**
   (b) Sketch the relation between short circuit power and short circuit current **P = f (I).**
   (c) Sketch the relation between short circuit PF and short circuit current **PF = f (I).**
6. At the **rated vaules** of the transformer, calculate the value of Req and Xeq.

Req	
Xeq	

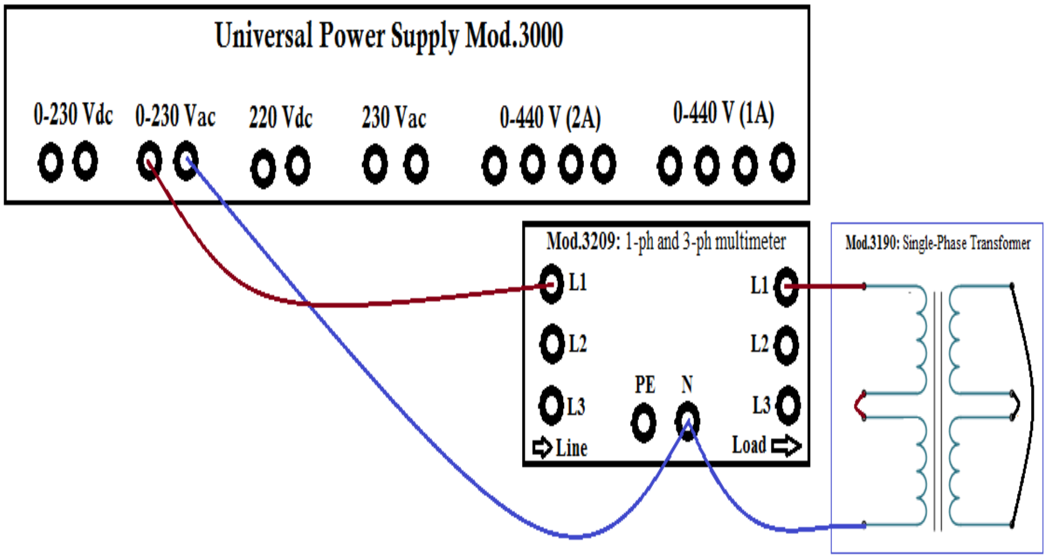


Figure (3)

Depending on the measured values on the experiment answer the following questions:

1. Draw the approximate equivalent circuit of the transformer in the form having all impedances on the **primary side** of the ideal transformer. Mark in the values calculated in this practical and include all the calculated parameters.

2. Calculate the efficiency of the transformer at the rated condition and PF =1.

$$\eta = \frac{P_{out}}{P_{out} + P_{loss}} \times 100\%$$

Ploss = Pcu (from short circuit test) + Pcore(iron) (from open circuit test)
Pout = Pin = rated power (from the nameplate of the transformer)

Questions:

1. What is a transformer? Explain the functions it fulfils as an element of a power system.

2. Why does the short-circuit test essentially show only i^2R losses and not excitation losses in a transformer?

3. Why does the open-circuit test essentially show only excitation losses and not i^2R losses?

4. A 1-kVA, 230/115 V, 50-Hz, single phase transformer has the following test data:
   Open Circuit Test (Primary Side): **230V, 0.45A, 30W.**
   Short Circuit Test (Primary Side): **19.1V, 8.7A, 42.3W.**
   Draw the approximate equivalent circuit of the transformer referred to the high voltage side.

5. Discuss the following statements briefly:
   (a) Ideally, The value of the impedance of the shunt branch in the equivalent circuit of a transformer is very large compared to that of series branch.
   (b) For a 220 (primary)/110 V (secondary) single phase transformer, if the voltage applied to this transformer is 440-V, the secondary voltage will not be 220 V.
   (c) When conducting the open circuit test on a transformer it is recommended to apply the rated voltage during test.
   (d) The transformer is rated in VA.
   (e) The leakage flux is represented by series reactance in the equivalent circuit of a transformer.
   (f) The copper losses in the coils of a transformer are represented by series resistance in the equivalent circuit of the transformer.

Experiment (2)	Three-Phase Transformers

Objectives:

1. To connect the primary and secondary of the given three-phase transformer in different connections and to perform the load test on the transformer.
2. To understand the relation between line and phase voltages.
3. To determine the voltage regulation of a loaded 3-phase transformer.

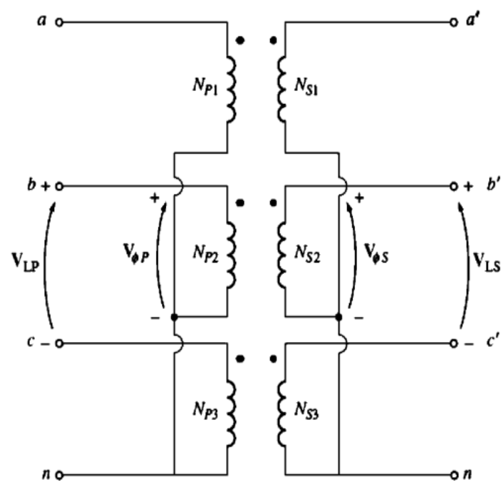
Theory and concepts:

Three Phase Transformers

A three-phase system is used to generate and transmit electric power. Three phase voltages are raised or lowered by means of three-phase transformers. A three-phase transformer can be built in two ways. One approach is by suitably connecting a bank of three single-phase transformers or by constructing a three-phase transformer on a common magnetic structure. In either case, the windings may be connected in Y-Y, Δ-Δ, Y-Δ or Δ-Y. Three similar single-phase transformers can be connected to form a three-phase transformer. The primary and secondary windings may be connected in star (Y) or delta (Δ) arrangement.

Three Phase Transformers Connections

A three-phase transformer consists of three transformers, either separate or combined on one core. The primaries and secondaries of any three-phase transformer can be independently connected in either a wye (Y) or a delta (Δ). This gives a total of four possible connections for a three-phase transformer bank:



1. **Wye-Wye (Y-Y)**
   The primary voltage on each phase of the transformer is given by $\mathbf{V_{\Phi P} = V_{LP} / \sqrt{3}}$. The primary-phase voltage is related to the secondary-phase voltage by the turns ratio of the transformer. The phase voltage on the secondary is then related to the line voltage on the secondary by $\mathbf{V_{LS} = \sqrt{3}\, V_{\Phi S}}$. therefore, overall the voltage ratio on the transformer is

$$\frac{V_{LP}}{V_{LS}} = \frac{\sqrt{3}V_{\phi P}}{\sqrt{3}V_{\phi S}} = a$$

The Y-Y connection has two very serious problems:

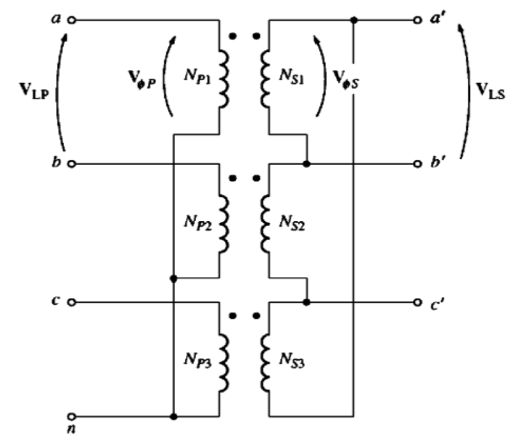
1. If loads on the transformer circuit are unbalanced, then the voltages on the phases of the transformer can become severely unbalanced.
2. Third-harmonic voltages can be large.

If a three-phase set of voltages is applied to a Y-Y transformer, the voltages in any phase will be **120^0** apart from the voltages in any other phase.

2. Wye-Delta (Y-Δ)

The primary voltage on each phase of the transformer is given by $\mathbf{V_{LP} = \sqrt{3}\, V_{\Phi P}}$. The primary-phase voltage is related to the secondary-phase voltage by the turns ratio of the transformer. The phase voltage on the secondary is then related to the line voltage on the secondary by $\mathbf{V_{LS} = V_{\Phi S}}$. therefore, overall the voltage ratio on the transformer is

$$\frac{V_{LP}}{V_{LS}} = \frac{\sqrt{3}V_{\phi P}}{V_{\phi S}} = \sqrt{3}a$$



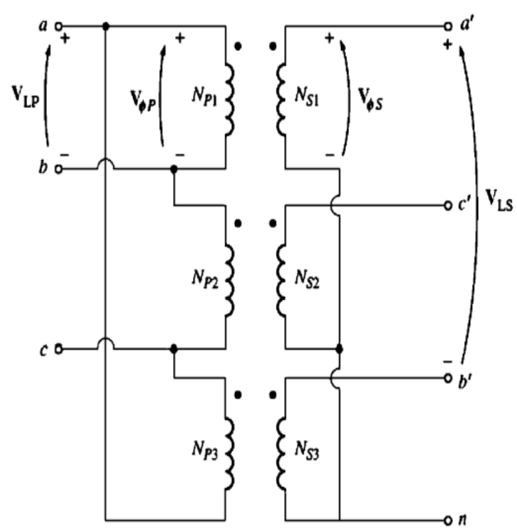
The Y-Δ connection has no problem with third-harmonic components in its voltages, since they are consumed in a circulating current on the Δ side. This connection is also more stable with respect to unbalanced loads, since the Δ partially redistributes any imbalance that occurs.

The secondary voltage is shifted 30^o relative to the primary voltage of the transformer. The fact that a phase shift has occurred can cause problems in paralleling the secondaries of two transformer banks together. The phase angles of transformer secondaries must be equal if they are to be paralleled, which means that attention must be paid to the direction of the 30^o phase shift occurring in each transformer bank to be paralleled together.

3. Delta-Wye (Δ-Y)

The primary voltage on each phase of the transformer is given by $\mathbf{V_{LP} = V_{\Phi P}}$. The primary-phase voltage is related to the secondary-phase voltage by the turns ratio of the transformer. The phase voltage on the secondary is then related to the line voltage on the secondary by $\mathbf{V_{LS} = \sqrt{3}\, V_{\Phi S}}$. therefore, overall the voltage ratio on the transformer is

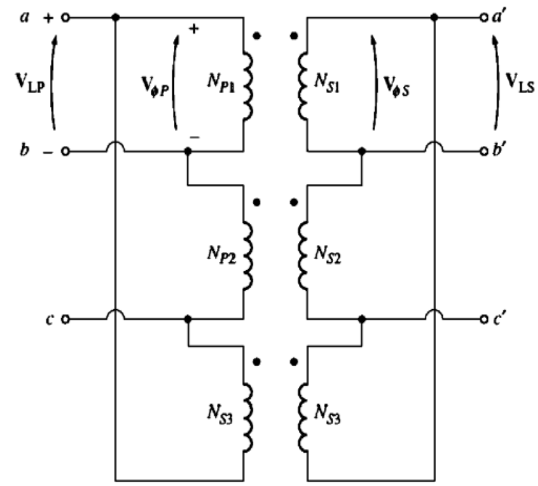
$$\frac{V_{LP}}{V_{LS}} = \frac{V_{\phi P}}{\sqrt{3}V_{\phi S}} = \frac{a}{\sqrt{3}}$$



4. **Delta-Delta (Δ- Δ)**

V_{LP} = $\mathbf{V_{\Phi P}}$ and V_{LS} = $\mathbf{V_{\Phi S}}$, so the relationship between primary and secondary line voltages is:

$$\frac{V_{LP}}{V_{LS}} = \frac{V_{\phi P}}{V_{\phi S}} = a$$



This transformer has no phase shift associated with it and no problems with unbalanced loads or harmonics.

The choice of connection of three phase transformer depends on the various factors likes the availability of a neutral connection for grounding protection or load connections, insulation to ground and voltage stress, availability of a path for the flow of third harmonics.

Transformer Voltage Regulation

Because a real transformer has series impedances within it, the output voltage of a transformer varies with the load even if the input voltage remains constant. To conveniently compare transformers in this respect, it is customary to define a quantity called *voltage regulation* (VR). *Full-load voltage regulation* is a quantity that compares the output voltage of the transformer at no load with the output voltage at full load. It is defined by the equation

$$\text{VR} = \frac{V_{S,nl} - V_{S,fl}}{V_{S,fl}} \times 100\%$$

Usually it is a good practice to have as small as voltage regulation as possible. For an ideal transformer, VR = 0 percent. It is not always a good idea to have a low-voltage regulation; though-sometimes high-impedance and high-voltage regulation transformers are deliberately used to reduce the fault currents in a circuit.

Necessary Material:

1. **Mod.3000:** Universal Power Supply
2. **Mod.3195:** Three-Phase Transformer
3. **Mod.3209:** 1-ph and 3-ph multimeter
4. **Mod.3020-R:** Resistive Load

Experimental Procedures:

Part I: Specifications of the Three-Phase Transformer.

1. Read the nameplate of the three-phase transformer and then tabulate the rating values of the transformer in the following table.

<table>
<tr><th colspan="5">Name Plate of the Three-Phase Transformer Mod.3195</th></tr>
<tr><td>Input:</td><td colspan="2"></td><td>Output:</td><td></td></tr>
<tr><td>Power:</td><td colspan="2"></td><td>Frequency:</td><td></td></tr>
<tr><td>Insulation Class:</td><td colspan="2"></td><td>Ingress Protection:</td><td></td></tr>
<tr><td>Rated Current:</td><td>HV Side:</td><td></td><td>LV Side:</td><td></td></tr>
</table>

Part II: Three Phase Transformer with Y-Y connection.

1. Connect three identical single-phase transformers in Y-Y configuration with a Y connected load (Resistive Load) on the secondary side as shown in figure 1.
2. Switch on the power supply and apply a 380-V to the primary windings.
3. Under no load condition, measure the primary and secondary line and phase voltages, phase shift between the primary and secondary sides and calculate the turns ratio of the transformer.

Connection	Primary Voltage		Secondary Voltage		Phase Shift	Turns Ratio
	Line	Phase	Line	Phase		
Y-Y						

4. Set the Three-Phase Transformer under load with the insertion of the resistive load (with different values of resistive load) and measure the following using the power analyzer:
   (a) Current drawn by the load (Line Current) (**I_{load}**) in **mA.**
   (b) Terminal voltage of the transformer (Line Voltage) (**V_T**) in **V.**
   (c) Power consumed by the load **(P)** in **W**.
5. Calculate the voltage regulation in each case.
6. Tabulate your result in the following table.

Connection	Load	Load Voltage (Line)	Load Current (Line)	Power Consumed (W)	%VR
Y-Y	A				
	B				

7. Switch off the load and then switch off the power supply.

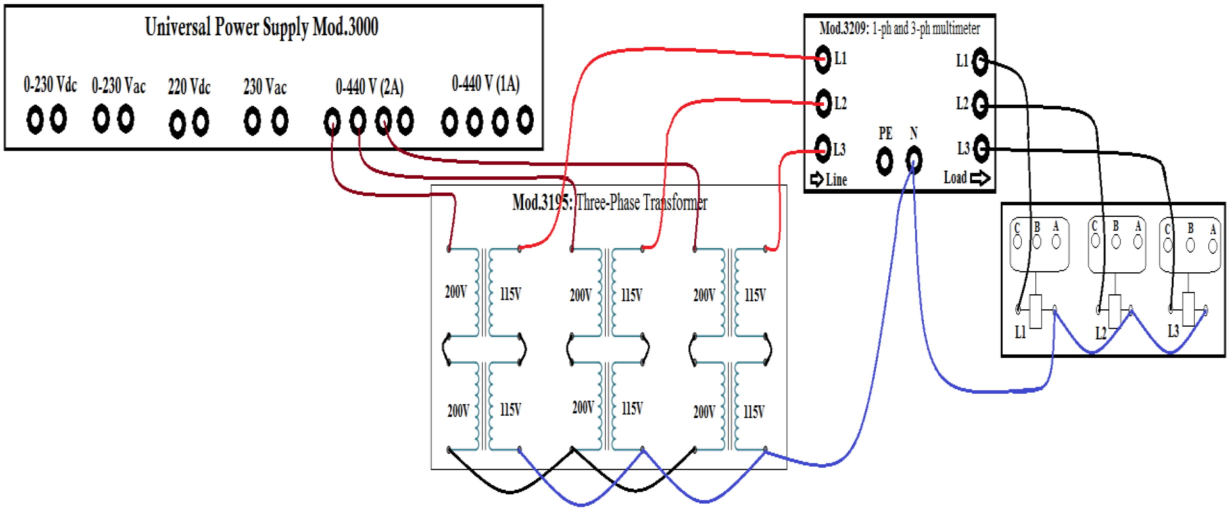


Figure (1)

Part III: Three Phase Transformer with Δ-Δ connection.

1. Reconnect the three-phase transformer as Δ-Δ connection as showwn in figure 2.
2. Switch on the power supply and apply a 220-V to the primary windings.
3. Under no load condition, measure the primary and secondary line and phase voltages, phase shift between the primary and secondary sides and calculate the turns ratio of the transformer.

Connection	Primary Voltage		Secondary Voltage		Phase Shift	Turns Ratio
	Line	Phase	Line	Phase		
Δ-Δ						

4. Set the Three-Phase Transformer under load with the insertion of the resistive load (with different values of resistive load) and measure the following using the power analyzer:
   (a) Current drawn by the load (Line Current) (**I_{load}**) in **mA.**
   (b) Terminal voltage of the transformer (Line Voltage) (**V_T**) in **V.**
   (c) Power consumed by the load **(P)** in **W**.
5. Calculate the voltage regulation in each case.
6. Tabulate your result in the following table.

Connection	Load	Load Voltage (Line)	Load Current (Line)	Power Consumed (W)	%VR
Δ-Δ	A				
	B				

7. Switch off the load and then switch off the power supply.

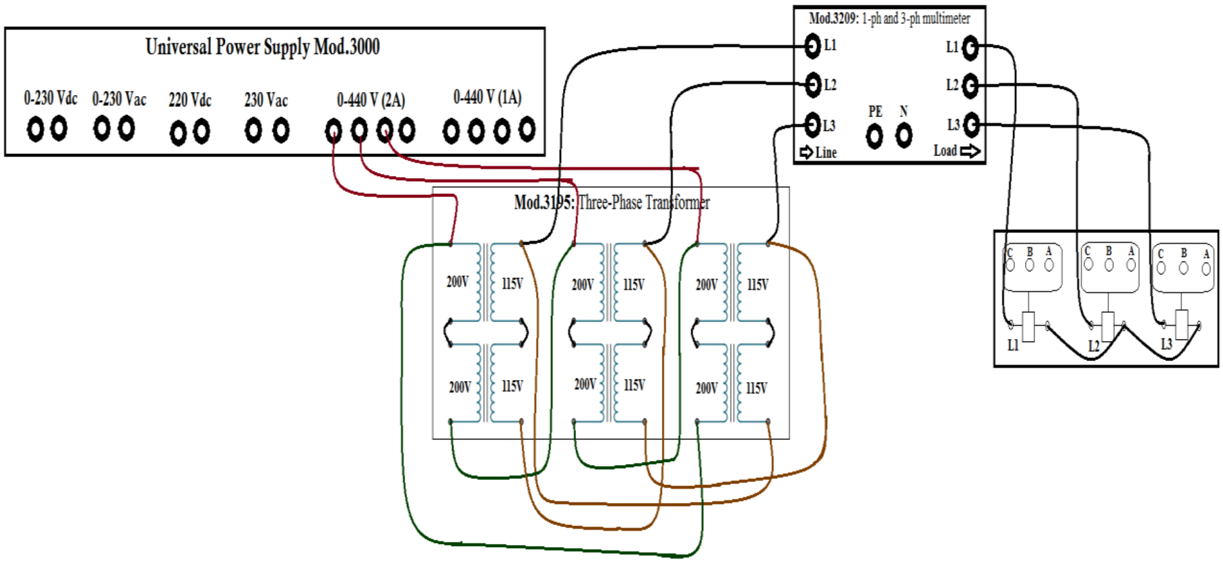


Figure (2)

Part IV: Three Phase Transformer with Δ-Y connection.

1. Reconnect the three-phase transformer as Δ-Y connection as showwn in figure 3.
2. Switch on the power supply and apply a 220-V to the primary windings.
3. Under no load condition, measure the primary and secondary line and phase voltages, phase shift between the primary and secondary sides and calculate the turns ratio of the transformer.

Connection	Primary Voltage		Secondary Voltage		Phase Shift	Turns Ratio
	Line	Phase	Line	Phase		
Δ-Y						

4. Set the Three-Phase Transformer under load with the insertion of the resistive load (with different values of resistive load) and measure the following using the power analyzer:
   (a) Current drawn by the load (Line Current) (**I_{load}**) in **mA.**
   (b) Terminal voltage of the transformer (Line Voltage) (**V_T**) in **V.**
   (c) Power consumed by the load **(P)** in **W**.
5. Calculate the voltage regulation in each case.
6. Tabulate your result in the following table.

Connection	Load	Load Voltage (Line)	Load Current (Line)	Power Consumed (W)	%VR
Δ-Y	A				
	B				

7. Switch off the load and then switch off the power supply.

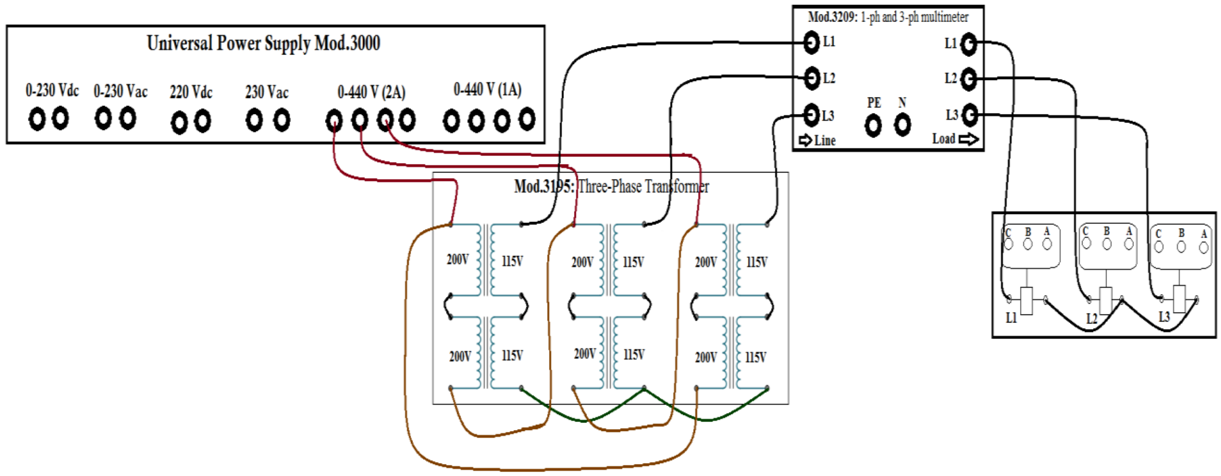


Figure (3)

Part V: Three Phase Transformer with Y-Δ connection.

1. Reconnect the three-phase transformer as Y-Δ connection as showwn in figure 3.
2. Switch on the power supply and apply a 380-V to the primary windings.
3. Under no load condition, measure the primary and secondary line and phase voltages, phase shift between the primary and secondary sides and calculate the turns ratio of the transformer.

Connection	Primary Voltage		Secondary Voltage		Phase Shift	Turns Ratio
	Line	Phase	Line	Phase		
Y-Δ						

4. Set the Three-Phase Transformer under load with the insertion of the resistive load (with different values of resistive load) and measure the following using the power analyzer:
(a) Current drawn by the load (Line Current) (**I_{load}**) in **mA.**
(b) Terminal voltage of the synchronous generator (Line Voltage) (**V_T**) in **V.**
(c) Power consumed by the load **(P)** in **W**.
5. Calculate the voltage regulation in each case.
6. Tabulate your result in the following table.

Connection	Load	Load Voltage (Line)	Load Current (Line)	Power Consumed (W)	%VR
Y-Δ	A				
	B				

7. Switch off the load and then switch off the power supply.

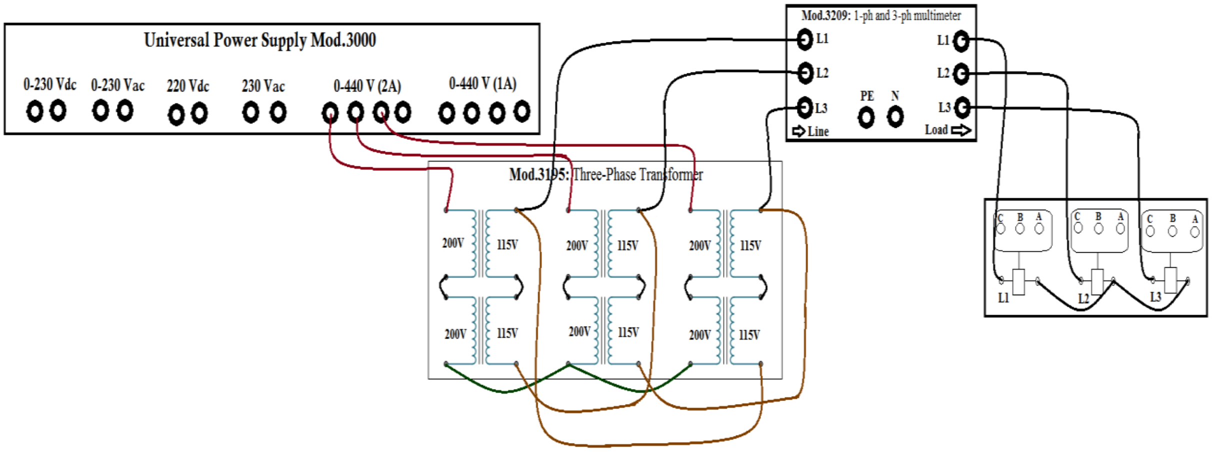


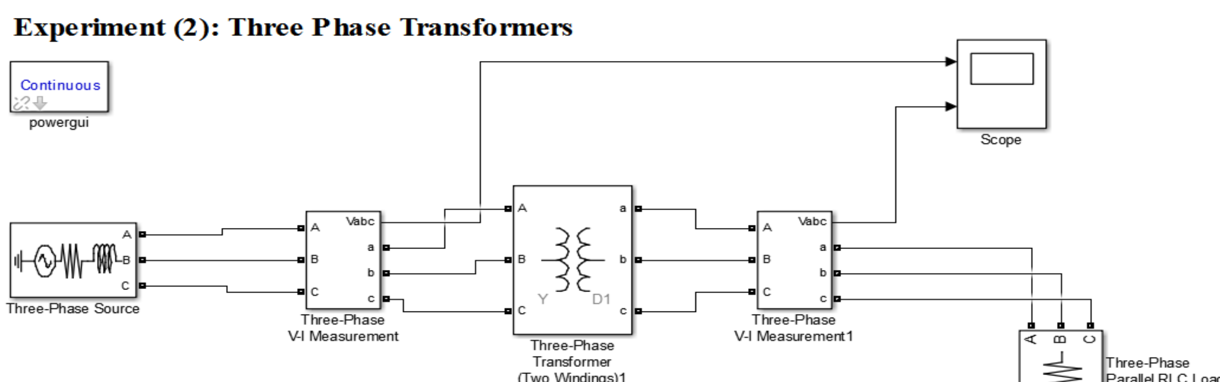
Figure (4)

Questions:

A 1-kVA three phase transformer has 500 turns on the primary and 100 turns on the secondary winding, the transformer connection is Δ-Y, if the transformer supplied with a 400-V, 50-Hz supply, calculate the secondary phase voltage.

Matlab Section:

Use **MATLAB SIMULINK** to build the following circuit to simulate a 3-Phase Transformer.



For each of the following connections of the three-phase transformer determine the phase shift between the primary and secondary line voltages.

1. Y-Y Connection
2. Δ-Δ Connection
3. Δ-Y Connection
4. Y-Δ Connection

Part 2

Induction Motors

Part 2 (A):

Single Phase Induction Motors

Experiment (3)	Capacitor Run Induction Motor

Objectives:

1. To familiarize with single-phase capacitor run induction motors components.
2. To investigate different characteristics (torque, speed, current, power, power factor and efficiency) of single-phase capacitor run induction motors.
3. To demonstrate how to reverse the direction of rotation of single-phase capacitor run induction motors.
4. To understand single-phase capacitor run induction motor ratings.

Theory and concepts:

Single-phase induction motors suffer from a severe handicap. Since there is only one phase on the stator winding, the magnetic field in a single-phase induction motor does **not rotate**. Instead, it ***pulses***, getting first larger and then smaller, but always remaining in the same direction. Because there is no rotating stator magnetic field, a single-phase induction motor has ***no starting torque***.

This fact is easy to see from an examination of the motor when its rotor is stationary. The stator flux of the machine first increases and then decreases, but it always points in the same direction. Since the stator magnetic field does not rotate, there is ***no relative motion*** between the stator field and the bars of the rotor. Therefore, there is no induced voltage due to relative motion in the rotor, no rotor current flow due to relative motion, and no induced torque. Actually, a voltage is induced in the rotor bars by transformer action *(dΦ/dt)*, and since the bars are short-circuited, current flows in the rotor. However, this magnetic field is lined up with the stator magnetic field, and it produces **no net torque on the rotor**,

$$\tau_{ind} = k\mathbf{B}_R \times \mathbf{B}_S = kB_R B_S \sin\gamma = kB_R B_S \sin 180^\circ = 0$$

However, *once the rotor begins to turn, an induced torque will be produced in it.* There are two basic theories which explain why a torque is produced in the rotor once it is turning. One is called the ***double-revolving-field theory*** of single-phase induction motors, and the other is called the ***cross-field theory*** of single-phase induction motors.

Starting Single-Phase Induction Motors

A single-phase induction motor has no intrinsic starting torque. There are three techniques commonly used to start these motors, and single-phase induction motors are classified according to the methods used to produce their starting torque. These starting techniques differ in cost and in the amount of starting torque produced, and an engineer normally uses the least expensive technique that meets the torque requirements in any given application.

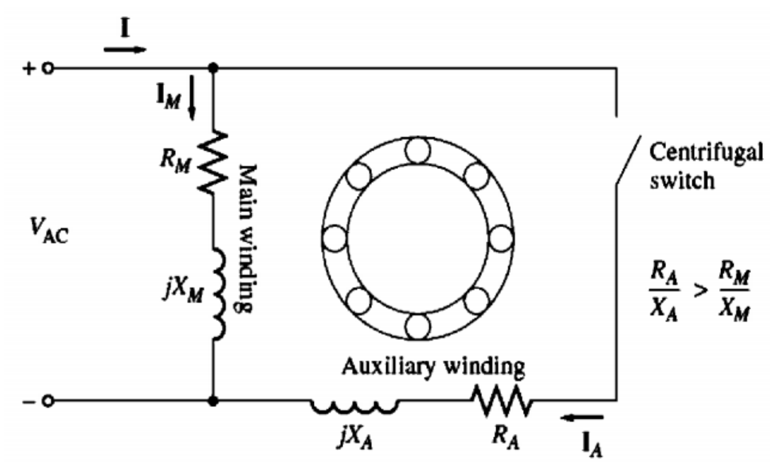
The three major starting techniques are

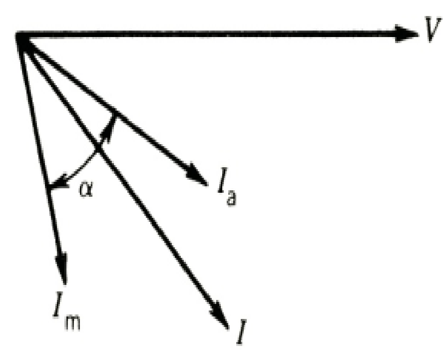
1. Split-phase windings
2. **Capacitor-type windings**
3. Shaded stator poles

All three starting techniques are methods of making one of the two revolving magnetic fields in the motor stronger than the other and so giving the motor an **initial nudge** in one direction or the other.

Split-Phase Motors

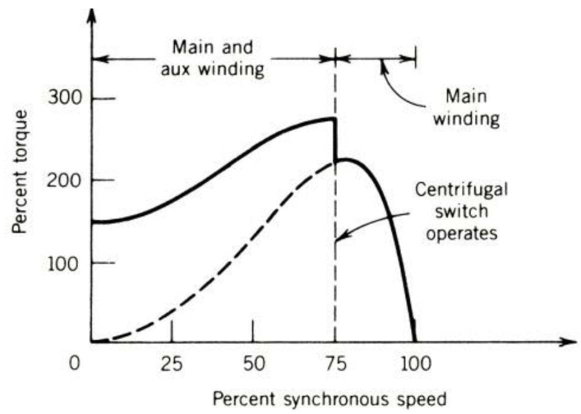
A split-phase motor is a single-phase induction motor with two stator windings, a main stator winding (M) and an auxiliary starting winding (A) (see the following Figure). These two windings are set 90 electrical degrees apart along the stator of the motor, and the auxiliary winding is designed to be switched out of the circuit at some set speed by a centrifugal switch.





The auxiliary winding is designed to have a higher resistance/reactance ratio than the main winding, so that the current in the auxiliary winding *leads* the current in the main winding. This higher R/X ratio is usually accomplished by using smaller wire for the auxiliary winding. Smaller wire is permissible in the auxiliary winding because it is used only for starting and therefore does not have to take full current continuously.

Since the current in the auxiliary winding leads the current in the main winding, the magnetic field B_A peaks before the main magnetic field B_M. Since B_A peaks first and then B_M, There is a net counterclockwise rotation in the magnetic field. In other words, the auxiliary winding makes one of the oppositely rotating stator magnetic fields larger than the other one and provides a net starting torque for the motor. A typical torque-speed characteristic is shown in the following Figure.

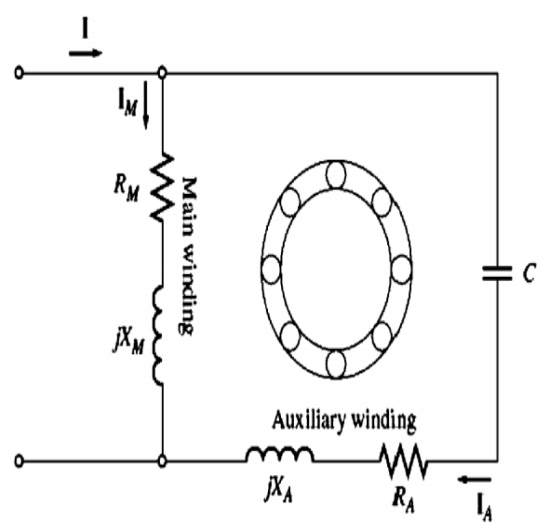


Split-phase motors have a moderate starting torque with a fairly low starting current. They are used for applications which do not require very high starting torques, such as fans, blowers, and centrifugal pumps. They are available for sizes in the fractional-horsepower range and are quite inexpensive.

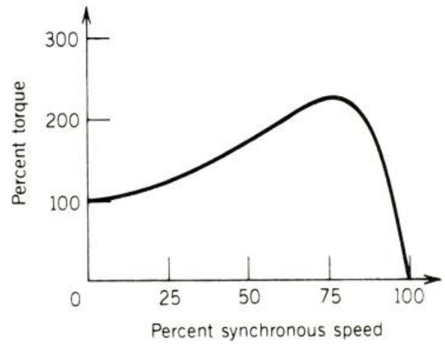
Since that angle can be changed from 90° ahead to 90° behind just by switching the connections on the auxiliary winding, the direction of rotation of the motor can be reversed by switching the connections of the auxiliary winding while leaving the main winding's connections unchanged.

Capacitor-Run Motors

The starting capacitor does such a good job of improving the torque-speed characteristic of an induction motor that an auxiliary winding with a smaller capacitor is sometimes left permanently in the motor circuit. If the capacitor's value is chosen correctly, such a motor will have a perfectly uniform rotating magnetic field at some specific load, and it will behave just like a three-phase induction motor at that point. Such a design is called a *permanent split-capacitor* or *capacitor run* motor (as shown in the Figure). At normal loads, they are more efficient and have a higher power factor and a smoother torque than ordinary single-phase induction motors.



A typical torque-speed characteristic is shown in the following Figure.



Speed Control of Single-Phase Induction Motors:

In general, the speed of single-phase induction motors may be controlled in the same manner as the speed of poly-phase induction motors. For squirrel-cage rotor motors, the following techniques are available:

1. Vary the stator frequency.
2. Change the number of poles.
3. **Change the applied terminal voltage (Slip Control Method).**

Speed Regulation

Speed regulation (SR) is a measure of the ability of a motor to keep a constant shaft speed as load varies. It is defined by the equation

$$SR = \frac{n_{nl} - n_{fl}}{n_{fl}} \times 100\%$$

It is a rough measure of the shape of a motor's torque-speed characteristic, positive speed regulation means that a motor's speed drops with increasing load, and a negative speed regulation means a motor's speed increases with increasing load. The magnitude of the speed regulation tells approximately how steep the slope of the torque-speed curve is.

Necessary Material:

1. **Mod.3000:** Universal Power Supply
2. **Mod.3090:** Capacitor Run Motor
3. **Mod.3180:** Electromagnetic Break
4. **Mod.3203:** DC digital VAW
5. **Mod.3209:** 1-ph and 3-ph multimeter
6. **Mod.3180C:** Torque and speed meter

Experimental Procedures:

Part I: Specifications of the Single-Phase Capacitor Run Induction Motor.

1. Read the nameplate of the Capacitor Run Induction Motor then tabulate the rating values of the motor in the following table:

Name Plate of the Capacitor Run Induction Motor Mod.3090					
Voltage:		Power:		PF	
Frequency:		Speed:			
Capacitor:		Current:			
Duty Cycle:		Ingress Protection:			
Insulation Class:					

Part II: Running the Capacitor Run Induction Motor under no-load condition.

1. Connect the circuit as shown in figure 1.
2. Apply a phase voltage of 230-V (rated voltage of the motor) at the terminals of the induction motor and run the motor.

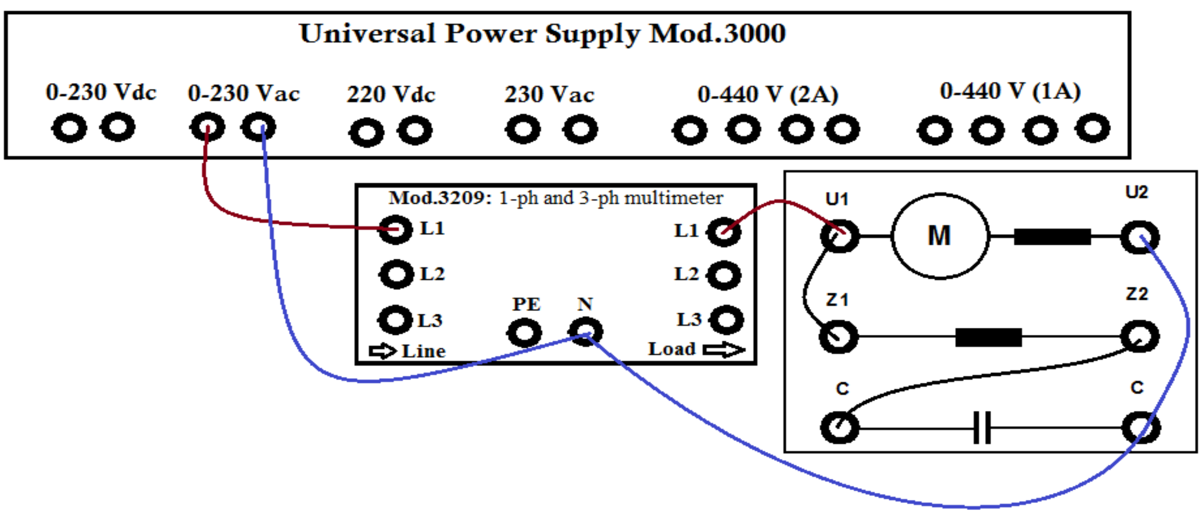


Figure (1)

3. Measure the speed of the motor, voltage applied to the motor, current and power drawn by the motor and the Power Factor of the motor in this case.

Speed	Line Voltage	Line Current	Power	PF

4. Observe the direction of rotation of the motor.

Direction of rotation:	
Note: In electrical machines, the direction is indicated with the shaft direction observed from the **front.**	

Part III: Reversing the direction of rotation of the Capacitor Run Induction Motor.

1. Change the connection of the capacitor run induction motor as shown in figure 2.
2. Apply a phase voltage of 230-V at the terminals of the induction motor and run the motor and then observe the direction of rotation of the motor.

Direction of rotation:	

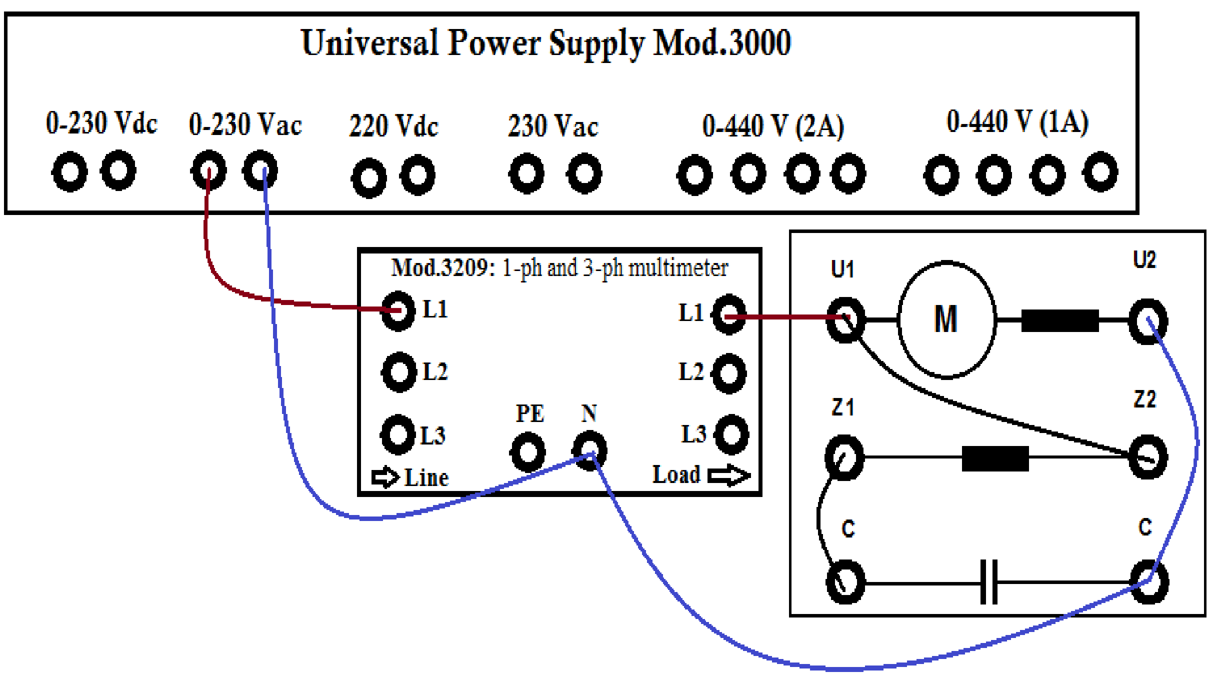


Figure (2)

Part IV: External characteristics of the Capacitor Run Induction Motor.

1. Make the mechanical coupling between the capacitor run induction motor and break unit.
2. Connect the circuit as shown in figure 3.
3. Apply a phase voltage of 230-V at the terminals of the induction motor and run the motor at no load condition.
4. Vary the meachanical load connected to the shaft of the motor by changing the dc voltage applied to the break unit.

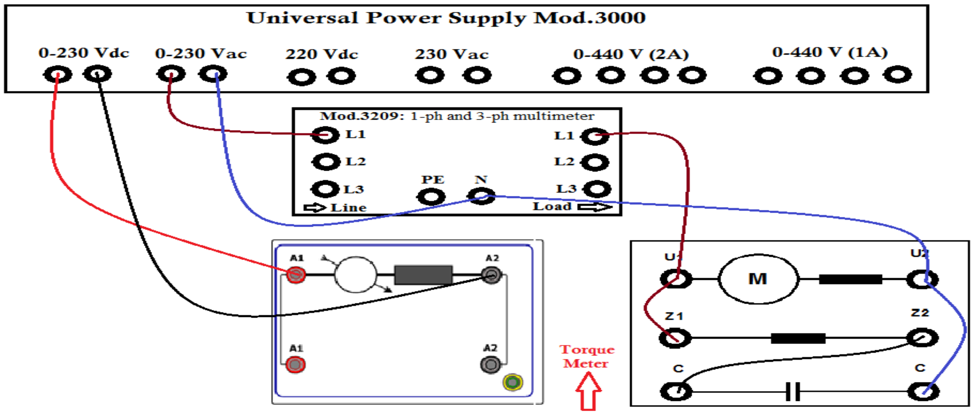


Figure (3)

5. Measure the speed, voltage applied to the motor, current and power absorbed by the motor and the Power Factor at each value of the torque of the load, use ItalTec Software.
6. Calcultae the output power, you may use the following relation:

   Pout = τ (N.m) * ω (rad/sec) = (τ (g.m) *(10/1000)) * (2*3.14*n (rpm)/60))

7. Calculate the efficiency of the motor, you may use the following relation:

   η = Pout/Pin *100%

8. Calculate the Speed regulation of the motor, you may use the following relation:

   SR = n_{nl} - n_{fl} / n_{fl} *100%

9. Tabulate the results in the following table.

Motor					**Break unit**	**Calculations**		
Speed (rpm)	Line Voltage	Line Current	Pin	PF	Torque (gr.m)	Pout	η	SR
	230				5			
	230				15			
	230				30			
	230				40			
	230				50			
	230				60			
	230				70			
	230				80			
	230				90			
	230				100			

10. Plot and explain the **mechanical characteristics** of the Capacitor Run IM.
(Torque (Y-axis) vs Speed (X-axis))

11. Plot and explain the **electromechanical characteristics** of the Capacitor Run IM.
X-axis: Output Power
Relations:

- Efficiency (Y-axis)
- Speed (Y-axis)
- Current (Y-axis)
- PF (Y-axis)

Questions:

1. Why single-phase induction motors are not self-starting?

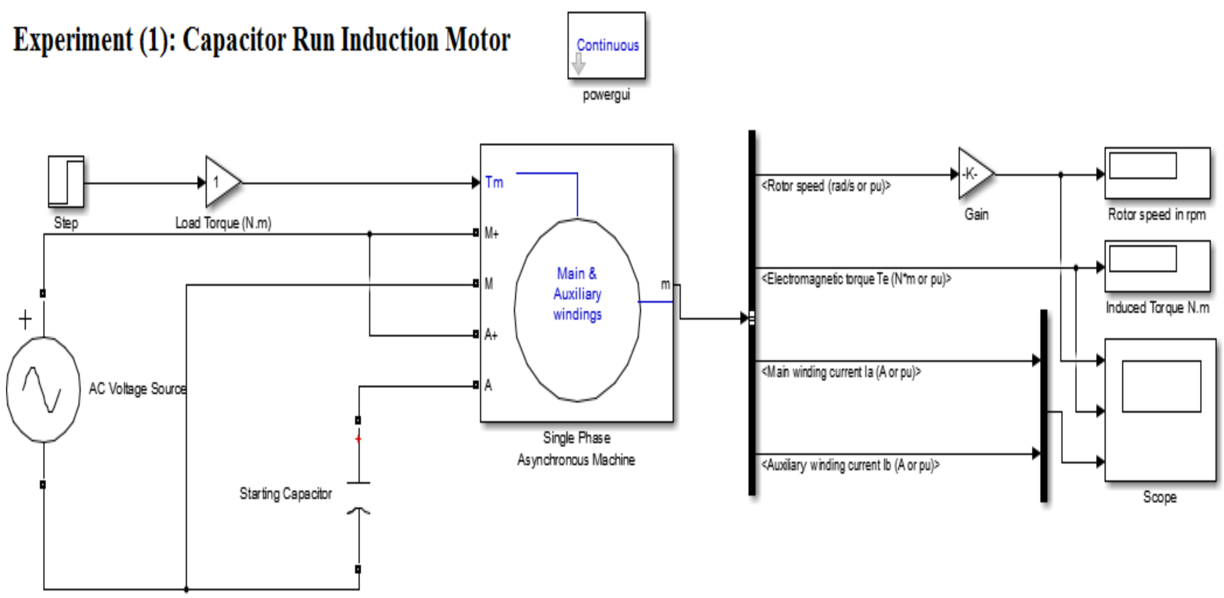
2. How does an auxiliary winding provide a starting torque for single-phase induction motors?

3. How is the current phase shift accomplished in the auxiliary winding of a capacitor-run induction motor?

4. How can the direction of rotation of the capacitor run motor be reversed?

Matlab Section:

Use **MATLAB SIMULINK** to build the following circuit to simulate a capacitor-run induction motor.



Hints: Put the motor's settings into MATLAB with using the nameplate of the motor.
Use the default values of the main and auxiliary windings parameters.

(a) At starting with no-load condition, obtain the speed curve and the stator currents waveforms. Set the simulation time to **1.3 sec**. Set the step time to **3 sec**.
(b) Change the starting capacitor value to **20 µF**, explain what changes will happen?
(c) Start to change the load torque in steps (5, 10, 15 and 20 N.m), at each step record the value of rotor speed and induced torque and then draw the torque speed characteristics of the motor.

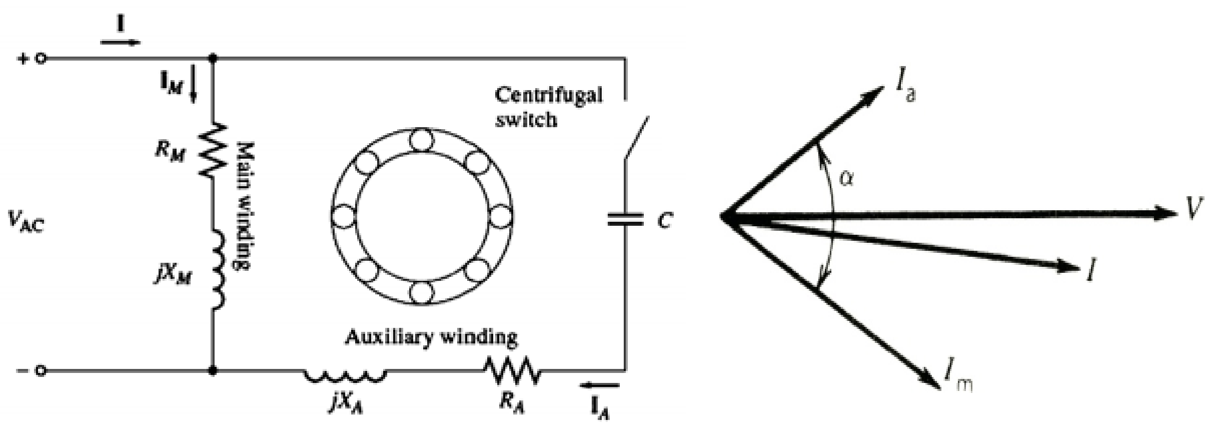
Experiment (4)	Capacitor Start/Run Induction Motor

Objectives:

1. To familiarize with single-phase capacitor start and capacitor start/run induction motors components.
2. To demonstrate how to reverse the direction of rotation of single-phase capacitor start and capacitor start/run induction motors.
3. To investigate different characteristics (torque, speed, current, power, power factor and efficiency) of single-phase capacitor start and capacitor start/run induction motors.
4. To understand single-phase capacitor start/run induction motors ratings.
5. To compare between capacitor-type single-phase induction motors.

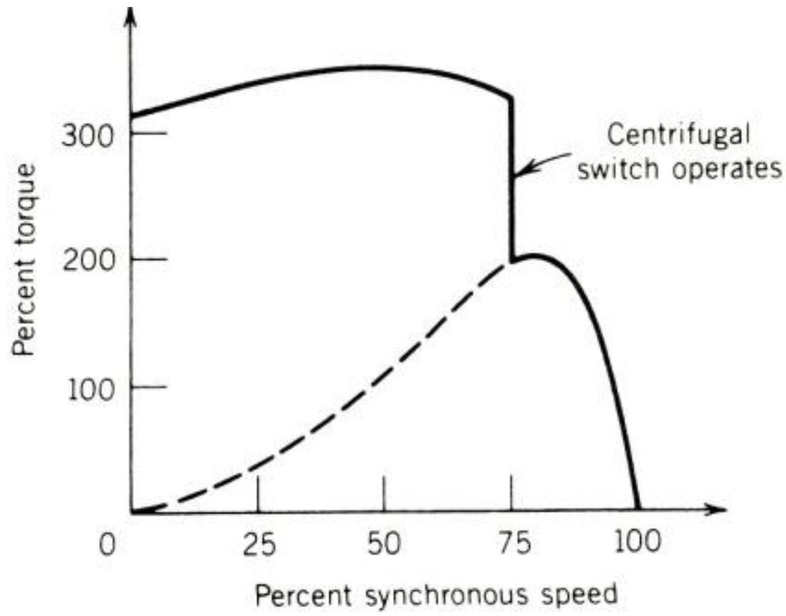
Theory and concepts:

For some applications, the starting torque supplied by a split-phase motor is insufficient to start the load on a motor's shaft. In those cases, capacitor-start motors may be used (see the following Figure).



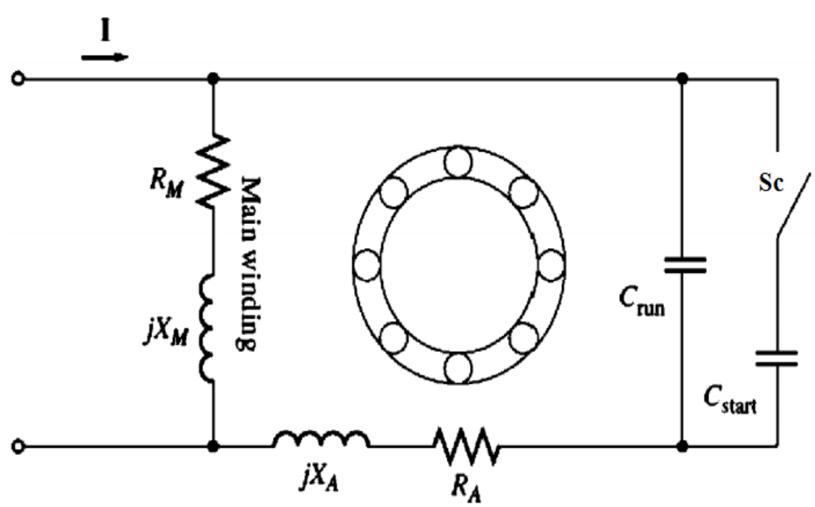
In a capacitor-start motor, a capacitor is placed in series with the auxiliary winding of the motor. By proper selection of capacitor size, the magnetomotive force of the starting current in the auxiliary winding can be adjusted to be equal to the magnetomotive force of the current in the main winding, and the phase angle of the current in the auxiliary winding can be made to lead the current in the main winding by 90°. Since the two windings are physically separated by 90°, a 90° phase difference in current will yield a single uniform rotating stator magnetic field, and the motor will behave just as though it were starting from a three-phase power source.

In this case, the starting torque of the motor can be more than 300 percent of its rated value (see the following Figure).



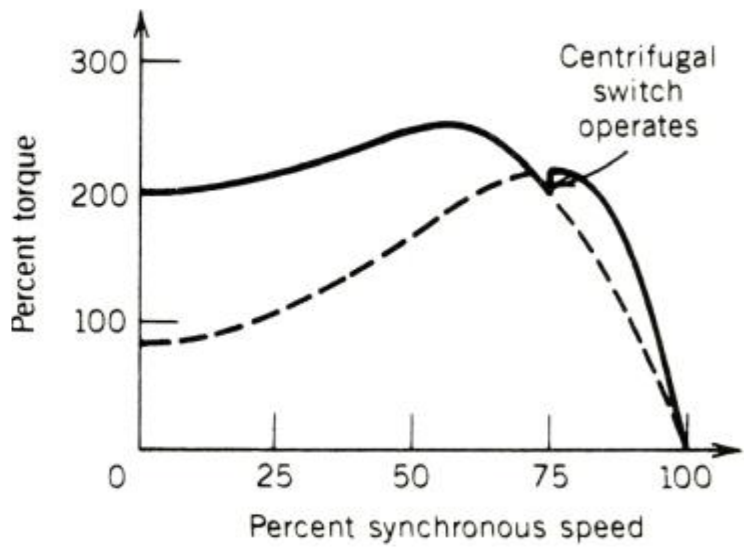
Capacitor-start motors are more expensive than split-phase motors, and they are used in applications where a high starting torque is absolutely required. Typical applications for such motors are compressors, pumps, air conditioners, and other pieces of equipment that must start under a load. Permanent split-capacitor motors are simpler than capacitor-start motors, since the starting switch is not needed. However, permanent split-capacitor motors have a *lower starting torque* than capacitor-start motors, since the capacitor must be sized to balance the currents in the main and auxiliary windings at normal-load conditions.

Since the starting current is much greater than the normal-load current, a capacitor that balances the phases under normal loads leaves them very unbalanced under starting conditions. If both the largest possible starting torque and the best running conditions are needed, two capacitors can be used with the auxiliary winding. Motors with two capacitors are called *capacitor-start, capacitor-run,* or *two-value capacitor* motors (see the following Figure).



The larger capacitor is present in the circuit only during starting, when it ensures that the currents in the main and auxiliary windings are roughly balanced, yielding very high starting torques. When the motor gets up to speed , the centrifugal switch opens, and the permanent capacitor is left by itself in the auxiliary winding circuit. The permanent capacitor is just large enough to balance the currents at normal motor loads, so the motor again operates efficiently with a high torque and power factor. The permanent capacitor in such a motor is typically about 10 to 20 percent of the size of the starting capacitor.

The torque-speed characteristic of the motor is shown in the following figure:



Characteristics and Typical Applications

The main features and the applications of single-phase induction motors are summarized in the following Table.

Single-Phase Induction Motors: Characteristics and Applications

Type of Motor	Torque as % of Rated Torque: Starting	Torque as % of Rated Torque: Breakdown	Rated Load: Power Factor	Rated Load: Efficiency	Horsepower Range	Approx. Comparative Price (%)	Application
Split-phase (resistance-start)	100–250	Up to 300	50–65	55–65	1/20–1	100	Fans, blowers, centrifugal pumps, washing machines, etc. Loads requiring low or medium starting torque
Capacitor-start	250–400	Up to 350	50–65	55–65	1/8–1	125	Compressors, pumps, conveyors, refrigerators, air-conditioning equipment, washing machines, and other hard-to-start loads
Capacitor-run	100–200	Up to 250	75–90	60–70	1/8–1	140	Fans, blowers, centrifugal pumps, etc. Low noise applications
Capacitor-start, capacitor-run	200–300	Up to 250	75–90	60–70	1/8–1	180	Compressors, pumps, conveyors, refrigerators, etc. Low noise and high starting torque applications

Note that for applications below 1/20 hp, shaded-pole motors are invariably used. However, for applications above 1/20 hp, the choice of the motor depends primarily on the **starting torque** and to **some extent on the quietness of operation**.

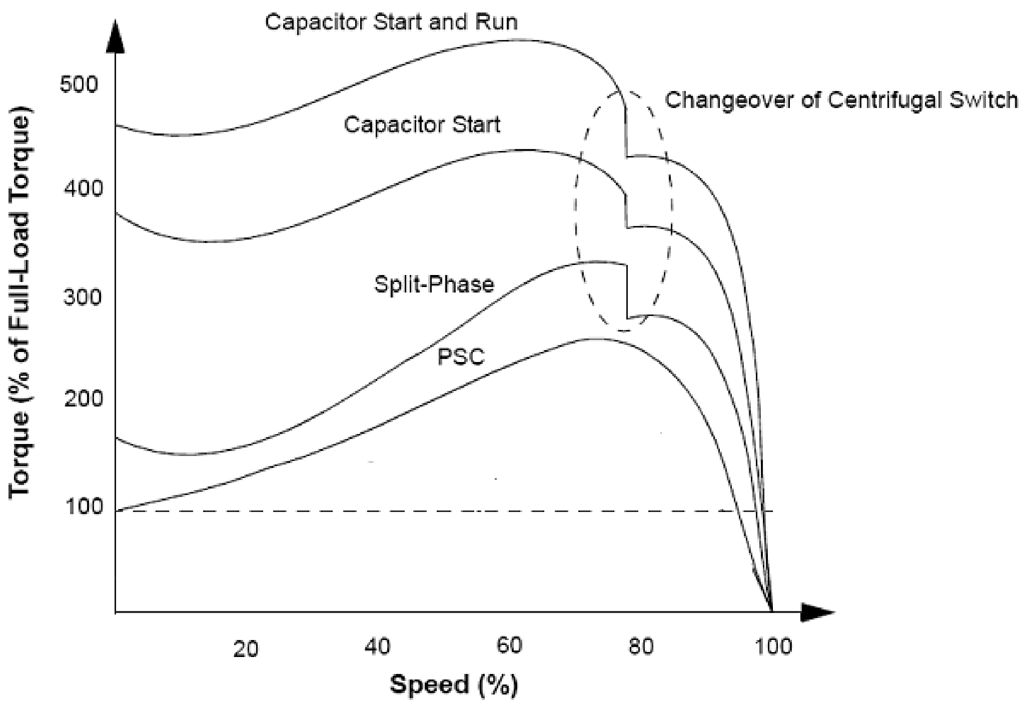
- ✓ If low noise is desired and low starting torque is adequate, such as for driving fans or blowers, capacitor-run motors can be chosen.
- ✓ If low noise is to be combined with high starting torque, as may be required for a compressor or refrigerator drive, then the expensive capacitor-start, capacitor-run motor is better.
- ✓ If the compressor is located in a noisy environment, the choice should be a capacitor start motor, which will be less expensive.

Comparison of Single-Phase Induction Motors

Single-phase induction motors may be ranked from best to worst in terms of their starting and running characteristics:

1. Capacitor-start , capacitor-run motor
2. Capacitor-start motor
3. Permanent split-capacitor motor
4. Split-phase motor

Naturally, the best motor is also the most expensive, and the worst motor is the least expensive. Also, not all these starting techniques are available in all motor size ranges. It is up to the design engineer to select the cheapest available motor for any given application that will do the job.



Necessary Material:

1. **Mod.3000:** Universal Power Supply
2. **Mod.3120:** Capacitor Start/Run Motor
3. **Mod.3180:** Electromagnetic Break
4. **Mod.3203:** DC digital VAW
5. **Mod.3209:** 1-ph and 3-ph multimeter
6. **Mod.3180C:** Torque and speed meter

Experimental Procedures:

Part I: Specifications of the Single-Phase Capacitor Start/Run Induction Motor.

1. Read the nameplate of the Capacitor Start/Run Induction Motor then tabulate the rating values of the motor in the following table:

Name Plate of the Capacitor Start/Run Induction Motor Mod.3120					
Voltage:		Power:		PF	
Frequency:		Speed:			
Starting Capacitor:		Running Capacitor:			
Current:		Duty Cycle:			
Insulation Class:		Ingress Protection:			

Part II: Capacitor Start Induction Motor

Part II-1: Running the Capacitor Start Induction Motor under no-load condition.

1. Connect the circuit as shown in figure 1.
2. Apply a phase voltage of 230-V (rated voltage of the motor) at the terminals of the induction motor and run the motor.
3. Measure the speed of the motor, voltage applied to the motor, current and power drawn by the motor and the Power Factor of the motor in this case.

Speed	Line Voltage	Line Current	Power	PF

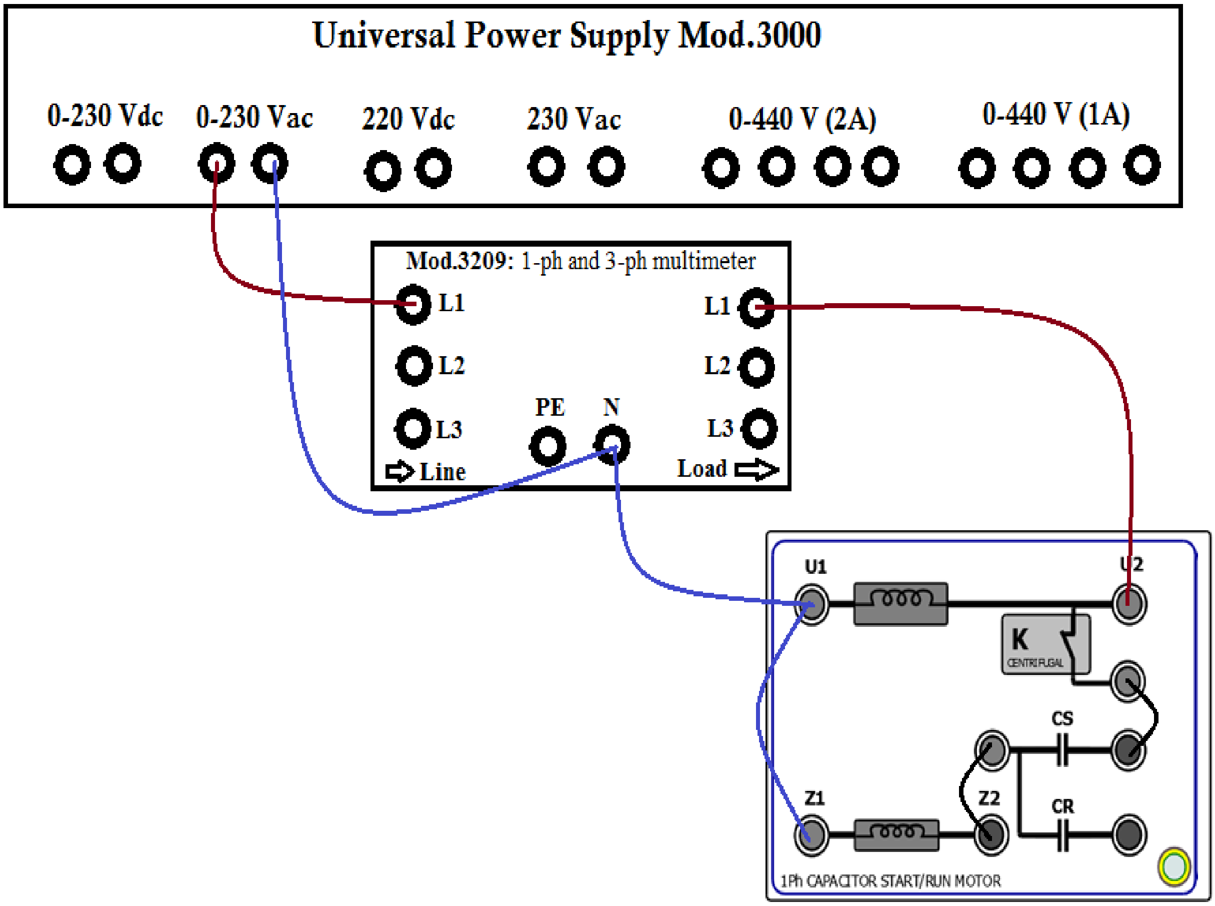


Figure (1)

4. Observe the direction of rotation of the motor.

Direction of rotation:	
Note: In electrical machines, the direction is indicated with the shaft direction observed from the **front.**	

Part II-2: Reversing the direction of rotation of the Capacitor-Start Induction Motor.

1. Change the connection of the capacitor start induction motor as shown in figure 2.
2. Apply a phase voltage of 230-V at the terminals of the induction motor and run the motor and then observe the direction of rotation of the motor.

Direction of rotation:	

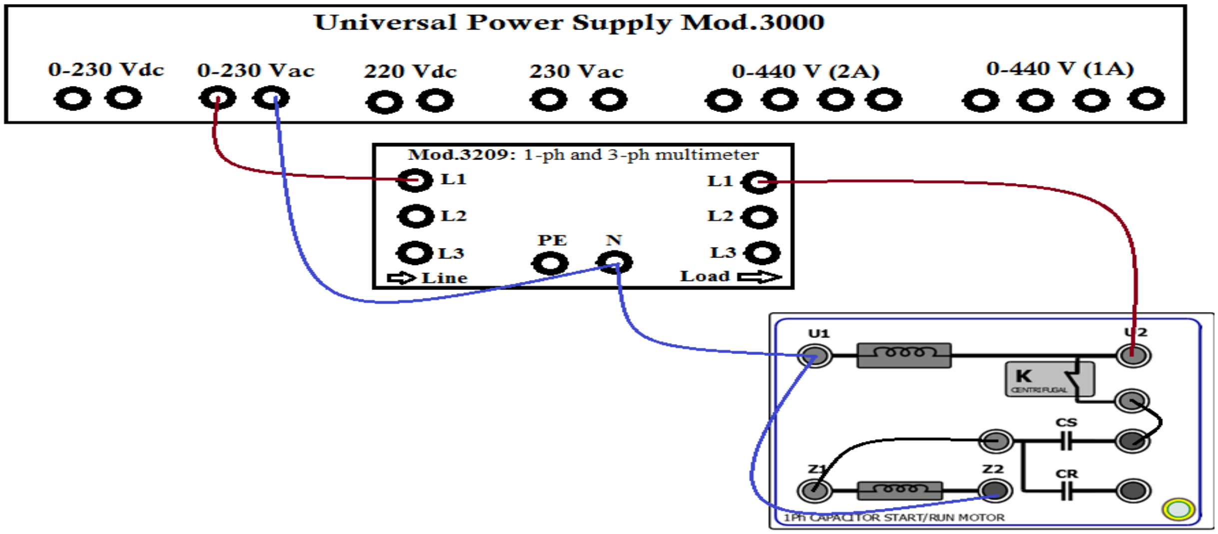


Figure (2)

Part II-3: External characteristics of the Capacitor Start Induction Motor.

1. Make the mechanical coupling between the capacitor start induction motor and break unit.
2. Connect the circuit as shown in Figure 3.
3. Apply a phase voltage of 230-V at the terminals of the induction motor and run the motor at no load condition.
4. Vary the meachanical load connected to the shaft of the motor by changing the dc voltage applied to the break unit.

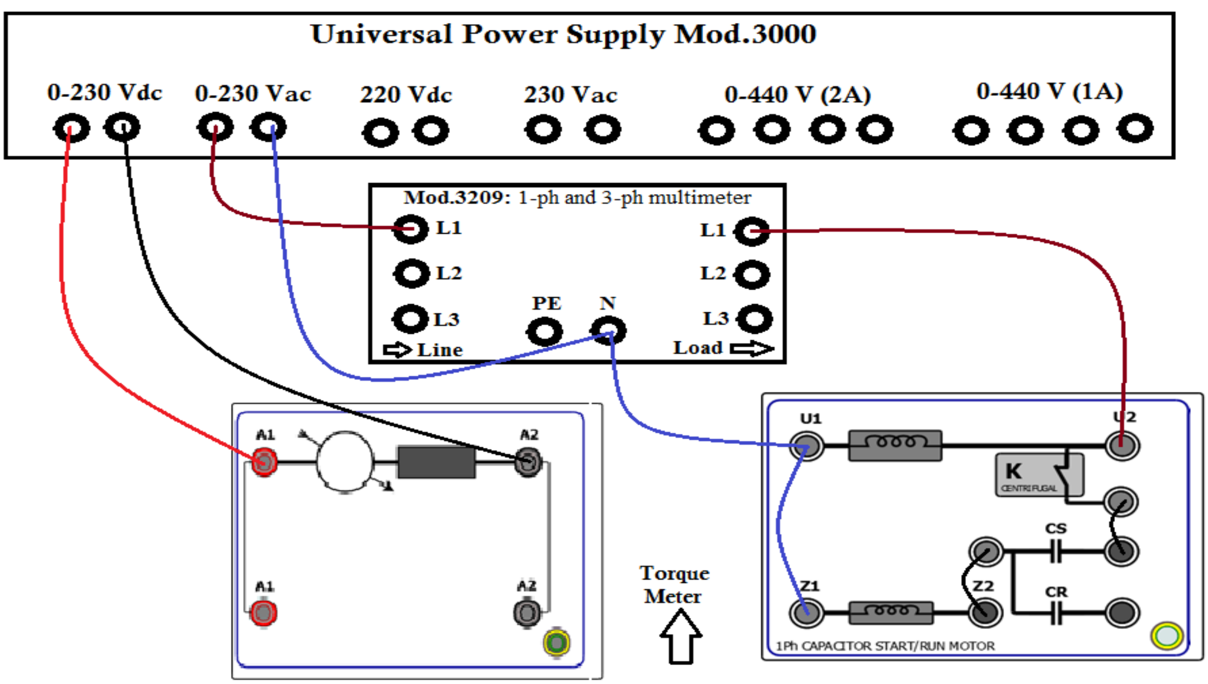


Figure (3)

5. Measure the speed, voltage applied to the motor, current and power absorbed by the motor and the Power Factor at each value of the torque of the load, use ItalTec Software.
6. Calcultae the output power, you may use the following relation:

   Pout = τ (N.m) * ω (rad/sec) = (τ (g.m) *(10/1000)) * (2*3.14*n (rpm)/60))

7. Calculate the efficiency of the motor, you may use the following relation:

   η = Pout/Pin *100%

8. Calculate the Speed regulation of the motor, you may use the following relation:

   SR = n_{nl} - n_{fl} / n_{fl} *100%

9. Tabulate the results in the following table.

Motor					**Break unit**	**Calculations**		
Speed (rpm)	Line Voltage	Line Current	Pin	PF	Torque (gr.m)	Pout	η	SR
	230				5			
	230				15			
	230				30			
	230				40			
	230				50			
	230				60			
	230				70			
	230				80			
	230				90			
	230				100			

10. Plot and explain the **mechanical characteristics** of the Capacitor Start IM.
    (Torque (Y-axis) vs Speed (X-axis))

11. Plot and explain the **electromechanical characteristics** of the Capacitor Start IM.
    X-axis: Output Power
    Relations:
    - Efficiency (Y-axis)
    - Speed (Y-axis)
    - Current (Y-axis)
    - PF (Y-axis)

Part III: Capacitor Start/Run Induction Motor.

Part III-1: Running the Capacitor Start/Run Induction Motor under no-load condition.

1. Connect the circuit as shown in figure 4.
2. Apply a phase voltage of 230-V (rated voltage of the motor) at the terminals of the induction motor and run the motor.
3. Measure the speed of the motor, voltage applied to the motor, current and power drawn by the motor and the Power Factor of the motor in this case.

Speed	Line Voltage	Line Current	Power	PF

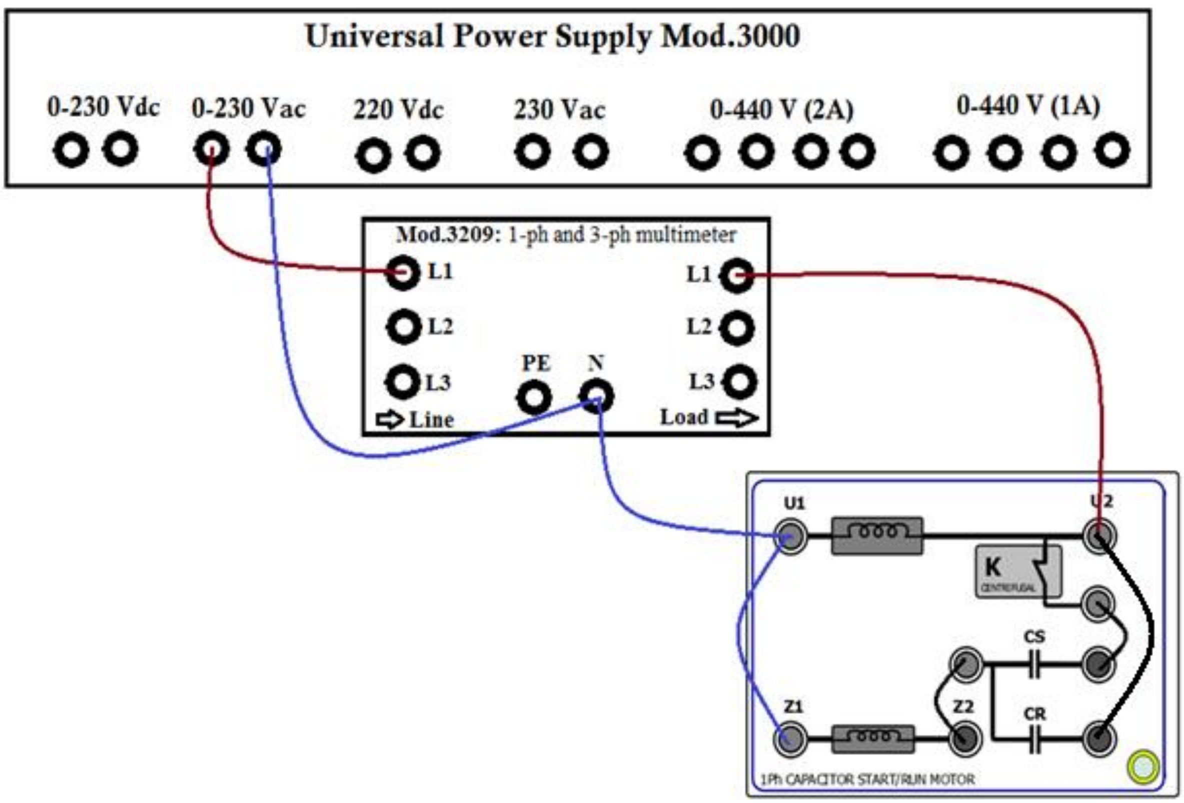


Figure (4)

4. Observe the direction of rotation of the motor.

Direction of rotation:	
Note: In electrical machines, the direction is indicated with the shaft direction observed from the **front.**	

Part III-2: Reversing the direction of rotation of the Capacitor Start/Run Induction Motor.

1. Change the connection of the capacitor start/run induction motor as shown in figure 5.
2. Apply a phase voltage of 230-V at the terminals of the induction motor and run the motor and then observe the direction of rotation of the motor.

Direction of rotation:	

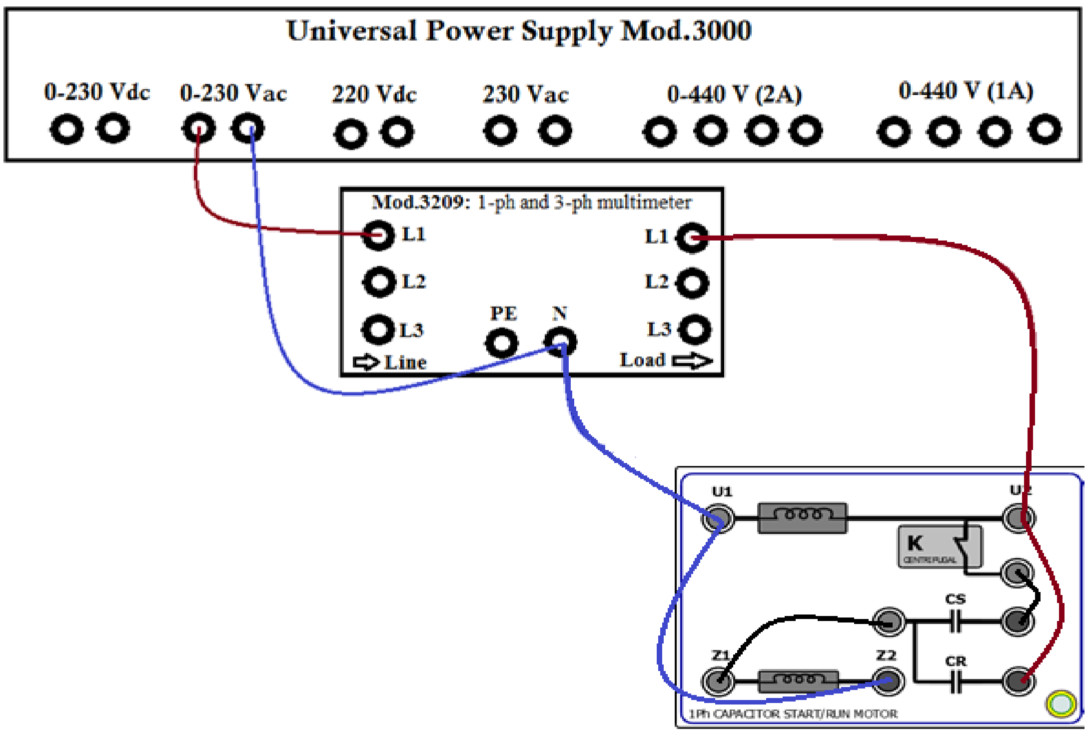


Figure (5)

Part III-3: External characteristics of the Capacitor Start/Run Induction Motor.

1. Make the mechanical coupling between the capacitor start/run induction motor and break unit.
2. Connect the circuit as shown in figure 6.
3. Apply a phase voltage of 230-V at the terminals of the induction motor and run the motor at no load condition.
4. Vary the meachanical load connected to the shaft of the motor by changing the dc voltage applied to the break unit.
5. Measure the speed, voltage applied to the motor, current and power absorbed by the motor and the Power Factor at each value of the torque of the load, use ItalTec Software.
6. Calcultae the output power, efficiency and speed regulation of the motor.
7. Tabulate the results in the following table.

Motor					Break unit	Calculations		
Speed (rpm)	Line Voltage	Line Current	Pin	PF	Torque (gr.m)	Pout	η	SR
	230				5			
	230				15			
	230				30			
	230				40			
	230				50			
	230				60			
	230				70			
	230				80			
	230				90			
	230				100			

8. Plot and explain the **mechanical characteristics** of the Capacitor Start/Run IM. (Torque (Y-axis) vs Speed (X-axis))

9. Plot and explain the **electromechanical characteristics** of the Capacitor Start /Run IM.
X-axis: Output Power
Relations:

- Efficiency (Y-axis)
- Current (Y-axis)
- Speed (Y-axis)
- PF (Y-axis)

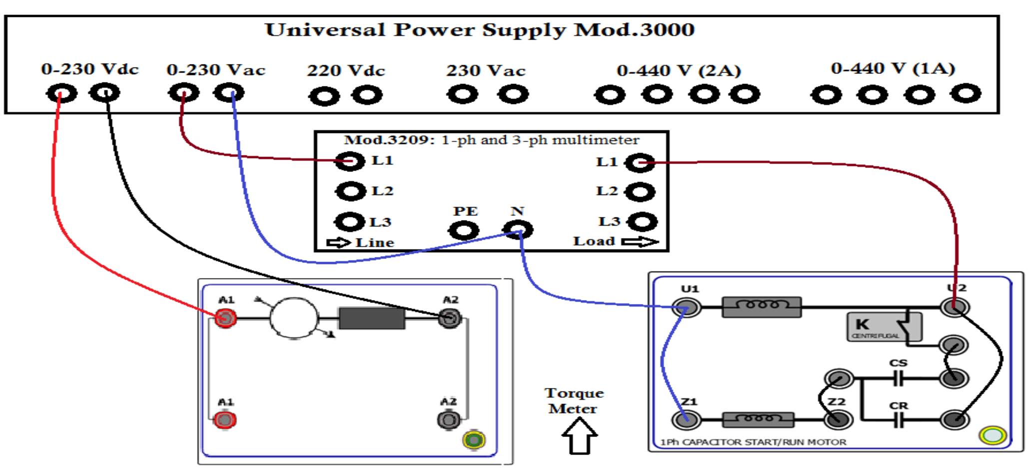


Figure (6)

Questions:

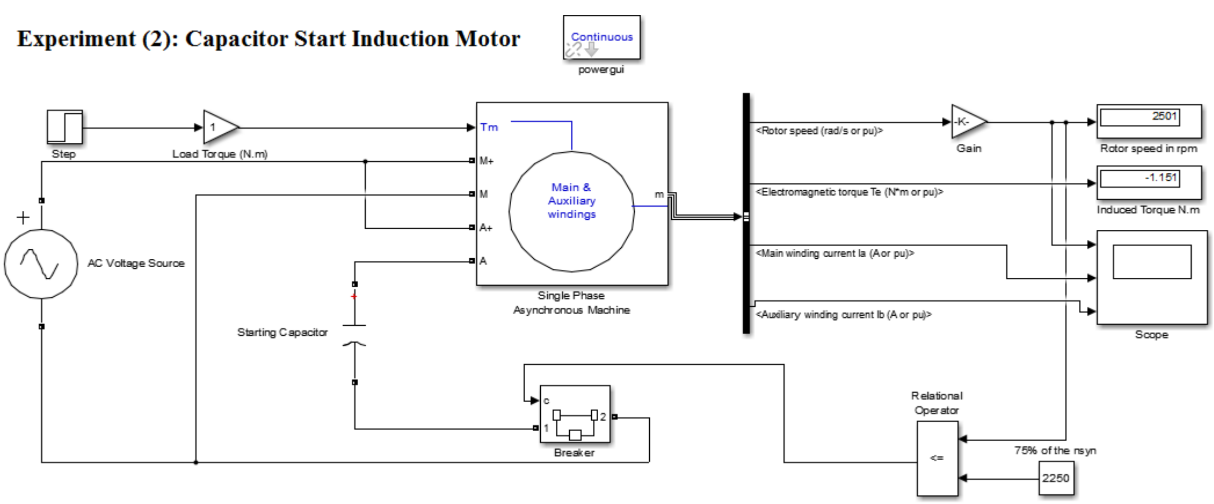
1. Compare between Single-Phase Induction motors (Split-Phase, Capacitor Run, Capacitor Start and Capacitor start capacitor run) in terms of:
   (a) Starting Torque;
   (b) Power Factor;
   (c) Torque-Speed Characteristic curve (In the same graph)

2. What type of motor would you select to perform each of the following jobs? Why?
   (a) Refrigerator ***(b)*** Air conditioner compressor ***(c)*** Air conditioner fan

3. A 120-V, 60-Hz, Capacitor-Start induction motor has the following main and auxiliary winding impedances:
   Main winding impedance: Zm= 4.2 + j3.6 Ω
   Auxiliary winding impedance: Za = 8.4 + j 3.0 Ω
   Determine the capacitance value required to obtain a 90^{o} phase shift between I_m and I_a?

Matlab Section

Use **MATLAB SIMULINK** to build the following circuit to simulate a capacitor-start IM.



<u>**Hints:**</u> Put the motor's settings into MATLAB with using the nameplate of the motor.
Use the default values of the main and auxiliary windings parameters.

(a) At starting with no-load condition, obtain the speed curve and the stator currents waveforms. Set the simulation time to **0.8 sec**. Set the step time to **5 sec**.

(b) Start to change the load torque in steps (10, 40, 70 and 100 N.m), at each step:
   1. Describe the operation of centrifugal switch.
   2. Record the value of rotor speed and induced torque and then draw the torque speed characteristics of the motor. Set the simulation time to **10 sec.**

Part 2

Induction Motors

Part 2 (B):

Three Phase Induction Motors

Experiment (5)	Three-Phase Squirrel Cage Induction Motor

Objectives:

1. To familiarize with three-phase Squirrel Cage Induction Motor components.
2. To obtain the equivalent circuit of the three-phase Squirrel Cage Induction Motor from DC, No-load and Locked Rotor tests.
3. To investigate different characteristics (torque, speed, current, power, power factor and efficiency) of Three-Phase Squirrel Cage Induction Motor.
4. To demonstrate how to reverse the direction of rotation of Three-Phase Squirrel Cage Induction Motor.
5. To study the difference between the Y and Δ connections of a Three-Phase Squirrel Cage Induction Motor in starting and running conditions.
6. To study the effect of the stator rheostat starter as a method of starting of Three-Phase squirrel cage induction motor.
7. Understand how the speed of three phase induction motors can be controlled.
8. Understand Three-Phase Squirrel Cage Induction Motor ratings.

Theory and concepts:

The three-phase, squirrel-cage induction motor normally consists of a stator, a rotor, and two end shields housing the bearings that support the rotor shaft.

A minimum of maintenance is required with this type of motor because:

- The rotor windings are shorted to form a squirrel cage.
- There are no commutator or slip rings to service (compared to the dc motor).
- There are no brushes to replace.

The motor frame is made of cast steel. The stator core is pressed directly into the frame. The two end shields housing the bearings are bolted to the cast steel frame. The bearings which support the rotor shaft are ball bearings.

Stator

A typical stator contains a three-phase winding mounted in the slots of a laminated steel core. The winding itself consists of formed coils of wire connected so that there are three single-phase windings spaced 120 electrical degrees apart. The leads from the three-phase stator windings are brought out to a terminal box mounted on the frame of the motor for voltage connections.

Rotor

The revolving part of the motor consists of steel laminations arranged in a cylindrical core. Copper bars are mounted near the surface of the rotor.

Squirrel Cage Rotors:

A cage induction motor rotor consists of a series of conducting bars laid into slots carved in the face of the rotor and shorted at either end by large shorting rings.

Wound Rotors:

A wound rotor has a complete set of three-phase windings that are mirror images of the windings on the stator.

Principle of operation

On the stator construction, the slots of the stator core contain three separate single-phase windings. When three currents 120 electrical degrees apart pass through these windings, a **rotating magnetic field results**. This field travels around the inside of the stator core. The speed of the rotating magnetic field depends on the **number of stator poles** and the **frequency of the power source**. This speed is called **the synchronous speed** and is determined by the formula:

Synchronous speed n_{syn} = (120 x frequency in hertz) / Number of poles

As this magnetic field rotates at synchronous speed, it **cuts** the copper bars of the rotor and **induces voltages in the bars of the squirrel-cage rotor**. These induced voltages set up currents in the rotor bars which in turn create a **field in the rotor core**. This rotor field reacts with the stator field to cause a **twisting effect or torque which turns the rotor.** The rotor always turns at a speed slightly less than the synchronous speed of the stator field. **This means that the stator field will always cut the rotor bars.** If the rotor turns at the same speed as the stator field, the stator field won't cut the rotor bars and there will be **no induced voltage or torque**.

Speed Regulation and Percent Slip

Speed performance can be measured in terms of **percent slip**. The synchronous speed of the rotating field of the stator is used as a reference point. The synchronous speed depends on the number of stator poles and the operating frequency. Since these two quantities remain constant, the synchronous speed also remains constant. If the speed of the rotor at full load is deducted from the synchronous speed of the stator field, the difference is the number of revolutions per minute that the rotor slips behind the rotating field of the stator.

Percent Slip (%s) = [(synchronous speed — mechanical speed) / synchronous speed] x 100

For a squirrel-cage induction motor, as the value of percent slip decreases toward 0%, the speed performance of the motor is improved. The average range of percent slip for squirrel-cage induction motors is **2 percent to 10 percent**.

The rotor speed at **no load** slips behind the synchronous speed of the rotating stator field just enough to create the torque required to overcome **friction and windage losses at no load**. **As a mechanical load is applied to the motor shaft, the rotor tends to slow down.** This means that the stator field (turning at a fixed speed) cuts the rotor bars a greater number of times in a given period. The induced voltages in the rotor bars increase, resulting in more current in the rotor bars and a stronger rotor field. There is a greater magnetic reaction between the stator and rotor fields which causes a stronger twisting effect or torque. This also increases stator current taken from the line. The motor is able to handle the increased mechanical load with little decrease in the speed of the rotor.

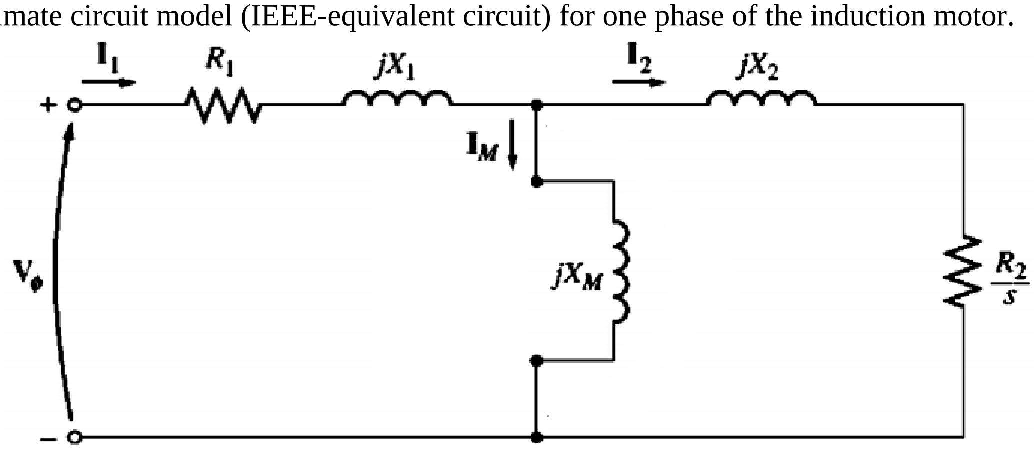
The torque output of the motor increases as a straight line with an increase in the value of percent slip as the mechanical load is increased to the point of full load. Beyond full load, the torque curve bends and finally reaches a maximum point called the **breakdown torque**. If the motor is loaded beyond this point, there will be a corresponding **decrease in torque** until the point is reached where the motor **stalls.** However, all induction motors have some slip in order to function. Starting torque is approximately **300% of running torque.**

Determining Circuit Model Parameters

The equivalent circuit of an induction motor is a very useful tool for determining the motor's response to changes in load. However, if a model is to be used for a real machine, it is necessary to determine what the element values are that go into the model. How can R1, R2, X1, X2, and XM be determined for a real motor? These pieces of information may be found by performing a series of tests on the induction motor that are analogous to the short-circuit and open-circuit tests in a transformer.

Equivalent Circuit

The per-phase equivalent circuit of Induction Motor is given in the following Figure, it serves as an approximate circuit model (IEEE-equivalent circuit) for one phase of the induction motor.

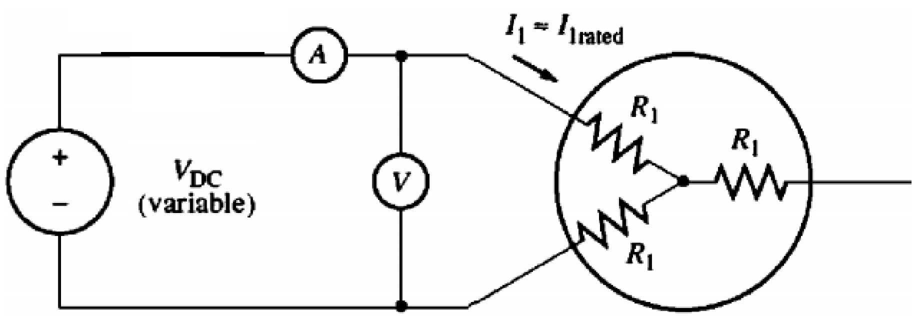


Where:

- **V_Φ** = line-to-neutral terminal voltage.
- **R_1** = stator resistance per phase.
- **X_1** = stator leakage reactance per phase.
- **R_2** = per phase rotor resistance referred to the stator.
- **X_2** = per phase rotor leakage reactance referred to the stator.
- **Xm** = a shunt reactance supplied to provide a path for the magnetizing component of the current flowing in the stator which produces the revolving field in the motor.

DC Test

Basically, a dc voltage is applied to the stator windings of an induction motor. Because the current is dc, there is no induced voltage in the rotor circuit and no resulting rotor current now. Also, the reactance of the motor is zero at direct current. Therefore, the only quantity limiting current now in the motor is the **stator resistance**, and that resistance can be determined. The basic circuit for the dc test is shown in the following Figure. This figure shows a dc power supply connected to two of the three terminals of a Y-connected induction motor.



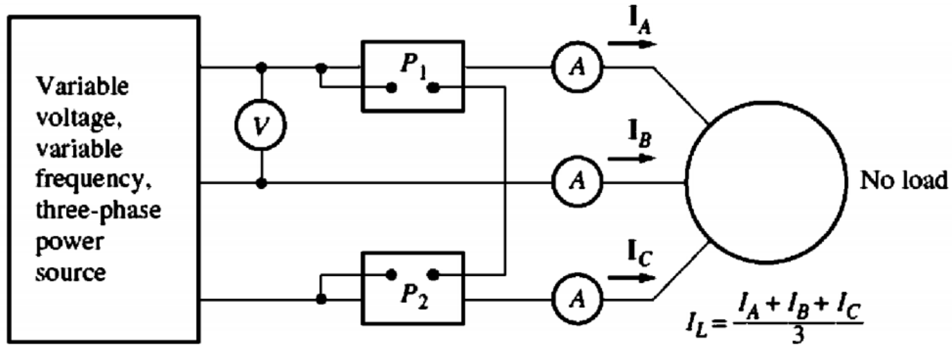
The current in the stator windings is adjusted to the **rated value** in an attempt to heat the windings to the same temperature they would have during normal operation.

The current flows through two of the windings, so the total resistance in the current path is $2R_1$ Therefore,

$$R_1 = \frac{V_{DC}}{2I_{DC}}$$

No-Load Test

The no-load test of an induction motor measures the **rotational losses** of the motor and provides information about its **magnetization current**. The test circuit for this test is shown in the following Figure.



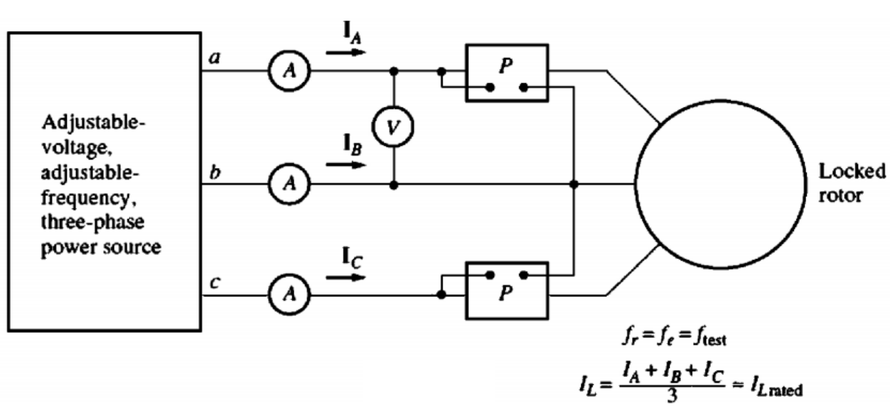
Wattmeters, a voltmeter, and three ammeters are connected to an induction motor, which is allowed to spin freely. The only load on the motor is the friction and windage losses, so all Pconv in this motor is consumed by mechanical losses, and the slip of the motor is very small.

In this test, rated voltages are applied to the stator terminals at the rated frequency with the rotor uncoupled from any mechanical load. Current, voltage and power are measured at the motor input. The losses in the no-load test are those due to core losses, winding losses, windage and friction. Since the slip is nearly zero, R_2/s is very large and thus the outer branch of the equivalent circuit can be considered open circuited. This assumption can be employed for calculations. We have, then,

$$\mathbf{Z_{nl} = R_1 + j\,(X_1 + X_m)}$$

The Locked-Rotor Test

This test which is also known as blocked-rotor test, short-circuit test or stalled torque test, In this test, the rotor is locked or blocked so that it cannot move (hence the slip is equal to unity), the following Figure shows the connections for the locked-rotor test. To perform the locked-rotor test, an ac voltage is applied to the stator, and the current flow is adjusted to be approximately full-load value. When the current is full-load value, the voltage, current, and power flowing into the motor are measured.



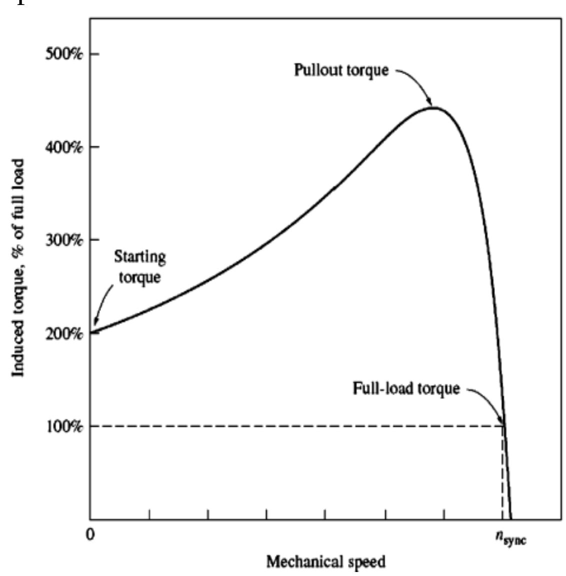
- The input power to the motor: $P = \sqrt{3}\, V_T\, I_L \cos\Theta$
- The impedance angle: $\Theta = \cos^{-1}(P/\sqrt{3}\, V_T\, I_L)$
- The magnitude of the total impedance: $|Z_{LR}| = V_\Phi/I_1 = V_T/\sqrt{3}\, I_L$
- $|Z_{LR}| = R_{LR} + j X'_{LR} = |Z_{LR}| \cos\Theta + j\,|Z_{LR}| \sin\Theta$
- The locked-rotor resistance: $R_{LR} = R_1 + R_2$
- The locked-rotor reactance: $X'_{LR} = X'_1 + X'_2$

IEEE test code recommends that the blocked-rotor test be made using 25% rated frequency with the test voltage adjusted to obtain approximately rated current. A 50-Hz motor would use a 12.5-Hz test voltage. The calculated reactance is corrected to 50-Hz by multiplying by 50/12.5. It must be realized that we are attempting to construct a 50-Hz equivalent circuit, while the blocked rotor test is performed at another frequency. The sum of actual reactances (for the 50 Hz circuit) $X_1 + X_2$ will be obtained by

- The total equivalent reactance at the normal operating frequency: $X_{LR} = f_{rated}/f_{test}\; X'_{LR}$
- $X_{LR} = X_1 + X_2$
- $X_1 = X_2$

Induction Motor Torque-Speed Curve

The induction motor torque-speed characteristic curve plotted in the following Figure provides several important pieces of information about the operation of induction motors. This information is summarized as follows:



1. The induced torque of the motor is zero at synchronous speed.
2. The torque- speed curve is nearly linear between no load and full load. In this range, the rotor resistance is much larger than the rotor reactance, so the rotor current, the rotor magnetic field, and the induced torque increase linearly with increasing slip.
3. There is a maximum possible torque that cannot be exceeded. This torque called the pullout torque or breakdown torque, is 2 to 3 times the rated full-load torque of the motor.
4. The starting torque on the motor is slightly larger than its full-load torque, so this motor will start carrying any load that it can supply at full power.
5. Notice that the torque on the motor for a given slip varies as the square of the applied voltage.

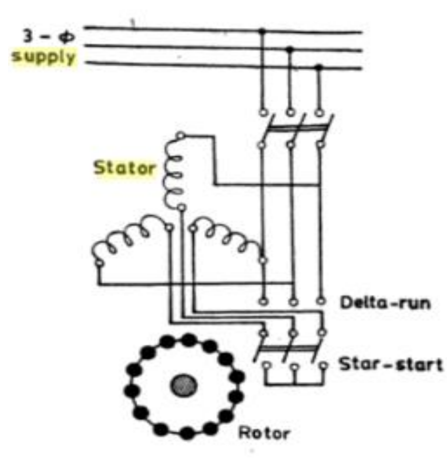
Starting Current

When a three-phase, squirrel-cage induction motor is connected across the full line voltage, the starting surge of current momentarily reaches as high a value as 400% to 600% or more of the rated full-load current. At the moment the motor starts, the rotor is at a standstill. At this instant, therefore, the stator field cuts the rotor bars at a faster rate than when the rotor is turning. This means that there will be relatively high induced voltages in the rotor which will cause heavy rotor current. The resulting input current to the stator windings will be high at the instant of starting. Because of this high starting current, starting protection rated as high as 300 percent of the rated full-load current is provided for squirrel-cage induction motor installations. Squirrel-cage induction motors can be started at full voltage. In the event that the feeders and protective devices of the electric power supply are unable to handle the large starting currents, reduced voltage starting circuits must be used with the motor.

Starting Induction Motors

For cage induction motors, the starting current can vary widely depending primarily on the motor's rated power and on the effective rotor resistance at starting conditions. One way to reduce the starting current is to insert extra resistors into the power line during starting. While formerly common, this approach is rare today. It is important to realize that while the starting current is reduced in direct proportion to the decrease in terminal voltage, the starting torque decreases as the square of the applied voltage. Therefore, only a certain amount of current reduction can be done if the motor is to start with a shaft load attached.

Star/Delta starter method is based up to the principle that with 3 windings connected in star, voltage across each winding is 1/3 i.e. 57.7%. Of the line-to-line voltage whereas the same winding connected in delta will have full line to line voltage across each. The star-delta starter is connected to the stator winding in star across the rated supply voltage at the starting instant. After the motor attain the speed up to 85% of its normal speed the same stator winding is reconnected in delta through a changeover switch across the same supply voltage as shown in the following Figure.



In the Autotransformer starter, reduced voltage is obtained by three-phase autotransformer. Generally 60 to 65% tapping can be used to obtain a safe value of starting current. The full rated voltage is applied to the motor by star connected autotransformer. When the motor has picked up the speed up to 85 % of its normal speed autotransformer is taking out from the motor circuit.

Speed Control of Induction Motors

There are really only two techniques by which the speed of an induction motor can be controlled. One is to **vary the synchronous speed**, which is the speed of the stator and rotor magnetic fields, since the rotor speed always remains near n_{sync}. The other technique is to **vary the slip of the motor for a given load**.

The synchronous speed of an induction motor is given by

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

So the only ways in which the synchronous speed of the machine can be varied are

1. By changing the electrical frequency and
2. By changing the number of poles on the machine.

Slip control may be accomplished by varying either the **rotor resistance** or the **terminal voltage of the motor.**

If the electrical frequency applied to the stator of an induction motor is changed, the rate of rotation of its magnetic fields n_{sync} will change in direct proportion to the change in electrical frequency.

Necessary Material:

1. **Mod.3000:** Universal Power Supply
2. **Mod.3040:** 3-Ph Squirrel Cage Induction Motor
3. **Mod.3180:** Electromagnetic Break
4. **Mod.3203:** DC digital VAW
5. **Mod.3209:** 1-ph and 3-ph multimeter
6. **Mod.3180C:** Torque and speed meter
7. **Mod.3308:** Star-Delta Reversing Switch

Experimental Procedures:

Part I: Specifications of the Three-Phase Squirrel Cage Induction Motor.

1. Read the nameplate of the Three-Phase Squirrel Cage Induction Motor then tabulate the rating values of the motor in the following table:

<table>
<tr><td colspan="9">Name Plate of the Three-Phase Squirrel Cage Induction Motor Mod.3040</td></tr>
<tr><td>Voltage:</td><td>Y</td><td colspan="2"></td><td>Δ</td><td colspan="2"></td><td>Power:</td><td></td></tr>
<tr><td>Current:</td><td>Y</td><td colspan="2"></td><td>Δ</td><td colspan="2"></td><td>Speed:</td><td></td></tr>
<tr><td>Frequency:</td><td colspan="2"></td><td colspan="2">Poles:</td><td colspan="2"></td><td>PF:</td><td></td></tr>
<tr><td>Duty Cycle:</td><td colspan="6"></td><td>Ingress Protection:</td><td></td></tr>
<tr><td colspan="7">Insulation Class:</td><td colspan="2"></td></tr>
</table>

Part II: DC Test for Stator Resistance.

1. Connect any two stator terminals of the induction motor to the two leads from the DC supply as shown Figure 1.
2. Measure the DC current through the two stator phase windings up to approximately the rated AC value.
3. Read and record Vdc and Idc in the following table:

DC Test for Stator Resistance of Three-Phase Squirrel Cage Induction Motor		
V_{dc}	I_{dc}	$R_{dc} = R_1$ (calculated)

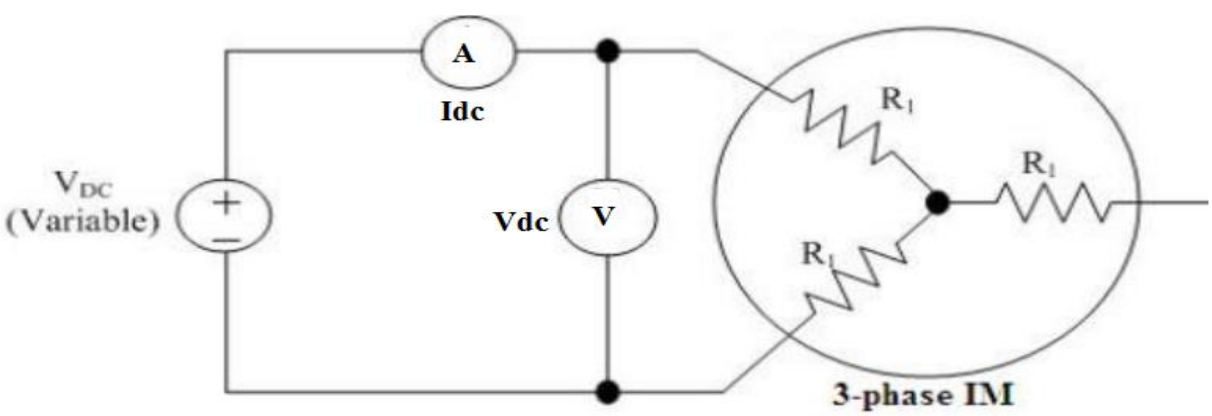


Figure (1)

Part III: No-Load Test of Three-Phase Squirrel Cage Induction Motor.

1. Connect the circuit as shown in Figure 2.
2. Make sure that the Motor is unloaded and the Variac is set at zero position.
3. Switch on the 3-phase AC supply and gradually increase the voltage through variac till its rated value. Thus the Motor is running at rated speed under No-Load condition.
4. Read and record the line currents, line voltage, and wattmeter readings.

No Load Test of Three-Phase Squirrel Cage Induction Motor.		
Vnl (Line Voltage)	Inl (Line Current)	Pnl
Stator Copper Losses P_{SCL} = $\mathbf{3I_{nl}^2R_1}$		
Rotational Losses = $\mathbf{P_{nl} - P_{SCL}}$		

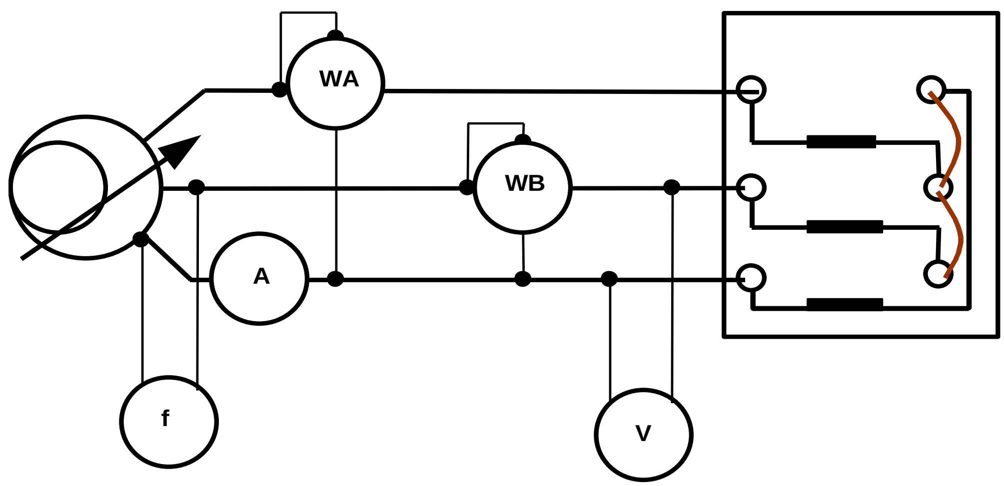


Figure (2)

Part IV: Locked Rotor Test of Three-Phase Squirrel Cage Induction Motor.

1. Connect the circuit as shown in Figure 3.
2. Before starting, ensure that the shaft is blocked completely from rotating.
3. Increase the voltage gradually, till the line current reaches to the rated value.
4. Read and record the line currents, line voltage, and wattmeter readings.
5. Take the readings quickly so that the machine does not heat up.

Locked-Rotor Test of Three-Phase Squirrel Cage Induction Motor.			
V_{nl} (Line Voltage)	I_{nl} (Line Current)	P_{nl}	PF

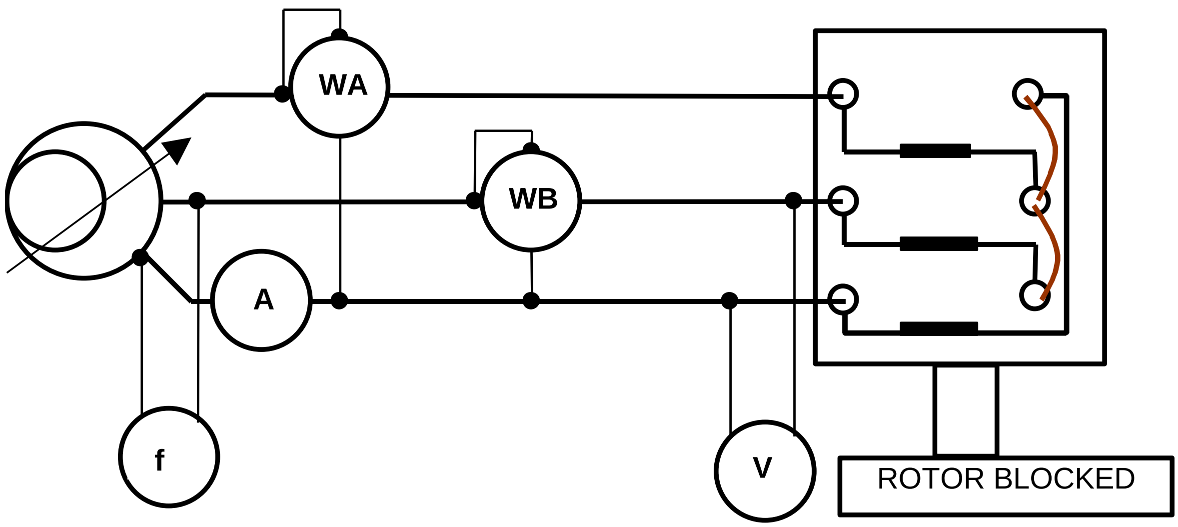


Figure (3)

Depending on the measured values on the experiment answer the following questions:

Draw the per-phase approximate equivalent circuit of the three-phase squirrel cage induction motor. Mark in circuit the values calculated in this practical and include all the calculated parameters.

Part V: Running the motor at no-load condition with Star connection.

1. Connect the circuit as shown in figure 4.
2. Apply a 3-phase voltage of 400-V at the terminals of the induction motor and run the motor.
3. Measure the speed at no-load condition and the line ans starting currents drawn by the motor.
4. Tabulate your results in the following table:

Condition	Speed	Starting Current	Line Current
No-load (Y-connection)			

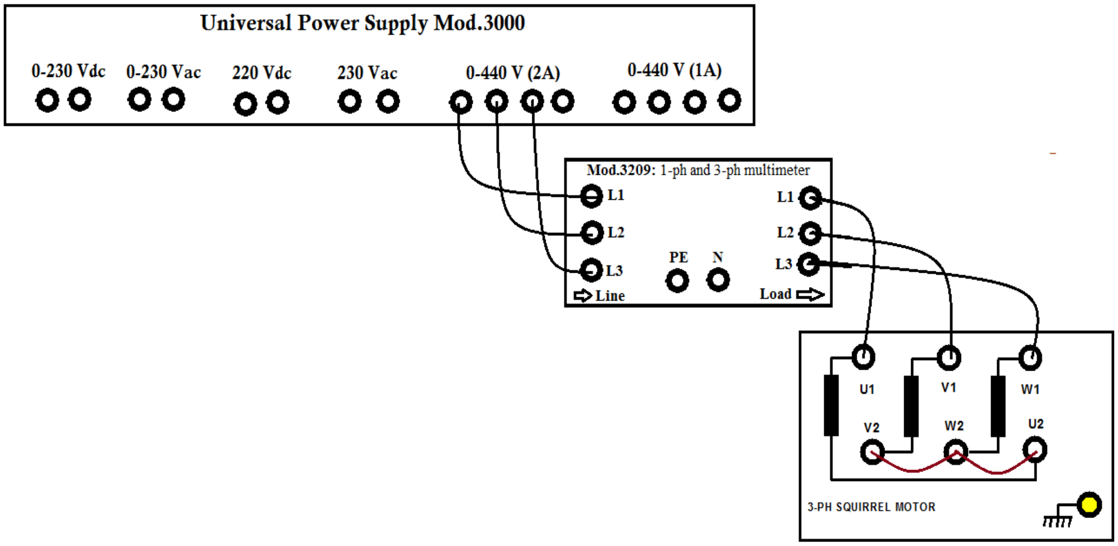


Figure (4)

Part VI: Running the motor at no-load condition with Delta connection.

1. Connect the circuit as shown in figure 5.
2. Apply a 3-phase voltage of 230-V at the terminals of the induction motor and run the motor.
3. Measure the speed at no-load condition and the line ans starting currents drawn by the motor.
4. Tabulate your results in the following table:

Condition	Speed	Starting Current	Line Current
No-load (Δ-connection)			

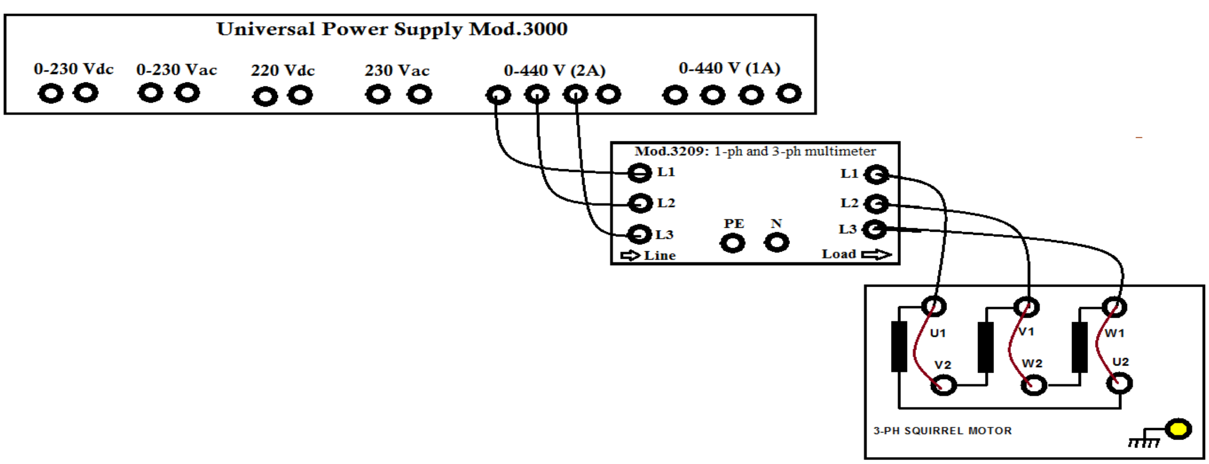


Figure (5)

Part VII: Reversing the direction of rotation of the Three-Phase Squirrel Cage Induction Motor.

1. Connect the circuit as shown in figure 6.
2. Apply a 3-phase voltage of 380 V at the terminals of the induction motor and run the motor, Observe the direction of rotation of the motor.
3. Now with two phases interchanged L2 and L3 as shown in Figure 3. Observe the direction of rotation of the motor.
4. Tabulate your result in the following table.

Lines			Direction (CW,CCW)
L1	L2	L3	
L1	L3	L2	

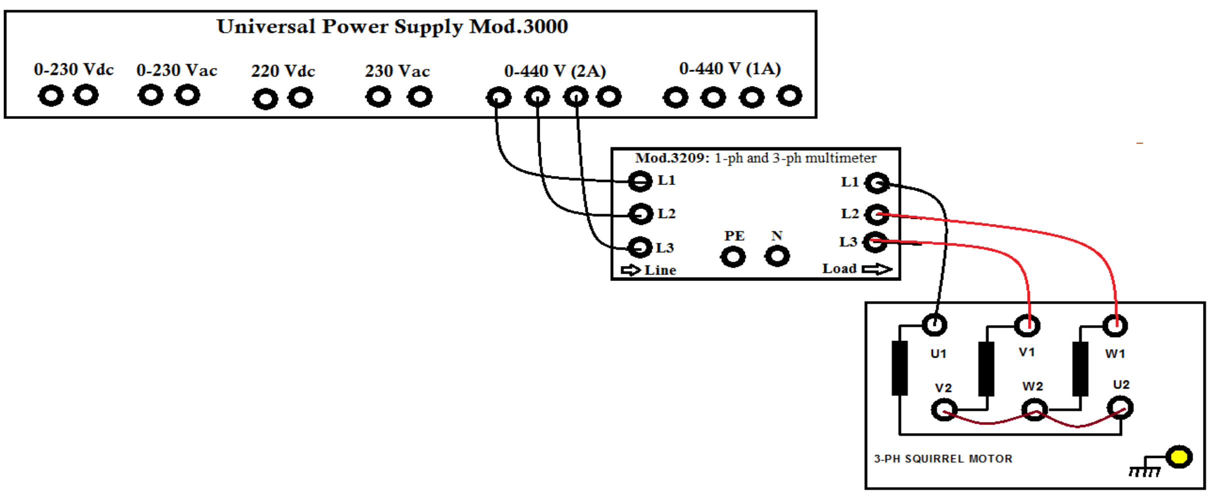


Figure (6)

Part VIII: Three phase squirrel cage Induction Motor with starting rheostat.

1. Connect the motor as shown in the figure 7 and supply the motor directly on line 400-V with the starting rheostat completely inserted (R_{MAX}).Read the current measured in the ammeter.
2. Decrease gradually the ohmic value (pass at 2/3 position). Read and note the current measured in the ammeter and note the speed variation.
3. Decrease again the ohmic value (pass at 1/3) position. Read and note the current measured in the ammeter and note the speed variation
4. Decrease again the ohmic value up to obtain the short circuit of V2-W2-U2. This position is the usual condition for operation.
5. Tabulate your results in the following table.

Rheostat	Line Current	Speed
R = Rmax		
R = 2/3 Rmax		
R = 1/3 Rmax		
R = 0 (short circuit)		

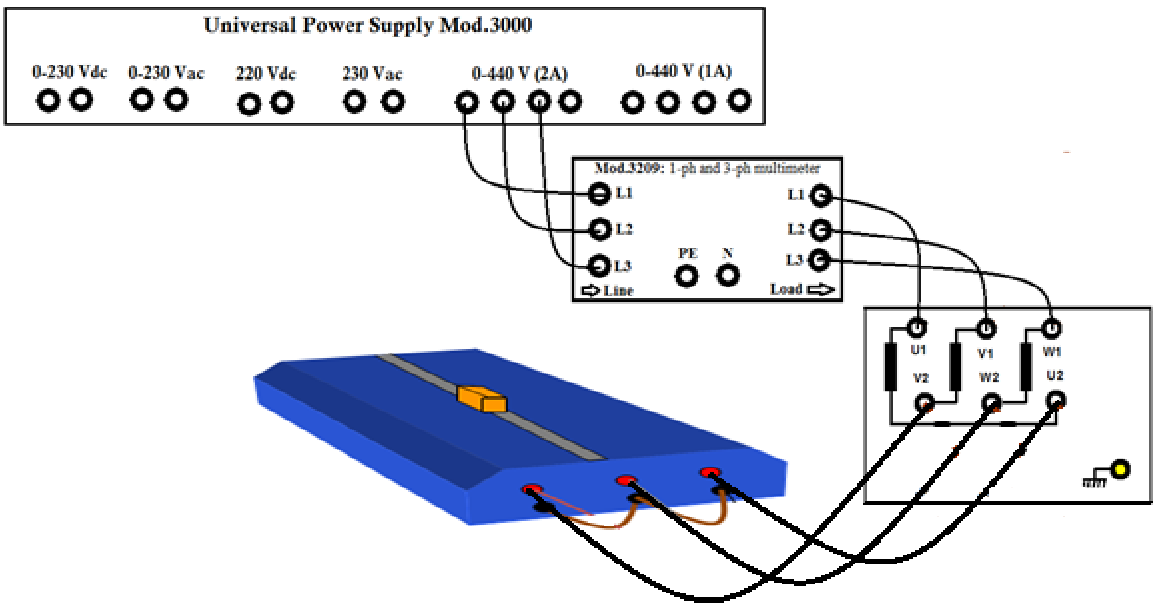


Figure (7)

Part IX: Three phase squirrel cage Induction Motor with Y-Δ Starter.

1. Make the connection as shown in Figure 8.
2. Apply a 3-phase voltage of 230-V at the terminals of the Y-Δ starter.
3. Put the handle of starter on start position and instantly note down the initial current.
4. When motor attain the speed up to 85 % of its normal speed put the handle of starter on run position and note down the voltage, current and speed of the motor.
5. Switch OFF the power supply and disconnect the motor.

Condition	Starting Current	Steady State Current	Line Voltage	Speed
Y				
Δ				

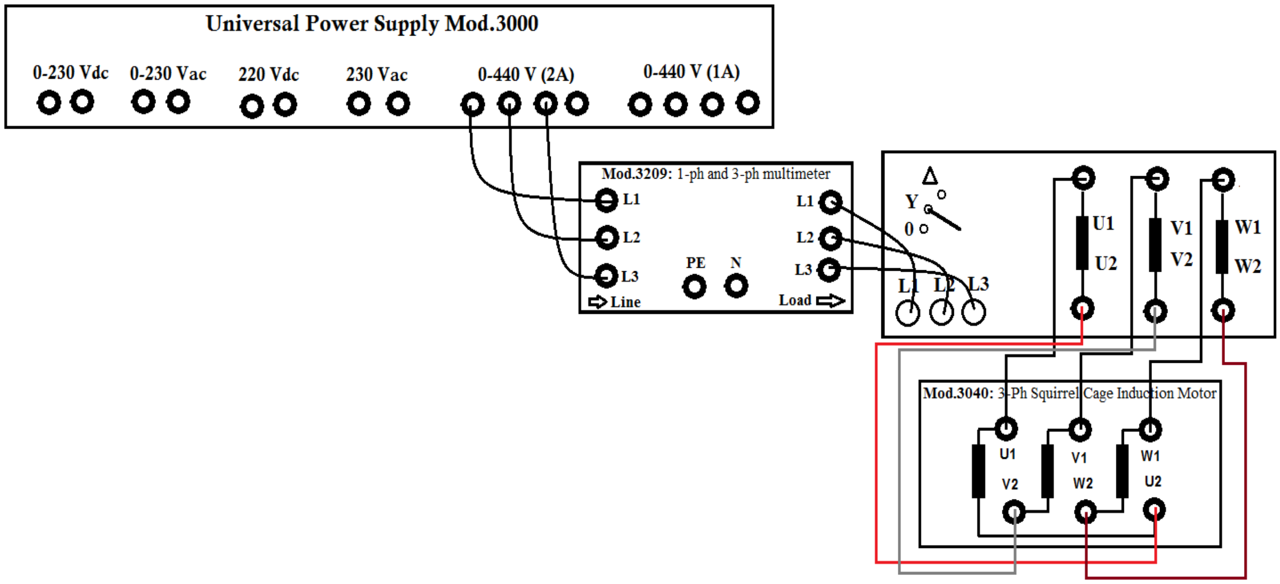


Figure (8)

Part X: Three phase squirrel cage Induction Motor with Autotransformer Starter.

1. Make the connection as shown in Figure 4.
2. Put the knob of starter on 25 % tap position and instantly note down the initial current.
3. When motor attain the rated speed note down the voltage, current and speed of the motor.
4. Follow the same procedure for 50 % tap and 100 % tap.
5. Switch OFF the power supply and disconnect the motor

Condition	Starting Current	Steady State Current	Line Voltage	Speed
25%				
50%				
100%				

Part XI: External characteristics of the Three-Phase Squirrel Cage Induction Motor.

1. Make the mechanical coupling between the squirrel cage Induction Motor and break unit.
2. Connect the circuit as shown in Figure 9.
3. Apply a line voltage of 400-V at the terminals of the induction motor and run the motor at no load condition.
4. Vary the meachanical load connected to the shaft of the motor by changing the dc voltage applied to the break unit.
5. Measure the speed, voltage applied to the motor, current and power absorbed by the motor and the Power Factor at each value of the torque of load, use ItalTec Software.

6. Calcultae the output power, you may use the following relation:

   Pout = τ (N.m) * ω (rad/sec) = (τ (g.m) *(10/1000)) * (2*3.14*n (rpm)/60))

7. Calculate the efficiency of the motor, you may use the following relation:

   η = Pout/Pin *100%

8. Calculate the Speed regulation of the motor, you may use the following relation:

   $SR = n_{nl} - n_{fl} / n_{fl}$ *100%

9. Tabulate the results in the following table.

Motor					**Break unit**	**Calculations**		
Speed (rpm)	Line Voltage	Line Current	Pin	PF	Torque (gr.m)	Pout	η	SR
	400				5			
	400				10			
	400				20			
	400				30			
	400				40			
	400				50			
	400				60			
	400				70			
	400				80			
	400				90			
	400				100			

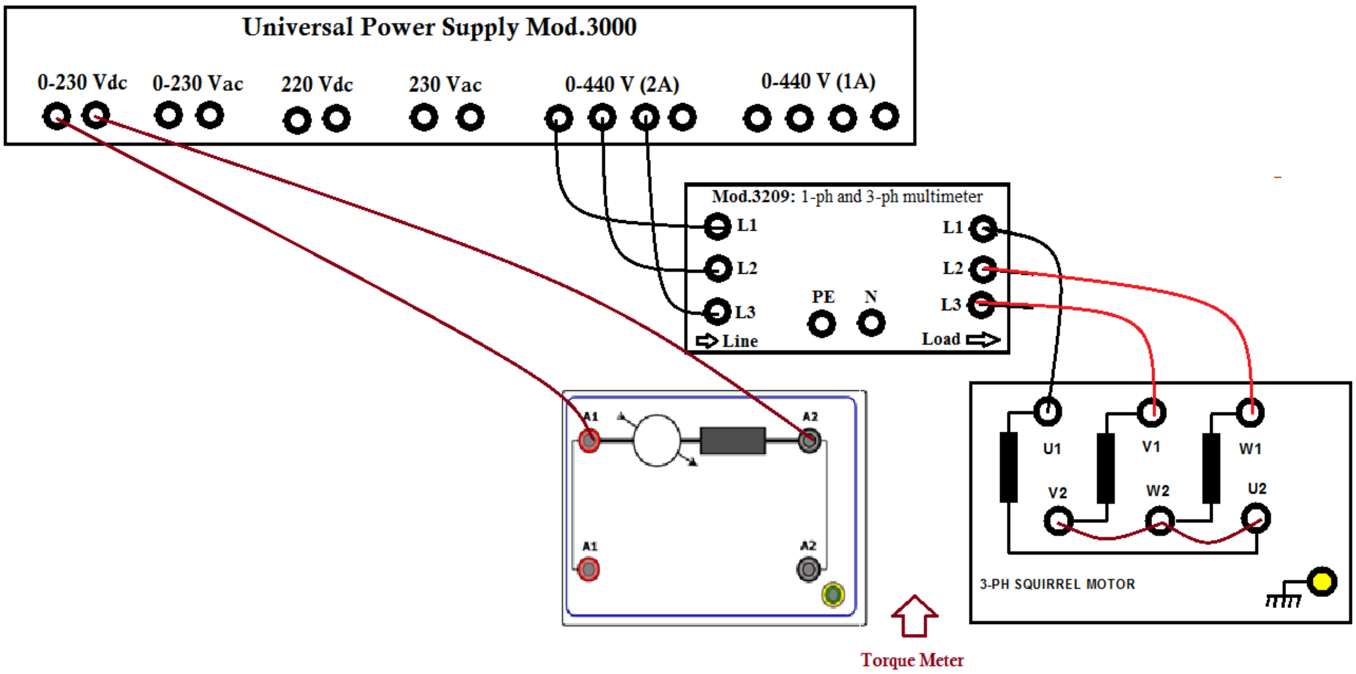


Figure (9)

10. Plot and explain the **mechanical characteristics** of the 3-ph Squirrel Cage IM.
(Torque (Y-axis) vs Speed (X-axis))

11. Plot and explain the **electromechanical characteristics** of the 3-ph Squirrel Cage IM.
X-axis: Output Power
Relations:

- Efficiency (Y-axis)
- Speed (Y-axis)
- Current (Y-axis)
- PF (Y-axis)

Questions:

1. Is 3-phase Induction Motor Self-starting or not, why?

2. Discuss the reason why the phase current with star connection is lower than the same current measured with delta connection.

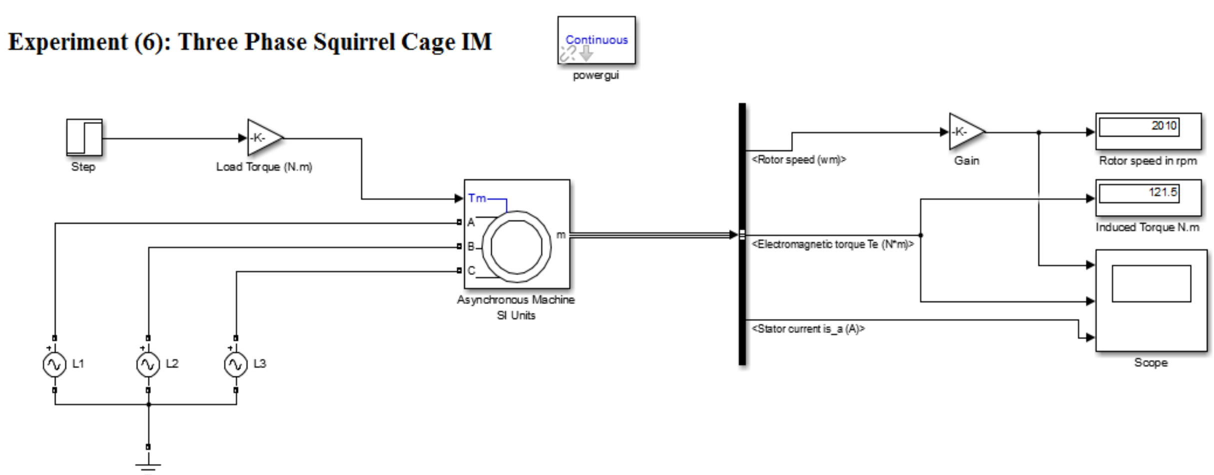
3. If you want to change the direction of a three phase rotating machine that is rotating in forward direction, you interchange two phases. Discuss.

4. A 208-V six-pole Y-connected 25-hp induction motor is tested in the laboratory, with the following results:
   No load: 208 V, 24.0 A, 1400 W, 60 Hz
   Locked rotor: 24.6 V, 64.5 A, 2200 W, 15 Hz
   Dc test: 13.5 V, 64 A
   Find the equivalent circuit of this motor.

5. State the advantage and disadvantage of each starter and Compare between them.

Matlab Section

Use **MATLAB SIMULINK** to build the following circuit to simulate a 3-ph SCIM.



<u>Hints:</u> Put the motor's settings into MATLAB with using the nameplate of the motor.
Use the default values of the main and auxiliary windings parameters.

(a) At starting with no-load condition, obtain the speed curve and the stator current waveform (phase a). Set the simulation time to **0.3 sec**. Set the step time to **5 sec**.

(b) Start to change the load torque in steps (20, 50, 75 and 100 N.m), at each step record the value of rotor speed and induced torque and then draw the torque speed characteristics of the motor. Set the simulation time to **10 sec.**

Experiment (6)	Three-Phase Slip Ring Induction Motor

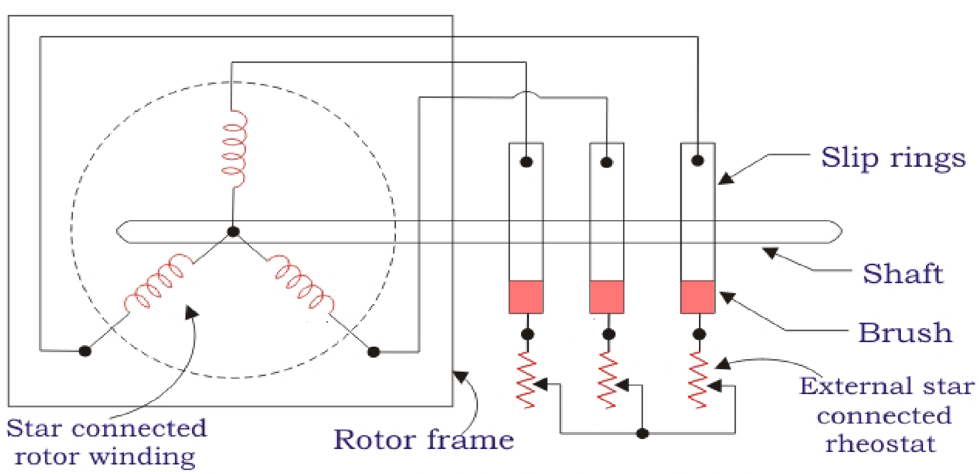
Objectives:

1. To familiarize with three-phase Slip Ring Induction Motor components.
2. To investigate different characteristics (torque, speed, current, power, power factor and efficiency) of three-phase Slip Ring Induction Motor.
3. To demonstrate how to reverse the direction of rotation of three-phase Slip Ring Induction Motor.
4. To understand how to control the speed of the three-phase Slip Ring Induction Motors using slip control method.
5. Understand Slip Ring Induction Motors ratings.

Theory and concepts:

Slip Ring or Wound Rotor Motor

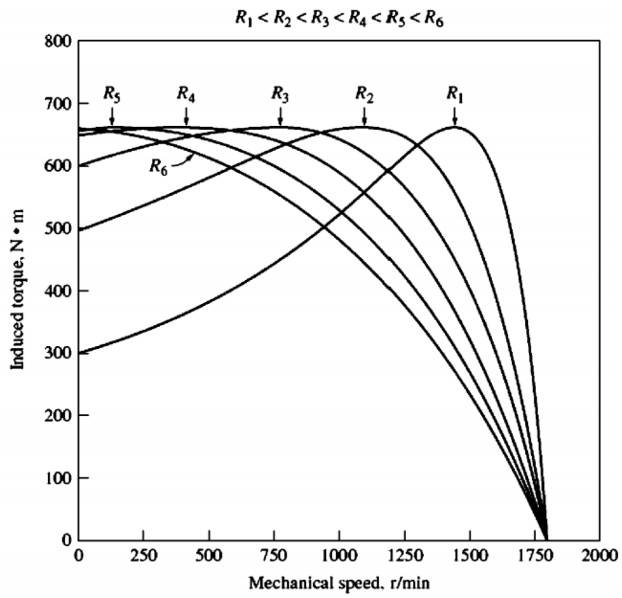
The slip ring or wound rotor motor is an induction machine where the rotor comprises a set of coils that are terminated in 3 slip-rings to which 3 external optional impedances can be connected. The stator is similar as is used with a standard squirrel cage motor. By changing the impedance connected to the rotor circuit, the speed/current and speed/torque curves can be modified in order to get many interesting advantage and benefits that we're going to explain below. **The slip ring motor is used primarily to start a high inertia load or a load that requires a very high starting torque across the full speed range.**



Slip Ring Three Phase Induction Motor

By correctly selecting the resistors used in the slip ring starting resistance, the motor is able to produce maximum torque at a relatively low current, from low speed to full speed. A secondary use of the slip ring motor, is to provide a means of **speed control**. Because the torque curve of the motor is effectively modified by the resistance connected to the rotor circuit, the speed of the motor can be varied.

Increasing the value of resistance on the rotor circuit will move down the 'maximum torque speed'. If the resistance connected to the rotor is increased beyond the point where the maximum torque occurs, the torque will be further reduced. When used with a load that has a torque curve that increases with speed, the motor can operate at the speed where the torque developed by the motor is equal to the load torque The torque-speed characteristic for a wound-rotor induction motor is shown in the following Figure.



Reducing the load will cause the motor to speed up, and increasing the load will cause the motor to slow down until the load and motor torque are equal. Operated in this manner is possible to control speed, the slip losses are dissipated in the resistors connected to slip rings.

However use of a frequency inverter is the best solution for speed control and soft starting of the three-phase asynchronous motor.

If a rotor is designed with high resistance, then the motor 's starting torque is quite high, but the slip is also quite high at normal operating conditions. Pconv = (1-s)P_{AG}, so the higher the slip, the smaller the fraction of air-gap power actually converted to mechanicalfonn, and thus the lower the motor's efficiency.

A motor with high rotor resistance has a good starting torque but poor efficiency at normal operating conditions. On the other hand, a motor with low rotor resistance has a low starting torque and high starting current, but its efficiency at normal operating conditions is quite high.

Starting Resistors

Resistance that are applied to the rotor circuit is gradually reduced in value as the motor accelerates to full speed. The rotor would normally be shorted out once the motor is at full speed. The resistor values have to be selected to provide the torque profile required and are sized to dissipate the slip power during start. The resistors can be metallic resistors such as wound resistors, and able to provide sufficient thermal mass to absorb the total slip loss during start. To select the values of the resistors, you need to know the frame voltage and the short circuit current.

Starting Current

If the slip motor is started with all the slip rings or the rotor terminals shorted, like a normal induction motor, then **it suffers extremely high locked rotor current**, ranging up to 100%, accompanied with very low locked rotor torque as low as 60%. It is not advised to start a slip ring induction motor with its rotor terminals shorted but using starting rheostats or an inverter.

Necessary Material:

1. **Mod.3000:** Universal Power Supply
2. **Mod.3050:** 3-Ph Slip Ring Induction Motor
3. **Mod.3180:** Electromagnetic Break
4. **Mod.3203:** DC digital VAW
5. **Mod.3209:** 1-ph and 3-ph multimeter
6. **Mod.3180C:** Torque and speed meter

Experimental Procedures:

Part I: Specifications of the Three-Phase Slip Ring Induction Motor.

1. Read the nameplate of the Three-Phase Slip Ring Induction Motor and then tabulate the rating values of the motor in the following table:

Name Plate of the Three-Phase Slip Ring Induction Motor Mod.3050						
Voltage:	Y		Δ		Power:	
Current:	Y		Δ		Speed:	
Frequency:		Poles:			PF:	
Duty Cycle:					Ingress Protection:	
Insulation Class:						

Part II: Running the motor under no-load condition with Star connection.

1. Connect the circuit as shown in figure 1.
2. Apply a 3-phase voltage of 400-V at the terminals of the induction motor and run the motor.
3. Measure the speed at no-load condition, the starting current and the steady state current drawn by the motor.
4. Tabulate your results in the following table.

Condition	Speed	Starting Current	Steady State Current
No-load (Y-connection)			

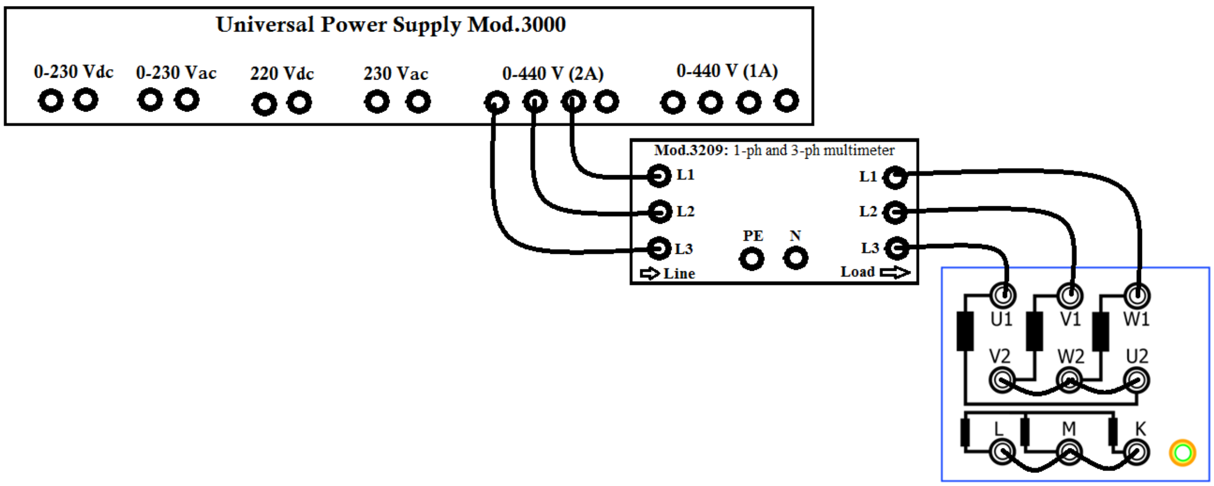


Figure (1)

Part III: Running the motor under no-load condition with Delta connection.

1. Connect the circuit as shown in figure 2.
2. Apply a 3-phase voltage of 230-V at the terminals of the induction motor and run the motor.
3. Measure the speed at no-load condition, the starting current and the steady state current drawn by the motor.
4. Tabulate your results in the following table.

Condition	Speed	Starting Current	Steady State Current
No-load (Δ-connection)			

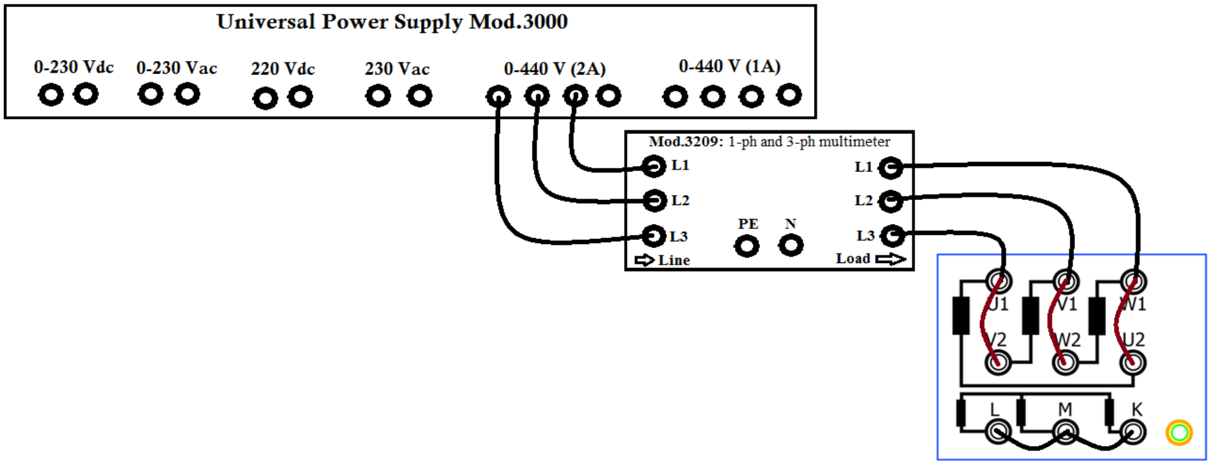


Figure (2)

Part VI: Reversing the direction of the Three-Phase Slip Ring Induction Motor.

1. Connect the circuit as shown in figure 3.
2. Apply a 3-phase voltage of 400-V at the terminals of the induction motor and run the motor, Observe the direction of rotation of the motor.
3. Now with two phases interchanged L2 and L3, Observe the direction of rotation of the motor.
4. Tabulate your result in the following table.

Lines			Direction (CW,CCW)
L1	L2	L3	
L1	L3	L2	

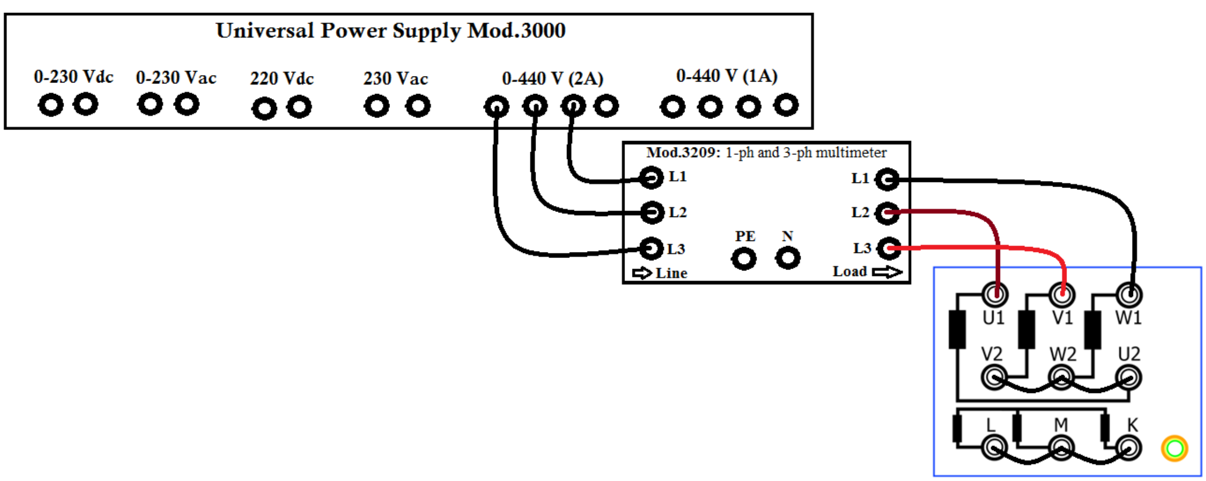


Figure (3)

Part V: Three-Phase Slip Ring Induction Motor with starting rheostat.

1. Connect the motor as shown in the Figure 4 and supply the motor directly on line 400V with the starting rheostat completely inserted (R_{MAX}).Read the currents measured in the ammeters.
2. Decrease gradually the ohmic value (pass at 2/3 position). Read and note the currents measured in the ammeters and note the speed variation.
3. Decrease again the ohmic value (pass at 1/3) position. Read and note the currents measured in the ammeters and note the speed variation
4. Decrease again the ohmic value up to obtain the short circuit of V2-W2-U2.
5. Tabulate your results in the following table.

Rheostat	Line Current	Rotor Current	Speed	Notes
R = Rmax				
R = 2/3 Rmax				
R = 1/3 Rmax				
R = 0 (short circuit)				

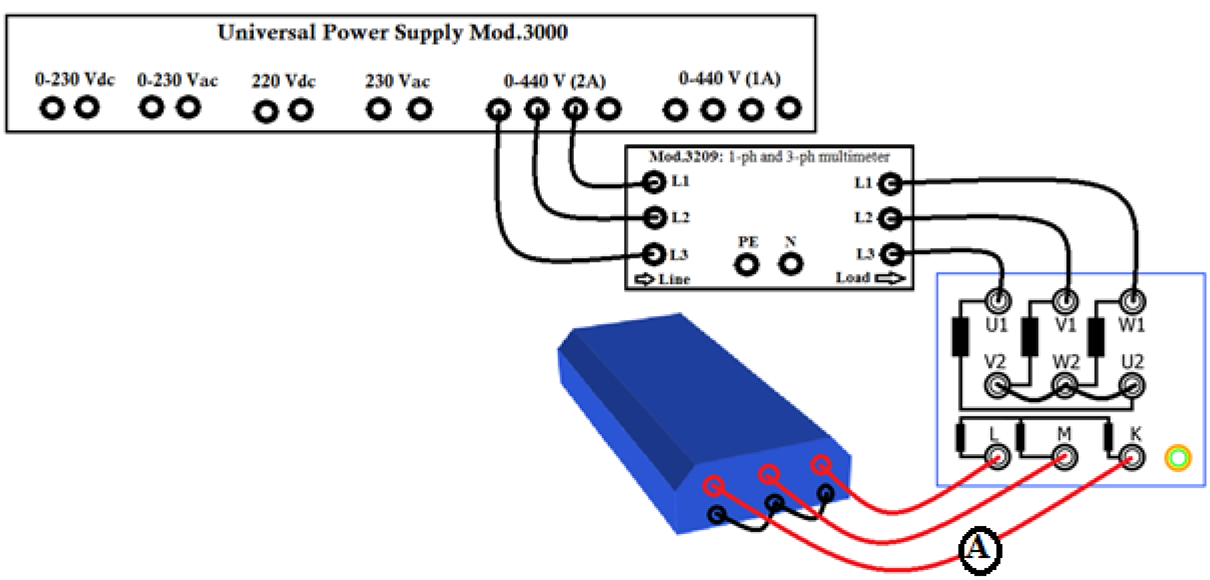


Figure (4)

Part VI: External characteristics of the Three-Phase Slip Ring Induction Motor.

1. Make the mechanical coupling between the Slip Ring Induction Motor and break unit.
2. Connect the circuit as shown in Figure 5.
3. Apply a line voltage of 400-V at the terminals of the induction motor and run the motor at no load condition.
4. Vary the meachanical load connected to the shaft of the motor by changing the dc voltage applied to the break unit.

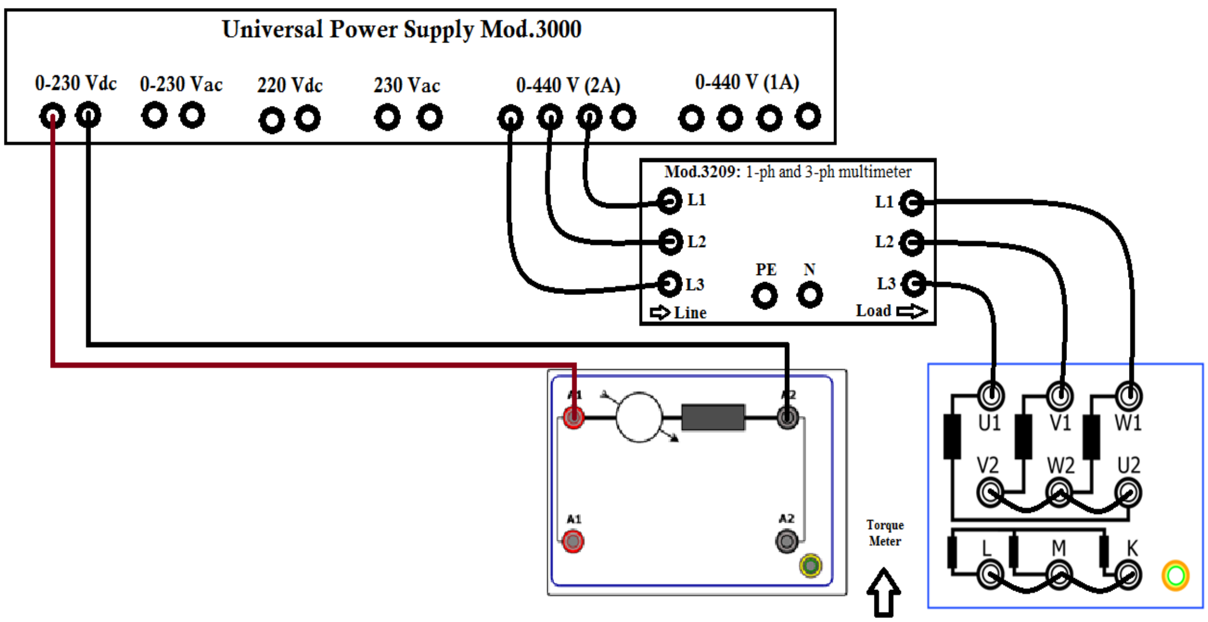


Figure (5)

5. Measure the speed, voltage applied to the motor, current and power absorbed by the motor and the Power Factor at each value of the torque of the load <u>use ItalTec Software</u>.
6. Calcultae the output power, you may use the following relation:

   Pout = τ (N.m) * ω (rad/sec) = (τ (g.m) *(10/1000)) * (2*3.14*n (rpm)/60))

7. Calculate the efficiency of the motor, you may use the following relation:

   η = Pout/Pin *100%

8. Calculate the Speed regulation of the motor, you may use the following relation:

   SR = $n_{nl} - n_{fl} / n_{fl}$ ***100%**

9. Tabulate the results in the following table.

Motor					Break unit	Calculations		
Speed (rpm)	Line Voltage	Line Current	Pin	PF	Torque (gr.m)	Pout	η	SR
	400				5			
	400				10			
	400				20			
	400				30			
	400				40			
	400				50			
	400				60			
	400				70			
	400				80			
	400				90			
	400				100			

10. Plot and explain the **mechanical characteristics** of the 3-ph Slip Ring IM.
(Torque (Y-axis) vs Speed (X-axis))

11. Plot and explain the **electromechanical characteristics** of the 3-ph Slip Ring IM.
X-axis: Output Power
Relations:
- Efficiency (Y-axis)
- Speed (Y-axis)
- Current (Y-axis)
- PF (Y-axis)

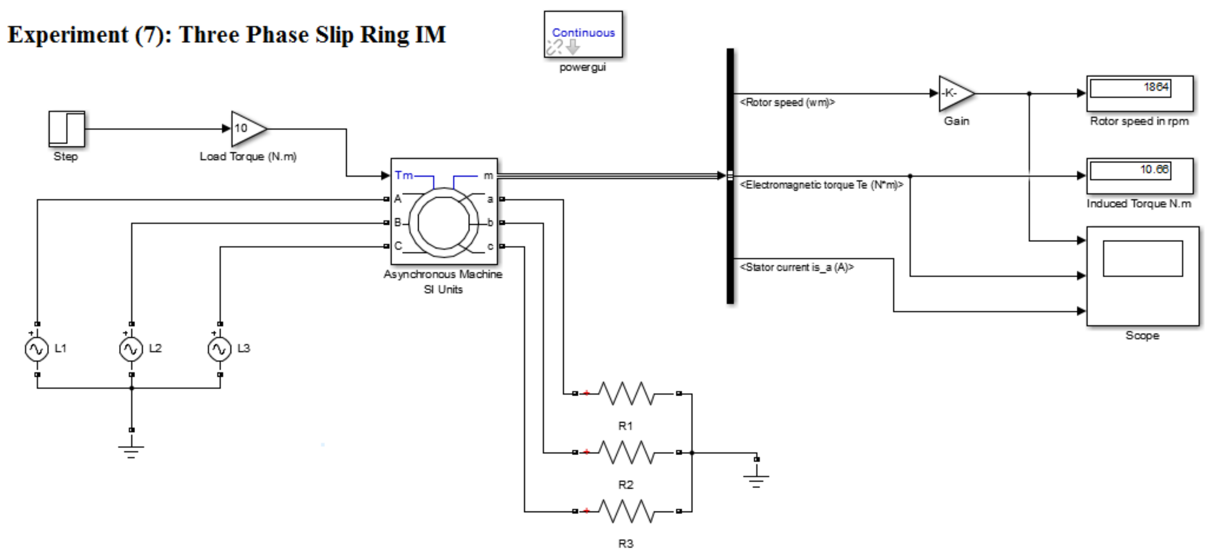
Questions:

1. Describe how the rotor resistance controlling the speed of Slip Ring induction motors.

2. It is not advised to start a slip ring induction motor with its rotor terminals shorted but using starting rheostats or an inverter. Discuss.

Matlab Section

Use **MATLAB SIMULINK** to build the following circuit to simulate a 3-ph SRIM.



Hints: Put the motor's settings into MATLAB with using the nameplate of the motor.
Use the default values of the main and auxiliary windings parameters.

Start to change the rotor resistance in steps (0, 1, 3, 5 and 10Ω) at each step record the value of rotor speed and starting current to determine the effect of this resistance on the operation and performance of the motor.

For the starting: Set the simulation time to **5 sec**. Set the step time to **10 sec**.

Part 3

Three Phase Synchronous Machines

Experiment (7)	Synchronous Generator

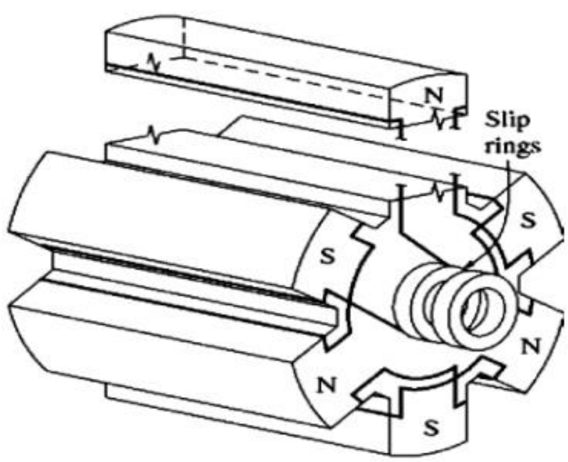
Objectives:

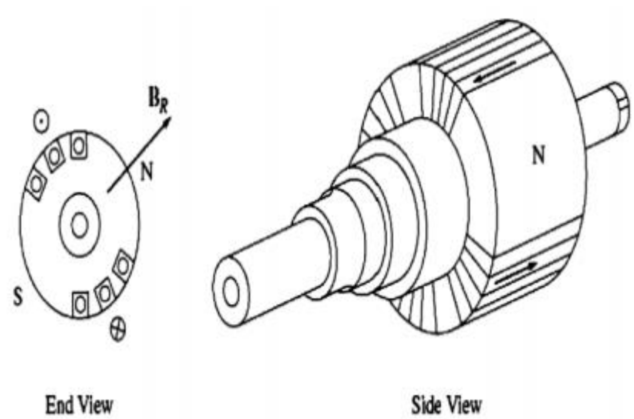
1. Mastering the exact procedures required for generator's starting and stop and their exact sequence.
2. To obtain the equivalent circuit of the three-phase Synchronous Generator from winding resistance, open-circuit and short-circuit tests.
3. To understand how terminal voltage varies with different loads in a synchronous generator operating alone.
4. To determine the voltage regulation of a synchronous generator under different loads.
5. To understand the regulation characteristic required to compensate the terminal voltage of the synchronous generator loaded with various loads.

Theory and concepts:

In a synchronous generator, a dc current is applied to the rotor winding, which produces a rotor magnetic field. The rotor of the generator is then turned by a prime mover, producing a rotating magnetic field within the machine. This rotating magnetic field induces a three-phase set of voltages within the stator windings of the generator.

Non-salient-pole rotors are normally used for two- and four-pole rotors, while salient pole rotors are normally used for rotors with four or more poles.

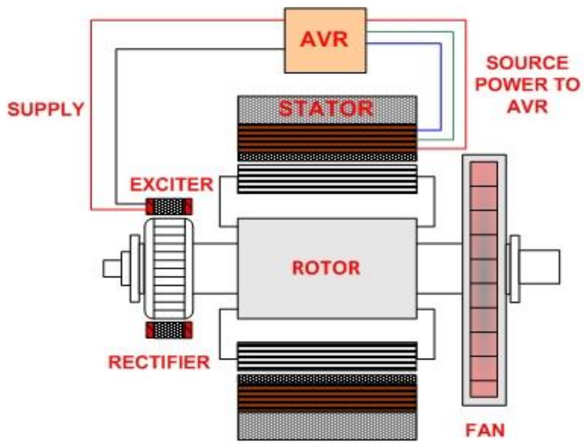


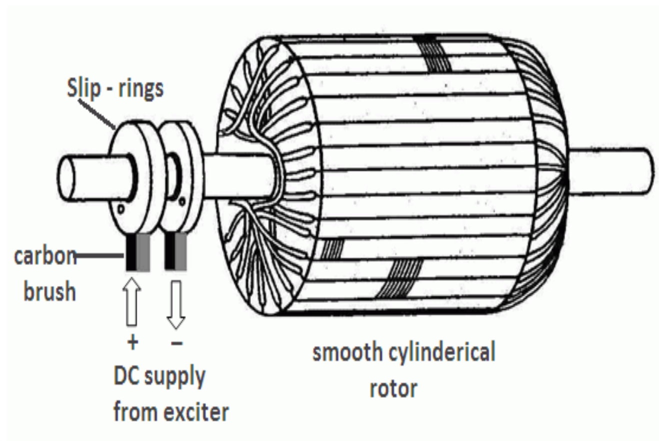


A nonsalient two-pole rotor for a synchronous machine.

A dc current must be supplied to the field circuit on the rotor. Since the rotor is rotating, a special arrangement is required to get the de power to its field windings. There are two common approaches to supplying this dc power:

1. Supply the dc power from an external dc source to the rotor by means of slip rings and brushes.
2. Supply the dc power from a special dc power source mounted directly on the shaft of the synchronous generator



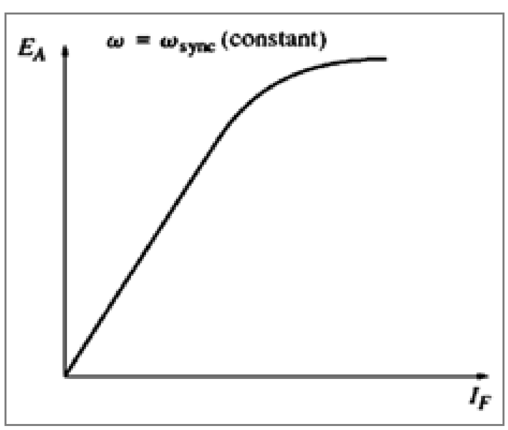


Synchronous generators are by definition synchronous, meaning that the electrical frequency produced is locked in or synchronized with the mechanical rate of rotation of the generator. The rate of rotation of the magnetic fields in the machine is related to the stator electrical frequency by Equation

$$f_e = \frac{n_m P}{120}$$

The internal generated voltage E_A is directly proportional to the flux and to the speed, but the flux itself depends on the current flowing in the rotor field circuit. The field circuit I_F is related to the flux Φ. Since E_A is directly proportional to the flux, the internal generated voltage E_A is related to the field current the magnetization curve or the open-circuit characteristic of the machine is shown in the following figure.

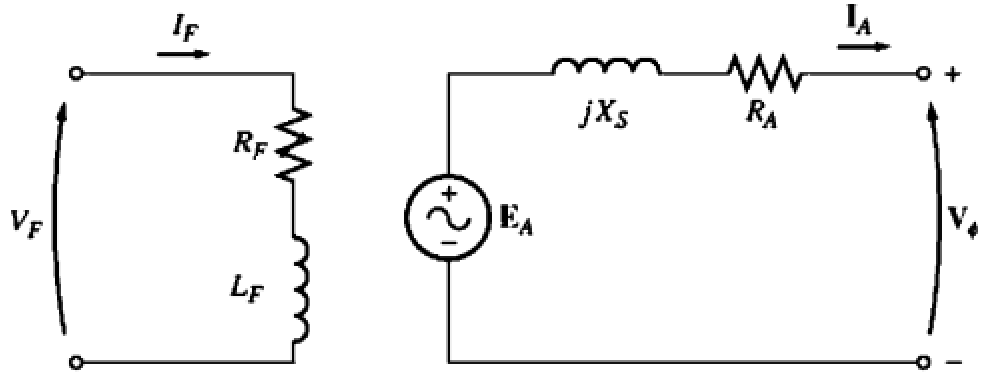
$$E_A = K\phi\omega$$



Measuring Synchronous Generator Model Parameters

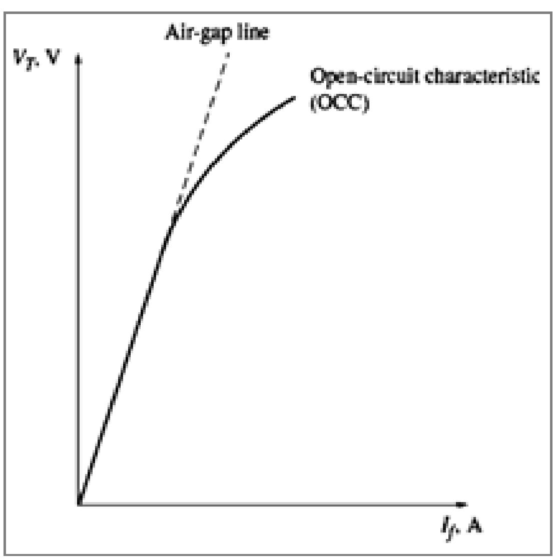
The equivalent circuit of a synchronous generator (as shown in the following figure) that has been derived contains three quantities that must be determined in order to completely describe the behavior of a real synchronous generator:

1. The relationship between field current and flux.
2. The relationship between the field current and $E_{A.}$
3. The synchronous reactance and armature resistance.

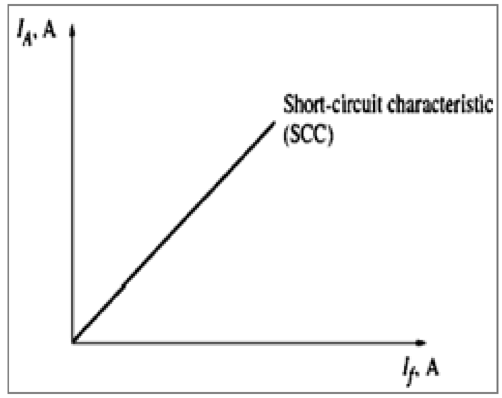


Open-Circuit Test

To perform this test, the generator is turned at the rated speed, the terminals are disconnected from all loads, and the field current is set to zero. Then the field current is gradually increased in steps, and the terminal voltage is measured at each step along the way. With the terminals open, $I_A = 0$, so E_A is equal to V_Φ. It is thus possible to construct a plot of E_A or V_T versus I_f from this information. This plot is the so-called **open-circuit characteristic (OCC) of a generator.** With this characteristic, **it is possible to find the internal generated voltage of the generator for any given field current**. A typical open-circuit characteristic is shown in the following Figure.



Short-Circuit Test



To perform the short-circuit test, adjust the field current to zero again and short-circuit the terminals of the generator through a set of ammeters. Then the armature current I_A or the line current I_L is measured as the field current is increased. Such a plot is called a **short-circuit characteristic (SCC)** and is shown in The following figure.

the internal machine impedance is given by

$$Z_S = \sqrt{R_A^2 + X_S^2} = \frac{E_A}{I_A} \qquad X_S \approx \frac{E_A}{I_A} = \frac{V_{\phi,oc}}{I_A} \quad X_S >> R_A$$

If E_A and I_A are known for a given situation, then the synchronous reactance X_S can be found.

Therefore, an approximate method for determining the synchronous reactance Xs at a given field current is

1. Get the internal generated voltage E_A from the OCC at that field current.
2. Get the short-circuit current now I_{Asc} at that field current from the SSC.
3. Find X_s

Winding Resistance Test:

If it is important to know a winding's resistance as well as its synchronous reactance, the resistance can be approximated by applying a dc voltage to the windings while the machine is stationary and measuring the resulting current flow. The use of dc voltage means that the reactance of the windings will be zero during the measurement process.

Synchronous Generator Operating Alone

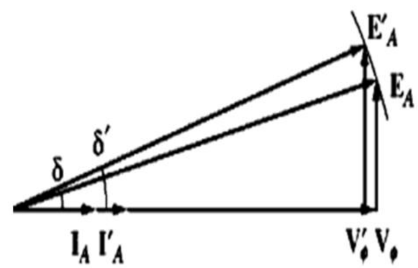
The behavior of a synchronous generator under load varies greatly depending on the power factor of the load and on whether the generator is operating alone or in parallel with other synchronous generators.

The Effect of Load Changes on a Synchronous Generator Operating Alone

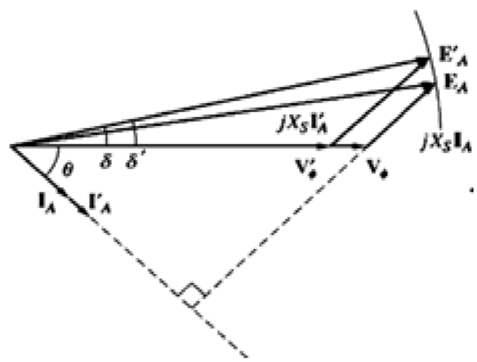
To understand the operating characteristics of a synchronous generator operating alone, examine a generator supplying a load. A diagram of a single generator supplying a load is shown in the following Figure. **What happens when we increase the load on this generator?**

An increase in the load is an increase in the real and/or reactive power drawn from the generator. Such a load increase increases the load current drawn from the generator.

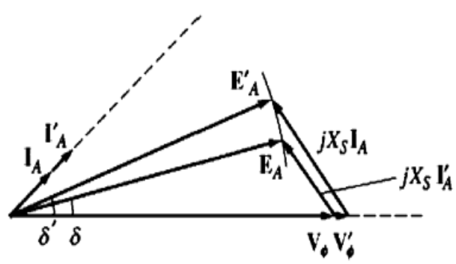
First, examine a generator operating at a lagging power factor. If more load is added at the same power factor, then $|I_A|$ increases but remains at the same angle Θ with respect to V_Φ. It is seen that as the load increases, the voltage V_Φ decreases rather sharply.



Now suppose the generator is loaded with unity-power-factor loads. What happens if new loads are added at the same power factor? It can be seen that this time V_Φ decreases only slightly.



Finally, let the generator b e loaded with leading-power-factor loads. If new loads are added at the same power factor this time, an increase in the load in the generator produced an increase in the terminal voltage. Such a result is not something one would expect on the basis of intuition alone.



General conclusions from this discussion of synchronous generator behavior are

1. If **lagging loads** (+ Q or inductive reactive power loads) are added to a generator, V_Φ and the **terminal voltage V_T decrease significantly.**
2. If **unity-power-factor loads** (no reactive power) are added to a generator, there is a **slight decrease in V_Φ and the terminal voltage.**
3. If **leading loads** (-Q or capacitive reactive power loads) are added to a generator, V_Φ and the **terminal voltage V_T will rise.**

Voltage Regulation

A convenient way to compare the voltage behavior of two generators is by their voltage regulation. The voltage regulation (VR) of a generator is defined by the equation:

$$VR = \frac{V_{nl} - V_{fl}}{V_{fl}} \times 100\%$$

where V_{nl} is the no-load voltage of the generator and V_{fl} is the full-load voltage of the generator. A synchronous generator operating at a **lagging power factor** has a **fairly large positive voltage regulation,** a synchronous generator operating at a **unity power factor** has a **small positive voltage regulation**, and a synchronous generator operating at a **leading power factor often** has a **negative voltage regulation.**

Regulation Characteristics of a Synchronous Generator

Normally, it is desirable to keep the voltage supplied to a load constant, even though the load itself varies. How can terminal voltage variations be corrected for?

The obvious approach is to vary the magnitude of E_A, to compensate for changes in the load. Recall that $E_A = K\Phi\omega$. Since the frequency should not be changed in a normal system, E_A must be controlled by varying the flux in the machine.

For example, suppose that a lagging load is added to a generator. Then the terminal voltage will fall. To restore it to its previous level, decrease the field resistor R_F. If R_F decreases, the field current will increase. An increase in I_F increases the flux, which in turn increases E_A and an increase in E_A increases the phase and terminal voltage.

Necessary Material:

1. **Mod.3000:** Universal Power Supply
2. **Mod.3070:** 3-Ph Synchronous Machine
3. **Mod.3160:** Compound DC Motor
4. **Mod.3203:** DC digital VAW
5. **Mod.3209:** 1-ph and 3-ph multimeter
6. **Mod.3020-R:** Resistive Load
7. **Mod.3020-L:** Inductive Load
8. **Mod.3020-C:** Capacitive Load

Experimental Procedures:

Part I: Specifications of the Three-Phase Synchronous Generator.

1. Read the nameplate of the Three-Phase Synchronous Generator and then tabulate the rating values of the generator in the following table:

Name Plate of the Three-Phase Synchronous Machine Mod.3070						
Voltage:	Y		Δ		Power:	
Current:	Y		Δ		Speed:	
Excitation voltage:					Excitation current:	
Frequency:			Poles:		PF:	
Duty Cycle:					Ingress Protection:	
Insulation Class:						

Part II: Winding Resistance Test/DC Test.

1. Connect the circuit as shown in figure 1.
2. Apply a dc voltage of 10-V to the winding of phase U then measure the current flow.
3. Repeat step 2 to phases V and W.
4. Calculate the armature resistance by using the following equation:
   $R_A = \frac{RU + RV + RW}{3}$
5. Repeat same steps (step 1 and 2) to measure the field resistance R_F.

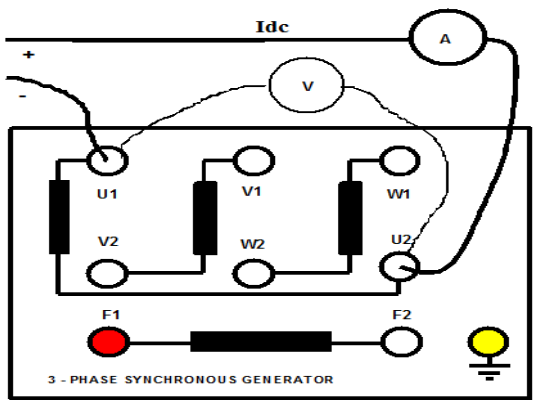


Figure (1)

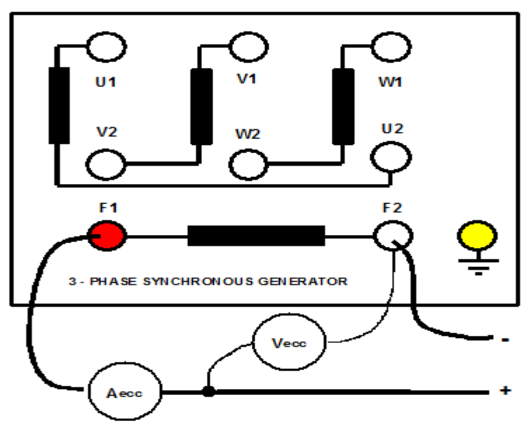


Figure (2)

Winding	Voltage	Current	$R_{(Phase)} = V/I$
U			
V			
W			
Field winding			

Part III: Open-Circuit Test of the Synchronous Generator

1. Make the mechanical coupling between the DC Motor and Synchronous Generator.
2. Connect the circuit as shown in figure 3.
3. Make sure the terminals are disconnected from all loads and the field current is set to zero.
4. Apply a DC voltage of 220-V at the terminals of the DC Compound Motor and run the motor to obtain a speed of 3000 rpm.
5. **Gradually** start to increase the field current in steps to match the requirements of the following table.
6. In each step measure the terminal voltage of the synchronous generator using voltmeter.
7. Tabulate your results in the following table.
8. Plot the OCC of the synchronous generator.

Excitation Current (A)	Output Voltage (phase) (V)	Speed (rpm)
0.05		3000
0.10		
0.15		
0.20		
0.25		
0.30		
0.35		
0.40		

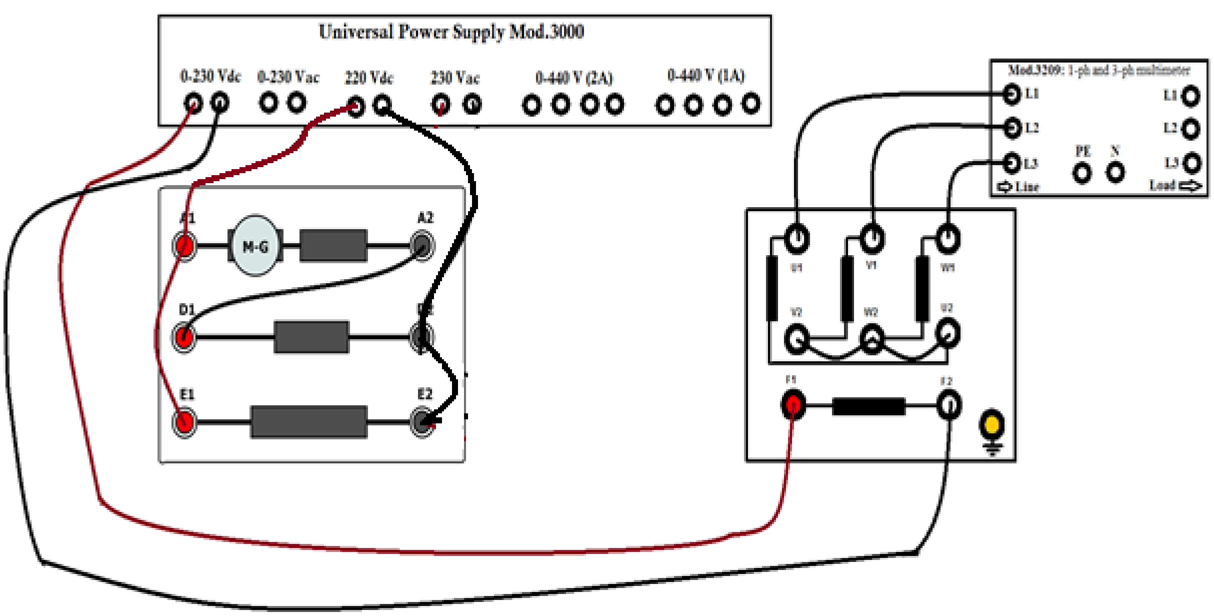


Figure (3)

Part IV: Short-Circuit Test of the Synchronous Generator

1. Make the mechanical coupling between the DC Motor and Synchronous Generator.
2. Connect the circuit as shown in figure 4.
3. Make sure the terminals are disconnected from all loads and the field current is set to zero.
4. Apply a DC voltage of 220-V at the terminals of the DC Compound Motor and run the motor to obtain a speed of 3000 rpm.
5. **Gradually** start to increase the field current in steps to match the requirements of the following table.
6. In each step measure the armature current of the synchronous generator using Ammeter and then calculate the value of the internal machine impedance |Zs|.
7. Tabulate your results in the following table.
8. Plot the SCC of the synchronous generator.

Excitation Current (A)	Armature Current (A)	Internal Machine Impedance $\lvert Z_s \rvert = V_{o.c(ph)}/I_A$	Speed (rpm)
0.05			3000
0.10			
0.15			
0.20			
0.25			
0.30			
0.35			
0.40			

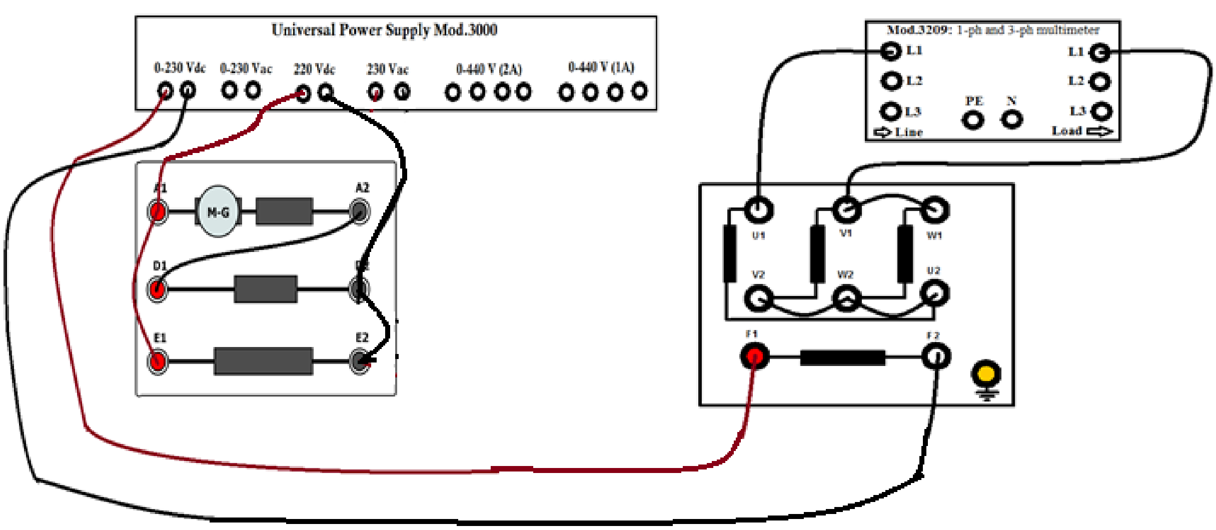


Figure (4)

9. Calculate the value of **synchronous reactance Xs** at each value of excitation current.

Part V: Study the behavior of the synchronous generator under different loads.

Part V-1: Resistive Load

1. Make the mechanical coupling between the DC Motor and Synchronous Generator.
2. Connect the circuit as shown in figure 5.
3. Make sure the terminals are disconnected from all loads and the field current is set to zero.
4. Apply a DC voltage of 220-V at the terminals of the DC Compound Motor and run the motor to obtain a speed of 3000 rpm.
5. Adjust the excitation of the synchronous generator to obtain a voltage equal to 400 V.

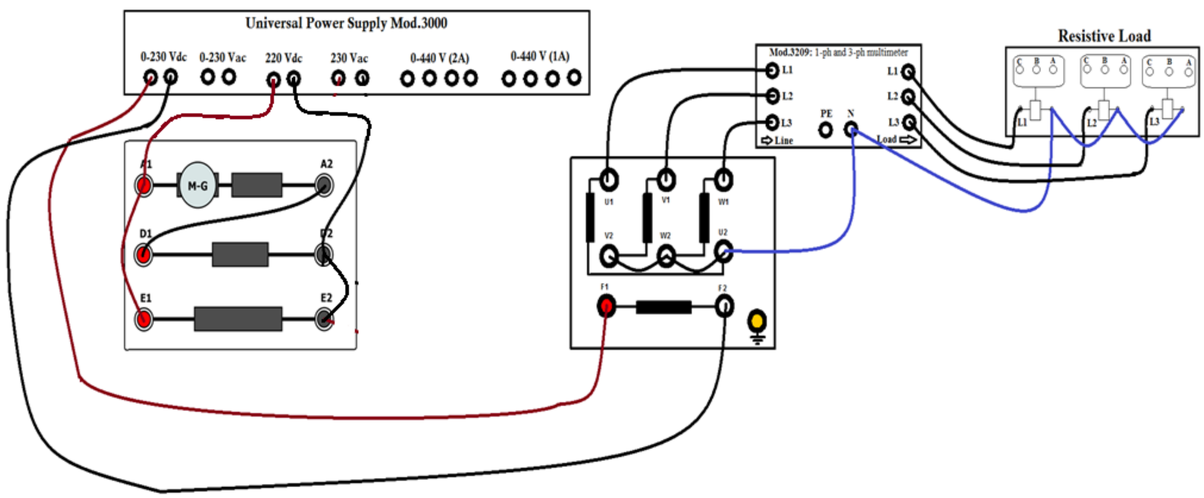


Figure (5)

6. Set the synchronous generator under load with the insertion of the resistive load (with different values of resistive load) and measure the following using the power analyzer:
   (a) Current drawn by the load (**I_{load}**) in **mA.**
   (b) Terminal voltage of the synchronous generator (**V_T**) in **V.**
   (c) Power consumed by the load **(P)** in **W**.
7. Calculate the voltage regulation in each case.
8. Tabulate your result in the following table.

Resistive Load in Ω		I_{load} (mA)	V_T (V)	P (W)	VR%
No-Load		0	400.0	0	--
A	3174				
B	1587				
A||B	1058				
C	794				
A||C	635				

Part IV-2: Resistive-Inductive Load

1. Switch off all loads and set the no-load voltage at 400V.
2. Connect the circuit as shown in figure 6.
3. Set the synchronous generator under load with the insertion of the resistive-inductive load (with different values of inductive load) and measure the following using the power analyzer:
   (a) Current drawn by the load (**I_{load}**) in **mA.**
   (b) Terminal voltage of the synchronous generator (**V_T**) in **V.**
   (c) Power consumed by the load **(P)** in **W**.
4. Calculate the voltage regulation in each case.

Resistive-Inductive Load		I_{load} (mA)	V_T (V)	P (W)	VR%
R (Ω)	L (mH)				
No-Load		0	400.0	0	--
A	A				
A	B				
A	A||B				
A	C				
A	A||C				

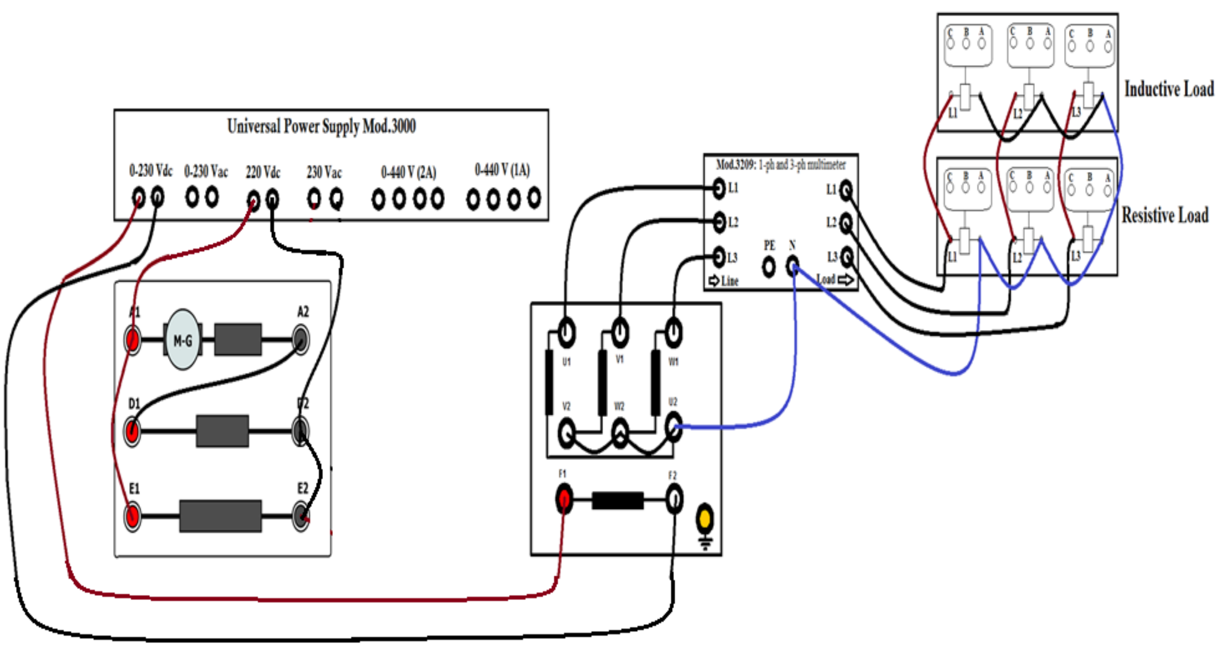


Figure (6)

Part IV-3: Resistive-Capacitive Load

1. Switch off all loads and set the no-load voltage at 300V.
2. Connect the circuit as shown in figure 7.
3. Set the synchronous generator under load with the insertion of the resistive-capacitive load (with different values of capacitive load) and measure the following using the power analyzer:
   (a) Current drawn by the load (**I_{load}**) in **mA.**
   (b) Terminal voltage of the synchronous generator (**V_T**) in **V.**
   (c) Power consumed by the load **(P)** in **W**.
4. Calculate the voltage regulation in each case.

Resistive-Capacitive Load		I_{load} (mA)	V_T (V)	P (W)	VR%
R (Ω)	C (μF)				
No-Load		0	300.0	0	--
A	A				
A	B				

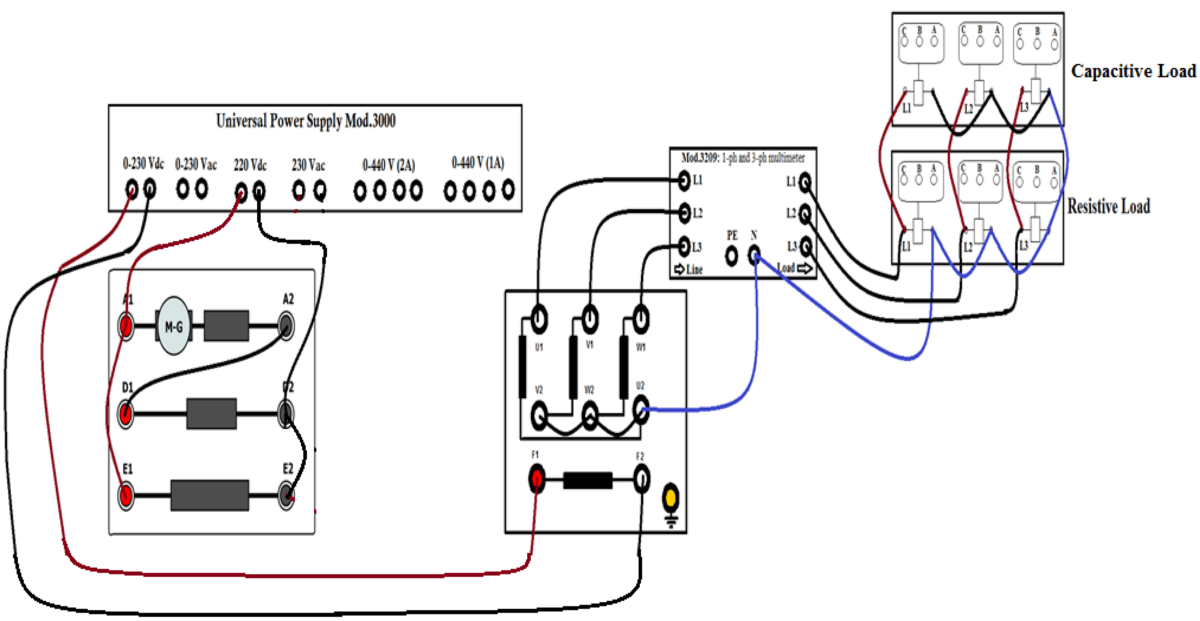


Figure (7)

Depending on the measured values from part IV answer the following question:

Sketch the terminal characteristic of this generator for different types of loads (R, R-L and R-C) (Terminal voltage versus load current).

Part V: Regulation Characteristics of a synchronous generator.

Part V-1: Output voltage regulation of a synchronous generator under RL load.

1. Set the synchronous generator under load with the insertion of the resistive-inductive load (with different values of the inductive load).
2. Connect the circuit as shown in figure 6.
3. At each load increase the excitation current to obtain a voltage equal to 400-V and then measure the following using the power analyzer:
   (a) Current drawn by the load (**I_{load}**) in **mA.**
   (b) Excitation current (**I_f**) in **mA** (use multimeter).
   (c) Power consumed by the load **(P)** in **W**.

Note: Do not let the excitation current exceed 0.40A.

Resistive-Inductive Load		I_{load} (mA)	I_f (mA)	P (W)
R (Ω)	L (mH)			
Open Circuit		0		0
A	A			
A	B			

Part V-2: Output voltage regulation of a synchronous generator under RC load.

1. Set the terminal no-load voltage at 300V.
2. Set the synchronous generator under load with the insertion of the resistive-capacitive load (with different values of the capacitive load).
3. Connect the circuit as shown in figure 7.
4. At each load decrease the excitation current to obtain a voltage equal to **300-V** and then measure the following using the power analyzer:
   (a) Current drawn by the load (**I_{load}**) in **mA.**
   (b) Excitation current (**I_f**) in **mA** (use multimeter).
   (c) Power consumed by the load **(P)** in **W**.

Note: Do not let the excitation current exceed 0.40A.

Resistive-Capacitive Load		I_{load} (mA)	I_f (mA)	P (W)
R (Ω)	C (μF)			
Open Circuit		0		0
A	A			
A	B			

Depending on the measured values from part V answer the following question:

Sketch the regulation characteristic of this generator for different types of loads (R-L and R-C) (Field current versus load current).

Questions:

1. Explain the effects of increasing loads on the terminal voltage of the synchronous generator and explain how to reduce these effects?

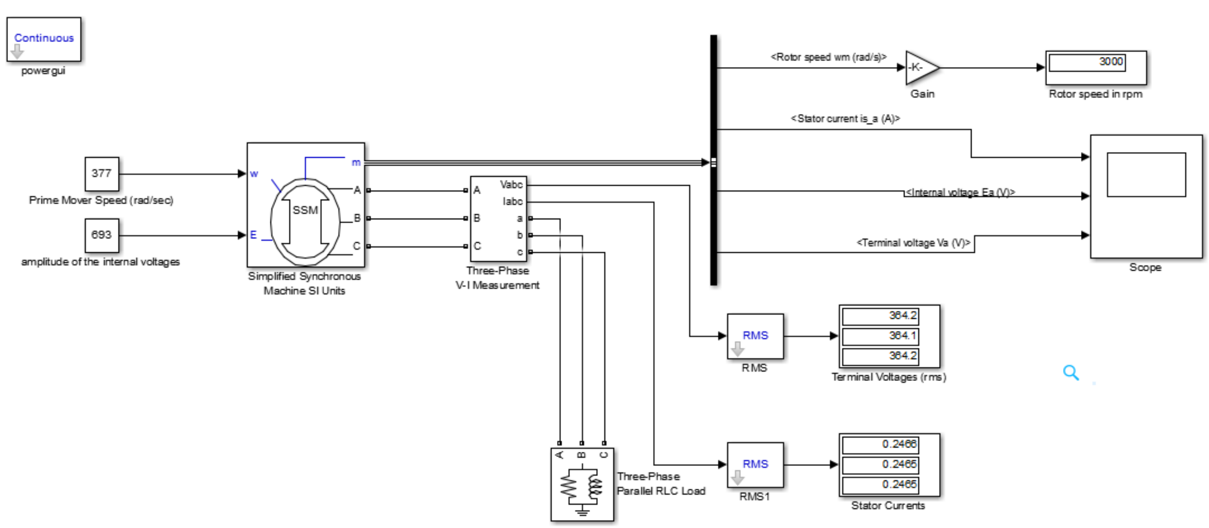
2. Show by drawing the effect of load changes on the phasor diagram of the synchronous generator with Constant Lagging PF;

Note: Use the **measured values** in this experiment to show the effect of load changes on the phasor diagram of the SG (**only 2 cases**).

Matlab Section

Use **MATLAB SIMULINK** to build the following circuit to simulate a 3-ph SG.

Experiment (8): Three Phase Synchronous Generator



<u>Hints:</u> Put the generator's settings into MATLAB with using the nameplate of the generator. Use the parameters of the equivalent circuit of the SG that determined from this experiment R_A and Xs (at $I_F = 0.3A$).

Start to change the load with steps (50W/20Var, 100W/60Var, 150W/100Var, 200W/150Var) at each step record the value of the terminal voltage and stator current then calculate the voltage regulation at each load.

Set the simulation time to **10 sec**.

Experiment (8)	Three-Phase Synchronous Motor

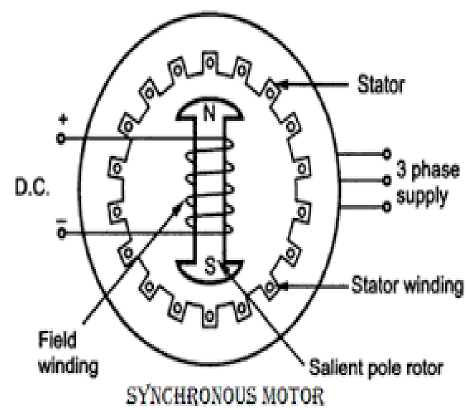
Objectives:

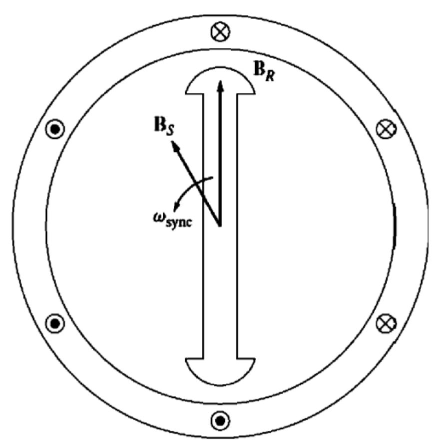
1. To familiarize with three phase Synchronous Motor components.
2. Mastering the exact procedures required for motor's starting and stop and their exact sequence.
3. To study the effect of variation of field current upon the stator current and power factor with synchronous motor running at no load, hence to draw V and inverted V curves of the motor (no-load and loaded Synchronous Motor).
4. To investigate different characteristics (torque, speed, current, power and efficiency) of the Three Phase Synchronous Motor.
5. Understand Three Phase Synchronous Motor ratings.

Theory and concepts:

Three Phase Synchronous Motor Construction

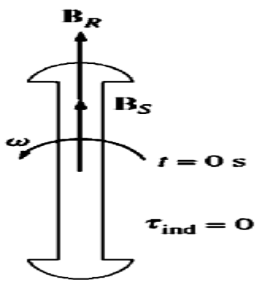
- The field current I_f of the motor produces a steady-state magnetic field B_R.
- A three-phase set of currents in an armature winding produces a uniform rotating magnetic field Bs.
- There are two magnetic fields present in the machine, and the rotor field will tend to line up with the stator field, just as two bar magnets will tend to line up if placed near each other.
- Since the stator magnetic field is rotating, the rotor magnetic field (and the rotor itself) will constantly try to catch up.
- The larger the angle between the two magnetic fields (up to a certain maximum), the greater the torque on the rotor of the machine.
- The basic principle of synchronous motor operation is that the rotor "chases" the rotating stator magnetic field around in a circle, never quite catching up with it.





Starting Synchronous Motors

To understand the nature of the starting problem, refer to Figure 1. This figure shows a 60-Hz synchronous motor at the moment power is applied to its stator windings. The rotor of the motor is stationary, and therefore the magnetic field B_R is stationary. The stator magnetic field Bs is starting to sweep around the motor at synchronous speed.

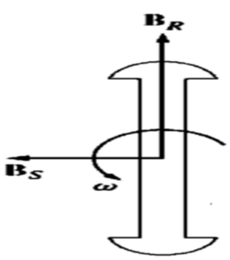


(a)

- The machine at time t = 0 s, when B_R and B_s are exactly lined up. By the induced-torque equation

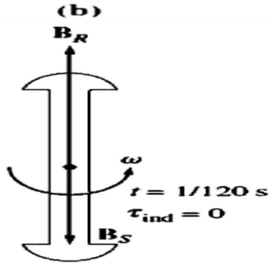
$$\tau_{ind} = k\mathbf{B}_R \times \mathbf{B}_S$$

The induced torque on the shaft of the rotor is zero.



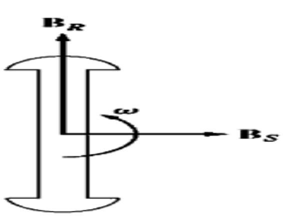
(b)

- Figure b shows the situation at time t=1/240 s. In such a short time, the rotor has barely moved, but the stator magnetic field now points to the left. By the induced-torque equation, **the torque on the shaft of the rotor is now counterclockwise**.



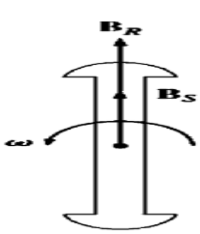
(c)

- Figure c shows the situation at time t=1/120 s. At that point BR and Bs point in opposite directions, and **Tind again equals zero.**



(d)

- At t = 3/240 s, the stator magnetic field now points to the right, and **the resulting torque is clockwise.**



- Finally, at t = 1/60 s, the stator magnetic field is again lined up with the rotor magnetic field, and $\mathbf{T_{ind} = 0}$.

During one electrical cycle, the torque was first counterclockwise and then clockwise, and the average torque over the complete cycle was zero. What happens to the motor is that it vibrates heavily with each electrical cycle and finally overheats.

Three basic approaches can be used to safely start a synchronous motor:

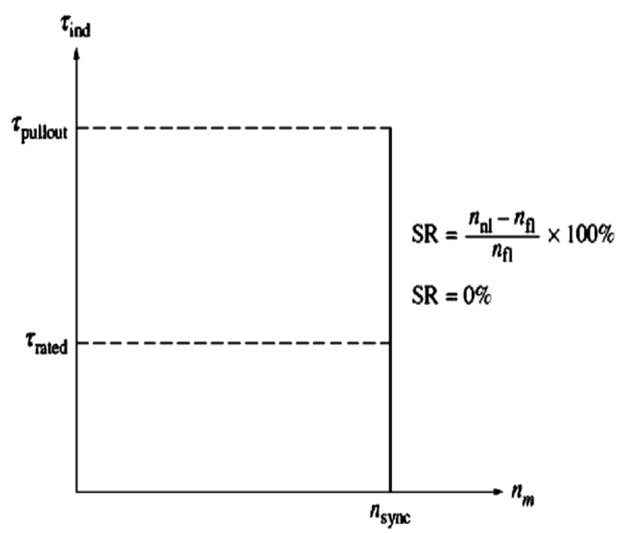
1. **Reduce the speed of the stator magnetic field to a low enough value** that the rotor can accelerate and lock in with it during one half-cycle of the magnetic field 's rotation. **This can be done by reducing the frequency of the applied electric power.**
2. **Use an external prime mover to accelerate the synchronous motor up to synchronous speed**, go through the paralleling procedure, and bring the machine on the line as a generator. Then, turning off or disconnecting the prime mover will make the synchronous machine a motor.
3. **Use damper windings**.

1. Disconnect the field windings from their dc power source and short them out.
2. Apply a three-phase voltage to the stator of the motor, and let the rotor accelerate up to near-synchronous speed. The motor should have no load on its shaft, so that its speed can approach n_{sync} as closely as possible.
3. Connect the dc field circuit to its power source. After this is done, the motor will lock into step at synchronous speed, and loads may then be added to its shaft.

The Synchronous Motor Torque-Speed Characteristic Curve

They are usually connected to power systems very much larger than the individual motors, so the power systems appear as infinite buses to the motors. This means that the terminal voltage and the system frequency will be constant regardless of the amount of power drawn by the motor. the speed of rotation of the motor is locked to the applied electrical frequency, so the speed of the motor will be constant regardless of the load.

The steady-state speed of the motor is constant from no load all the way up to the maximum torque that the motor can supply (called the pullout torque), so the speed regulation of this motor is 0 percent.



The Effect of Field Current Changes on a Synchronous Motor

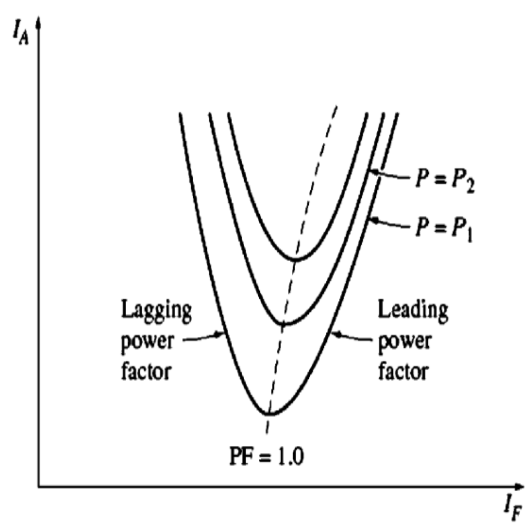
- **An increase in field current increases the magnitude of E_A but does not affect the real power supplied by the motor**. **The power supplied by the motor changes only when the shaft load torque changes**. Since a change in If does not affect the shaft speed nm ,and since the load attached to the shaft is unchanged, **the real power supplied is unchanged.**

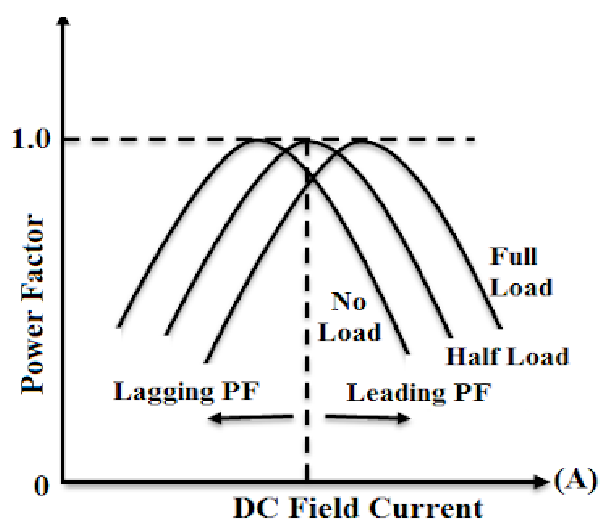
- Notice that as the value of **E_A increases**, **the magnitude of the armature current I_A first decreases and then increases again**. **At low E_A, the armature current is lagging**, **and the motor is an inductive load**. It is acting like an inductor-resistor combination, **consuming reactive power Q.**

- As the **field current is increased**, **the armature current eventually lines up with V_Φ**, and the **motor looks purely resistive.**

- **As the field current is increased further**, the armature current becomes **leading**, and the motor becomes a **capacitive load**. It is now acting like a **capacitor-resistor combination**, **supplying reactive power Q to the system.**

A plot of I_A versus I_f for a synchronous motor is shown in the Figure 2. Such a plot is called a **synchronous motor 'V' curve .** There are several V curves drawn, **corresponding to different real power levels**. For each curve, the **minimum armature current** occurs **at unity power factor,** when only **real power is being supplied to the motor**. At any other point on the curve, **some reactive power is being supplied to or by the motor as well**. **For field currents less than the value giving minimum I_A, the armature current is lagging, consuming Q. For field currents greater than the value giving the minimum I_A, the armature current is leading**, **supplying Q to the power system as a capacitor would.** Therefore, **by controlling the field current of a synchronous motor, the reactive power supplied to or consumed by the power system can be controlled**. The characteristic curve plotted between input power factor and the field current for a constant mechanical load on the motor are of the shape of **inverted 'V'** and are known as inverted 'V' curves.





The Effect of Load Changes on a Synchronous Motor

To find out, examine a synchronous motor operating initially with a leading power factor. If the load on the shaft of the motor is increased, the rotor will initially slow down. As it does, the torque angle δ becomes larger, and the induced torque increases. The increase in induced torque eventually speeds the rotor back up, and the motor again turns at synchronous speed but with a larger torque angle δ.

Necessary Material:

1. **Mod.3000:** Universal Power Supply
2. **Mod.3070:** 3-Ph Synchronous Machine
3. **Mod.3180:** Electromagnetic Break
4. **Mod.3203:** DC digital VAW
5. **Mod.3209:** 1-ph and 3-ph multimeter
6. **Mod.3180C:** Torque and speed meter

Experimental Procedures:

Part I: Specifications of the Three-Phase Synchronous Motor.

1. Read the nameplate of the Three-Phase Synchronous Motor and then tabulate the rating values of the motor in the following table:

<table>
<tr><th colspan="6">Name Plate of the Three-Phase Synchronous Machine Mod.3070</th><th></th><th></th></tr>
<tr><td>Voltage:</td><td>Y</td><td></td><td>Δ</td><td colspan="2"></td><td>Power:</td><td></td></tr>
<tr><td>Current:</td><td>Y</td><td></td><td>Δ</td><td colspan="2"></td><td>Speed:</td><td></td></tr>
<tr><td>Excitation voltage:</td><td colspan="5"></td><td>Excitation current:</td><td></td></tr>
<tr><td>Frequency:</td><td colspan="2"></td><td>Poles:</td><td colspan="2"></td><td>PF:</td><td></td></tr>
<tr><td>Duty Cycle:</td><td colspan="5"></td><td>Ingress Protection:</td><td></td></tr>
<tr><td colspan="6">Insulation Class:</td><td colspan="2"></td></tr>
</table>

Part II: Starting the machine as a Synchrouns Motor.

1. Connect the circuit as shown in figure 1.
2. At the beginning connect F1 and F2 together (**short-circuit**).
3. Supply the motor with three-phase voltage up to 400-V. The motor will start as asynchronous motor at this point measure the speed of motor.
4. Remove the short-circuit and at the same time feed the motor with DC voltage by using the power supply.
5. Increase gradually the excitation up to 220V and then measure the speed.

Condition	Speed
As Induction Motor	
As Synchronous Motor	

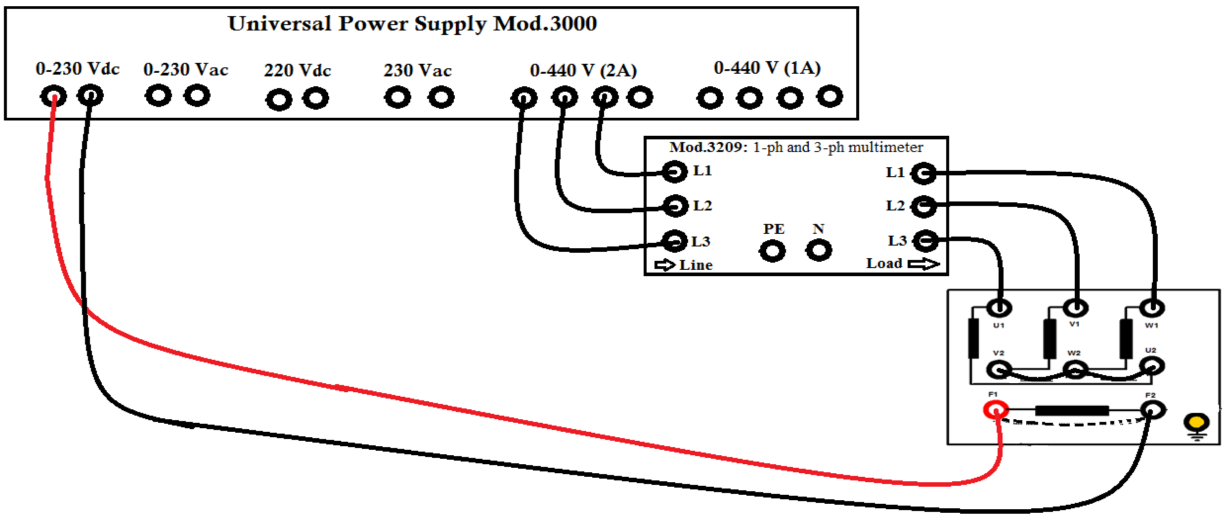


Figure (1)

Part III: Obtaining the 'V' and inverted 'V' Curves of a Synchronous Motor.

1. Make the mechanical coupling between the 3-phase Synchronous Motor and break unit.
2. Connect the circuit as shown in figure 2.
3. Apply a 3-phase voltage of 400-V at the terminals of the Synchronous Motor and run the motor with no-load condition as described in part II.
4. With **no-load condtion**, adjust the field voltage of the motor with starting from low field voltage and then rise the value in steps to match the requirements of the following table.
5. Tabulate your results in the following table.

Field Voltage (V)	Field Current (A)	Armature Current (A)	Power Factor (lag or lead or unity with its value)
80			
100			
120			
140			
160			
180			
200			
220			

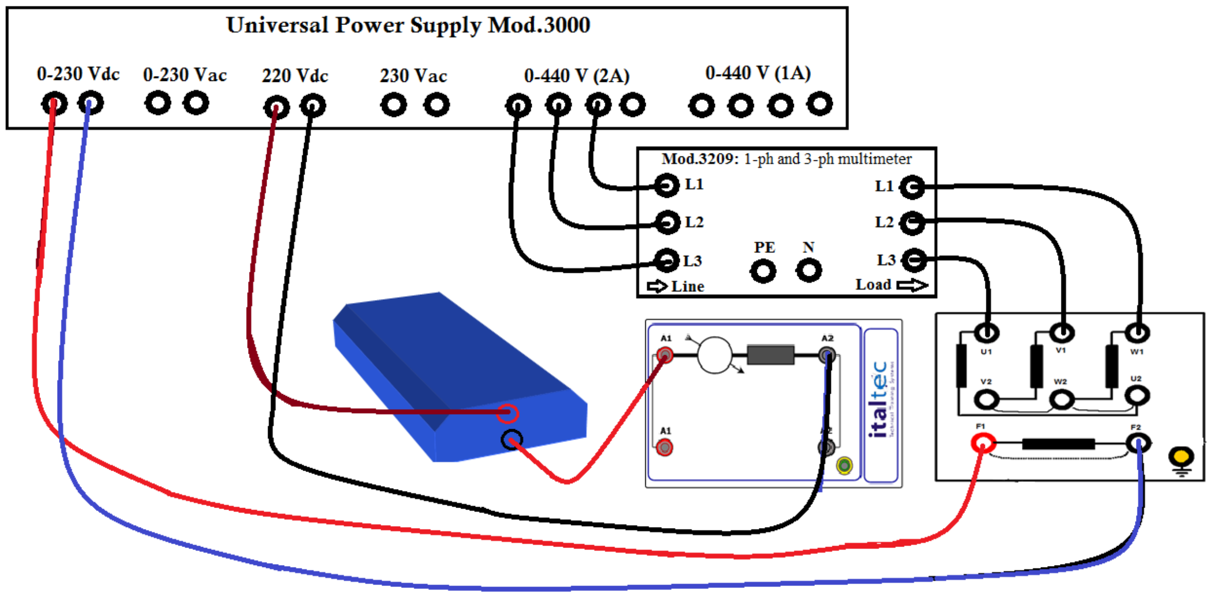


Figure (2)

6. Vary the meachanical load connected to the shaft of the motor by changing the dc voltage applied to the break unit (28-g.m (R is max)).
7. Adjust the field voltage of the motor with starting from low field voltage and then rise the value in steps to match the requirements of the following table.
8. Tabulate your results in the following table.

Field Voltage (V)	Field Current (A)	Armature Current (A)	Power Factor (lag or lead or unity with its value)
80			
100			
120			
140			
160			
180			
200			
220			

9. Draw the **'V' and inverted 'V' curves** under no-load and under load conditions (same graph).

Part IV: External characteristics of the three phase Synchronous Motor.

1. Make the mechanical coupling between the Synchronous Motor and break unit.
2. Connect the circuit as shown in Figure 2.
3. Apply a line voltage of 400-V at the terminals of the induction motor and run the motor at no load condition.
4. Vary the meachanical load connected to the shaft of the motor by changing the dc voltage applied to the break unit.
5. Measure the speed, voltage applied to the motor, current and power absorbed by the motor and the Power Factor at each value of the torque of the load, use ItalTec Software.
6. Calcultae the output power, you may use the following relation:

   Pout = τ (N.m) * ω (rad/sec) = (τ (g.m) *(10/1000)) * (2*3.14*n (rpm)/60))

7. Calculate the efficiency of the motor, you may use the following relation:

   η = Pout/Pin *100%

8. Tabulate the results in the following table.

Motor					Break unit	Calculations	
Speed (rpm)	Line Voltage	Line Current	Pin	PF	Torque (gr.m)	Pout	η
	400				5		
	400				10		
	400				20		
	400				30		
	400				40		
	400				50		
	400				60		
	400				70		
	400				80		
	400				90		
	400				100		

9. Plot and explain the **mechanical characteristics** of the 3-ph synchronous Motor. (Torque (Y-axis) vs Speed (X-axis))

10. Plot and explain the **electromechanical characteristics** of the 3-ph synchronous Motor.
    X-axis: Output Power
    Relations:
    - Efficiency (Y-axis)
    - Speed (Y-axis)
    - Current (Y-axis)
    - PF (Y-axis)

Questions:

1. What is the speed regulation of a synchronous motor?

2. Why can't a synchronous motor start by itself?

3. What happens to a synchronous motor as its field current is varied?

4. A synchronous motor is operating at a fixed real load, and its field current is increased. If the armature current **falls**, was the motor initially operating at a lagging or a leading power factor?

Chapter 3

DC Machines

Contents

Experiment (1)	Self-Excited Motors Series, Shunt and Compound DC Motors

Objectives:

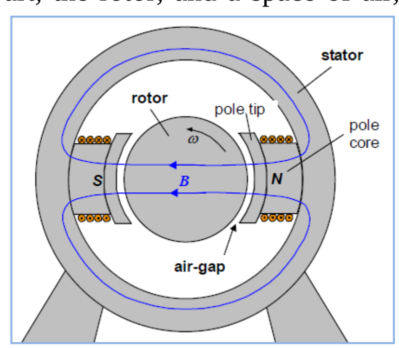
1. To familiarize with series, shunt and compound DC motors.
2. To measure the characteristics of a series, shunt and compound DC motors.
3. To demonstrate how to reverse the direction of rotation of series, shunt and compound DC Motors.
4. Understand series, shunt and compound DC Motors ratings.
5. Understand the techniques used for series, shunt and compound DC motor starting.
6. Understand how the speed of series, shunt and compound DC motors can be controlled.

Theory and concepts:

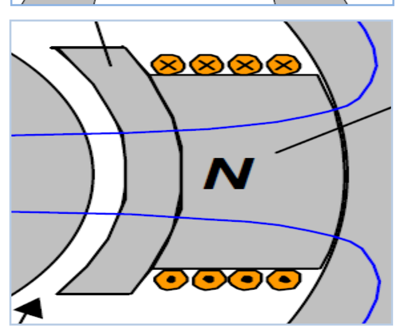
Introduction

DC machines are generators that convert mechanical energy to dc electric energy and motors that convert dc electric energy to mechanical energy. Most dc machines are like ac machines in that they have ac voltages and currents within them-dc machines have a dc output only because a mechanism exists that converts the internal ac voltages to dc voltages at their terminals. Since this mechanism is called a **commutator**, dc machinery is also known as *commutating machinery*.

DC machine is composed by a stationary part, the stator, a rotating part, the rotor, and a space of air, called air-gap between the two.



The stator contains a winding made by connecting in series (Al) the conductors shown in their cross-section in figure. A simplified idea on how these connections are made can be inferred from the second image that shows winding.This winding, called field winding, during the machine operation is connected to a DC source and therefore is traversed by a DC current.



To analyse what happens in the machine the field winding currents can be imagined to be flowing according to the signs indicated in following figure, i.e. they exit the page surface when a small dot is reported in the conductors, and enter it when a cross is reported. By effect of these currents, a magnetic field is created, whose force lines that flow in the stator, traverse the small air gap, enter the rotor, traverse it then returns to the stator .

In basic analyses of DC machines, the field H produced in the air-gap, and therefore the corresponding flux density B, can be considered to be uniform. B will be proportional to the current I_F circulating in the field winding.

All the windings (on S and on N pole) are connected in series, and are thus traversed by the same current. The analysis of the machine behavior that will be presently propose is based on the interaction rotor-conductors and flux density produced by the stator, and is therefore applicable to machine with two or four pole. The rotor of a DC machine contains conductors at its periphery, these conductors are inserted into the slots, that are spaces from which iron has been moved, and are able to keep the conductors mechanically tightly connected to the basic iron structure of the rotor.

In the electric machines terminology, the armature is the part of the machine in which an EMF is induced by the Faraday's law. Therefore in a DC machine the armature is the rotor. In other machines (such as the synchronous machine, it is located in the stator). As far as the rotor rotates, the brushes become connected to different conductors, so that the total voltage E that is corresponding to the instantaneous sum the voltages generated on half conductors (the left half or the right one can be equivalently considered) maintains roughly always the same amplitude.

The actual connection of the brushes to the rotor is not, made directly on the rotor conductors, but indeed these conductors are linked to a commutator, that contains conductive segments separated by small layers of insulating material. The conductive elements are connected to the active conductor in the rotor periphery, creating a situation that reproduce the principle scheme as on next image. The collector is mounted on the machine shaft, the conductive sectors connected with the rotor active conductors, and rotates with the rotor; the brushes do not rotate, are pressed using suitable springs against the commutator. The brushes are constituted by a material based on carbon, that is much softer than copper in such a way that the sliding between them and commutator causes some wearing of the brushes instead of the commutator, This causes the need of periodically substituting the brushes, but reduces dramatically wearing the commutator, much more expensive to substitute.

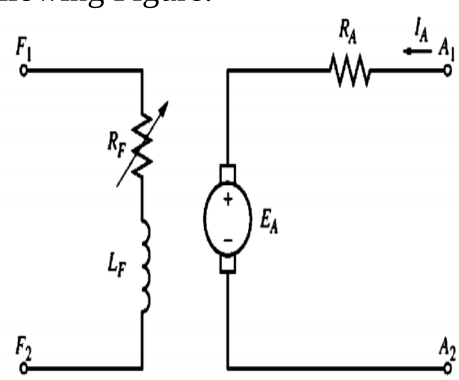
There are five major types of dc motors in general use:

1. Separately excited dc motor
2. Series dc motor
3. Shunt dc motor
4. Compounded dc motor
5. Permanent-magnet dc motor

Equivalent Circuit of a DC Motor

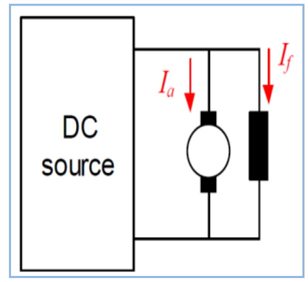
The equivalent circuit of a dc motor is shown in the following Figure:

- The field coils, which produce the magnetic flux in the generator, are represented by inductor L_F and resistor R_F.
- The armature circuit is represented by an ideal voltage source E_A, and a resistor R_A.
- The internal generated voltage in this machine is given by the equation $E_A = K\phi\omega$
- And the induced torque developed by the machine is given by $\tau_{\text{ind}} = K\phi I_A$



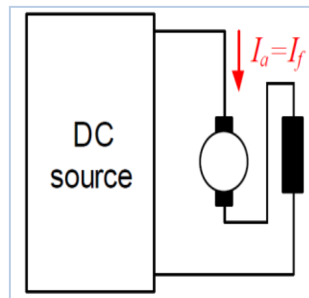
Shunt excitation DC Machines

With this type of machine the supply to the field coil can be the same source that feeds the armature. This is called shunt excitation. Usually excitation coil terminals are separate so that is possible to connect the same machine also with an external independent (or separate,) power source. In addition it is possible to connect a variable rheostat between the two windings in order to get different voltage to the two coils even using only one power source.



Series excitation DC Machines

The field winding can be connected in series with the machine armature. The machine can be started at a reduced voltage, and the reduction can be obtained at low speeds by interposition of a starting resistor Rs, that is then bypassed when the current has become acceptable, in correspondence to the speed ω. Series excited machines are used when the load might have sudden peaks of torque: in this case this machine slows down, and rises its torque by large amounts, thus overcoming the difficulty.



Compound DC Machines

A compound wound DC motor is made up of both series field coils and shunt field coils. Both the field coils provide for the required amount of magnetic flux, that links with the armature coil and brings about the torque necessary to facilitate rotation at desired speed. A compound wound DC motor is formed by the amalgamation of a shunt wound DC motor and series wound DC motor to achieve the better of properties of both these types. Like a shunt wound DC motor it **is** extremely efficient with speed regulation characteristic, whereas the DC series motor has high starting torque.

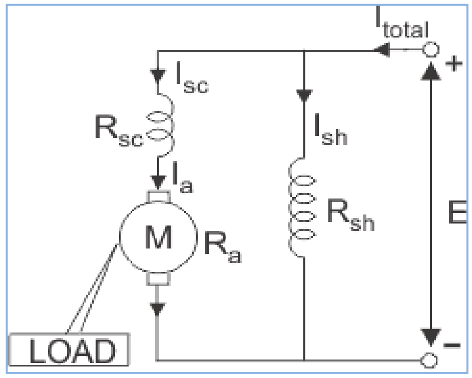
So the compound wound DC motor reaches a compromise in terms of both this features and has a good combination of proper speed regulation and high starting toque. The construction of a DC Compound Machine is the same as any other DC machine. It contains all the fundamental parts, which include a stator (field windings), a rotor (also known as armature), and a commutator.

The compound wound DC motor can further be subdivided into two major types on the basis of its field winding connection with respect to the armature winding, and they are:

1. Long Shunt Compound DC Motor
2. Short Shunt Compound DC Motor

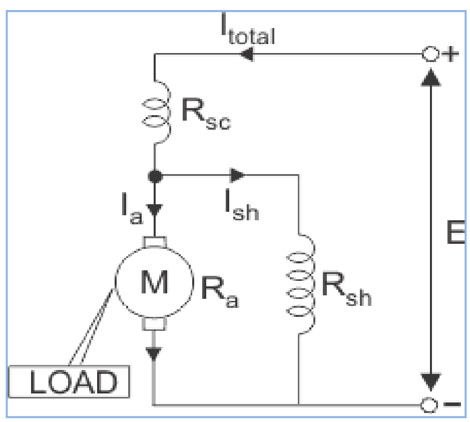
Long Shunt Compound Wound DC Motor

In case of long shunt compound wound DC motor, the shunt field winding is connected in parallel across the series combination of both the armature and series field coil, as shown in the diagram below.



Short Shunt Compound Wound DC Motor

In case of short shunt compound wound DC motor, the shunt field winding is connected in parallel across the armature winding only. And series field coil is exposed to the entire supply current, before being split up into armature and shunt field current as shown in the diagram below.



Reversing the direction of Series and Shunt DC motors:

For Series DC Motors the armature current and field current is always equal. If the polarity of applied armature voltage is changed the direction of the field current and the armature current both get changed and therefore, the direction of the torque and speed will remain unaltered. Thus in the case of DC series motor the speed cannot be changed by changing the polarity of the armature voltage. The direction of rotation of the DC series motor can be changed only if the direction of either field current or armature current is changed.

For Shunt DC Motors the direction of armature rotation may be changed by reversing the direction of current in either the field circuit or the armature circuit. For a motor with a simple shunt field circuit, it may be easier to reverse the field circuit lead.

Speed Control of Shunt and Compound DC Motors

The two common ways in which the speed of a shunt dc machine can be controlled are by:

1. Adjusting the field resistance R_F (and thus the field flux)
2. Adjusting the terminal voltage applied to the armature.

The less common method of speed control is by inserting a resistor in series with the armature circuit.

The techniques available for the control of speed in a compounded dc motor are the same as those available for a shunt motor.

Speed Control of Series DC Motors

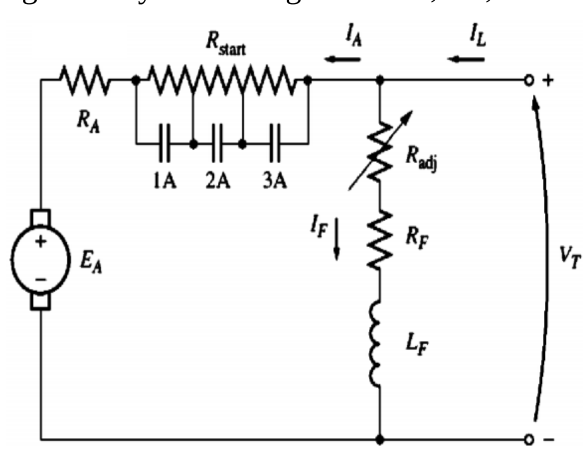
Change the terminal voltage of the motor. If the terminal voltage is increased resulting in a higher speed for any given torque. The speed of series dc motors can also be controlled by the insertion of a series resistor into the motor circuit, but this technique is very wasteful of power.

DC Motor Starting

In order for a dc motor to function properly, it must be protected from physical damage during the starting period. At starting conditions, the motor is not turning, and so $E_A = 0$ V. Since the internal resistance of a normal dc motor is very low a *very* high current flows.

A solution to the problem of excess current during starting is to insert a starting resistor in series with the armature to limit the current flow until E_A can build up to do the limiting. This resistor must not be in the circuit permanently, because it would result in excessive losses and would cause the motor's torque-speed characteristic to drop off excessively with an increase in load. Therefore, a resistor must be inserted into the armature circuit to limit current flow at starting, and it must be removed again as the speed of the motor builds up.

In modern practice, a starting resistor is made up of a series of pieces, each of which is removed from the motor circuit in succession as the motor speeds up, in order to limit the current in the motor to a safe value while never reducing it to too low a value for rapid acceleration. The following Figure shows a shunt motor with an extra starting resistor that can be cut out of the circuit in segments by the closing of the 1A, 2A, and 3A contacts.



Necessary Material:

1. **Mod.3000:** Universal Power Supply
2. **Mod.3160:** DC Compound Motor
3. **Mod.3180:** Electromagnetic Break
4. **Mod.3203:** DC digital VAW
5. **Mod.3180C:** Torque and speed meter
6. **Mod.3012:** Field Regulator for DC motor.

Experimental Procedures:

Part I: Specifications of the Compound DC Machine.

1. Read the nameplate of the Compound DC Machine and then tabulate the rating values of the motor in the following table.

Name Plate of the Compound DC Motor Mod.3160.			
Armature Voltage:		Armature Current:	
Excitation Voltage:		Excitation Current:	
Power:		Speed:	
Duty Cycle:		Ingress Protection:	
Insulation Class:			

Part II: Measure of the Winding Resistance of the machine.

1. Connect the circuit as shown in figure 1.
2. Measure the Resistance of the windings 1, 2 and 3 respectively.
3. Determine which winding is armature winding or series winding or shunt winding.

Winding	Winding Resistance	Winding type
Winding 1 (A1-A2)		
Winding 2 (D1-D2)		
Winding 3 (E1-E2)		

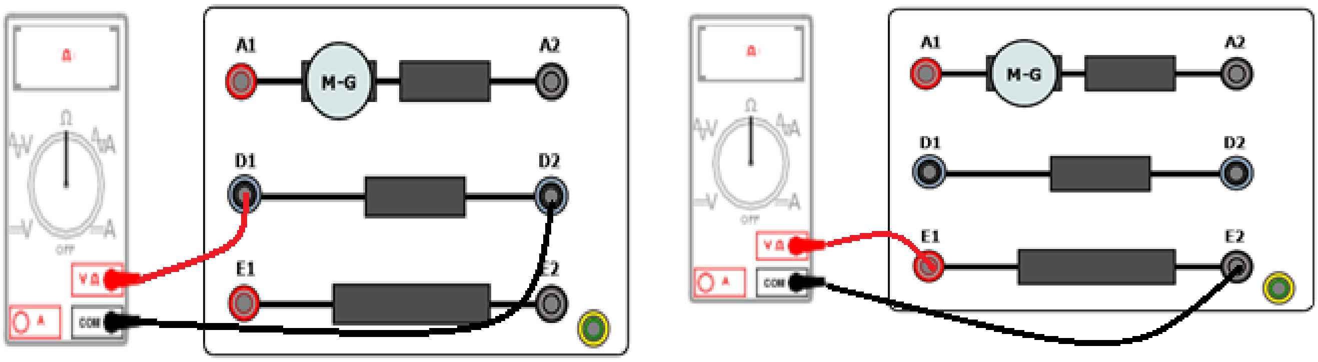


Figure (1)

Part III: Running the Motor as Series DC Motor.

1. Connect the circuit as shown in the Figure 3.
2. Switch on the general switch; Switch on DC and acting on the regulating knob, increase the voltage **very slowly**. Without a load a maximum voltage of about the **25% of the nominal voltage** can be used and if the motor speed increases in spite of you are not increasing voltage, <u>switch off immediately the motor power supply</u>.
3. Measure the speed, absorbed current and power when the motor is unloaded.
4. Vary the meachanical load connected to the shaft of the motor by changing the dc voltage applied to the break unit.
5. Decrease gradually the voltage till the motor will stop.
6. Tabulate your results in the following table.

Applied Voltage	Speed (rpm)	Absorbed Current	Absorbed Power	Load (W)
55				0
90				100
100				120

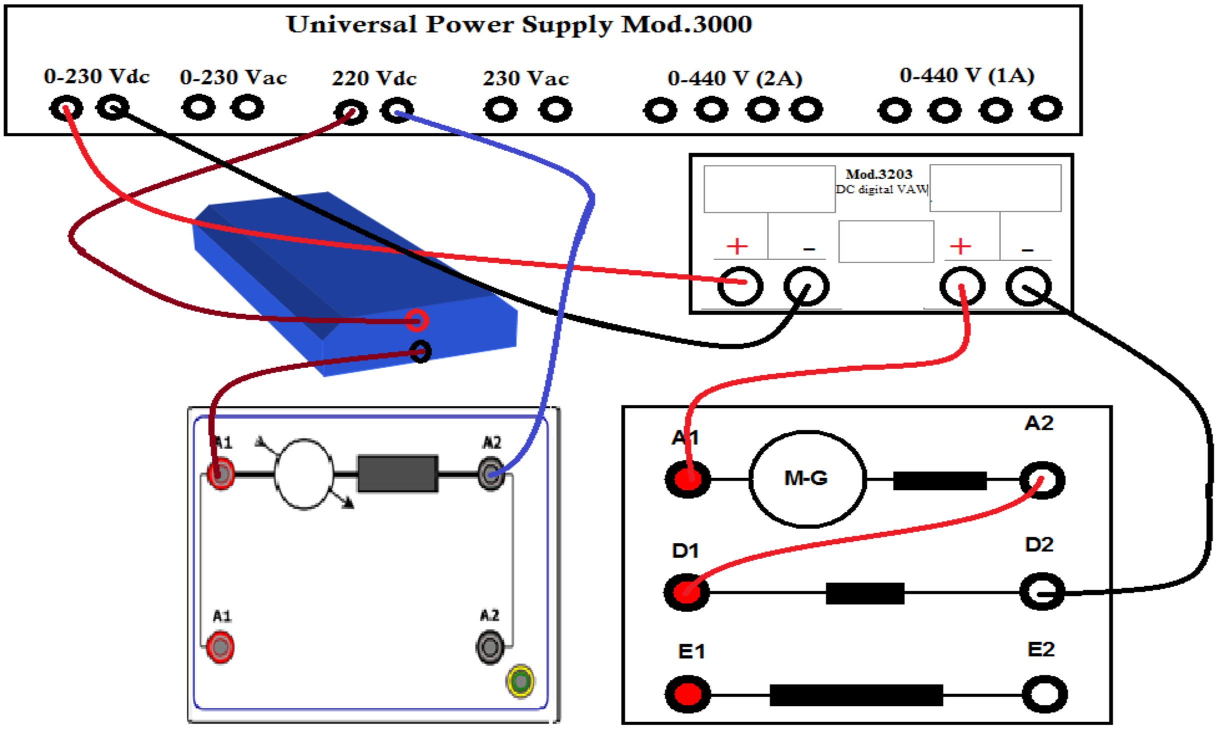


Figure (2)

Part IV: Running the Motor as Shunt DC Motor.

Part IV-1: Shunt DC Motor (with Starting rheostat)

1. Connect the circuit as shown in the Figure 3.
2. For starting purpose set the value of Rs to 100 Ω,
3. Switch on the general switch; Switch on DC and acting on the regulating knob, increase the voltage up to nominal voltage of the motor (230 V).
4. Measure the speed, absorbed current and power when the motor is unloaded.
5. Set the starting resistor to 0 Ω and Vary the meachanical load (120 W) connected to the shaft of the motor by changing the dc voltage applied to the break unit.
6. Measure the speed, absorbed current and power of the motor.
7. Tabulate your results in the following table.

Applied Voltage	R_S (Ω)	Speed (rpm)	Absorbed Current	Absorbed Power	Load (W)
230	0				0
230	100				0

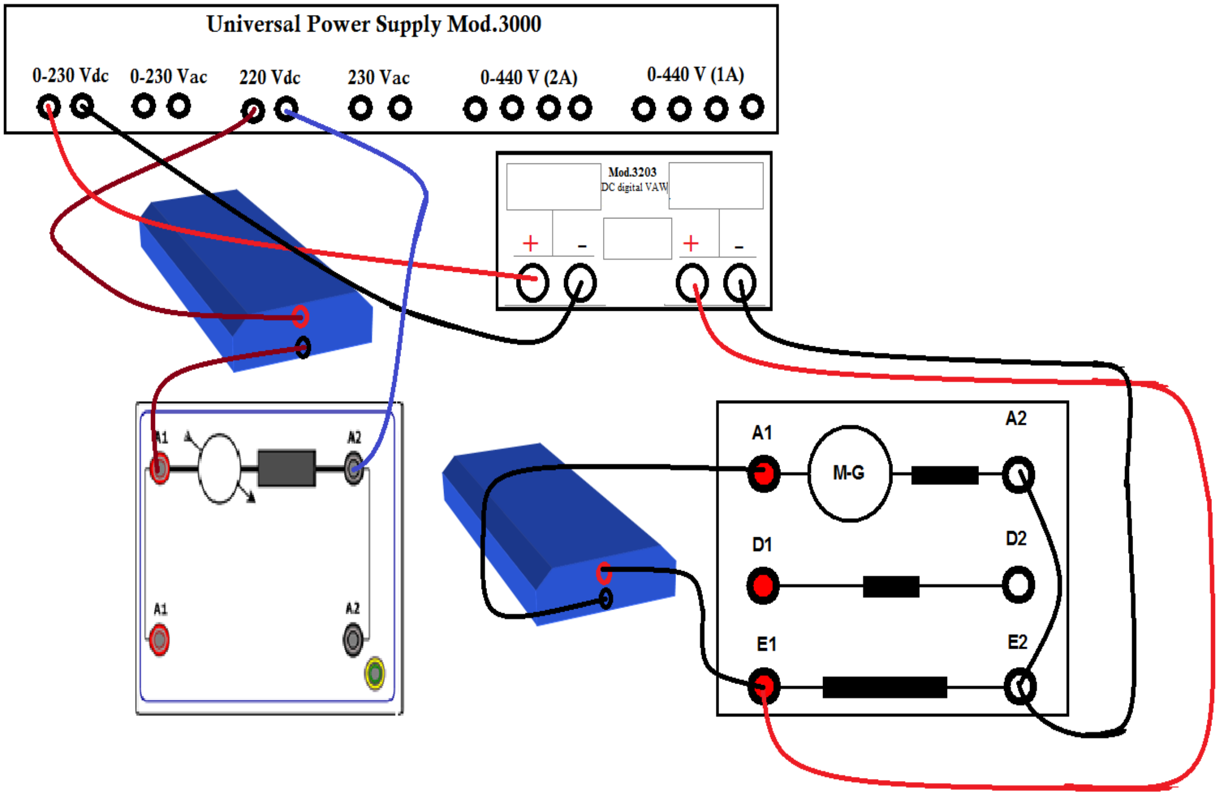


Figure (3)

Part IV-2: Shunt DC Motor (with Speed Control)

1. Connect the circuit as shown in the Figure 4.
2. Switch on the general switch; Switch on DC and acting on the regulating knob, increase the voltage up to nominal voltage of the motor (230 V).
3. Set the excitation rheostate at 0 Ω. Read the speed of the rotation of the motor.
4. Increase the ohmic value (pass at 1/3 position). Read and note the speed variation.
5. Increase the ohmic value (pass at 2/3 position). Read and note the speed variation.
6. Increase the ohmic value (pass at 3/3 position). Read and note the speed variation.
7. Tabulate your results in the following table.

Applied Voltage	R_E (Ω)	Speed (rpm)	Note
230	0		
230	1/3 Rmax		
230	2/3 Rmax		
230	3/3 Rmax		

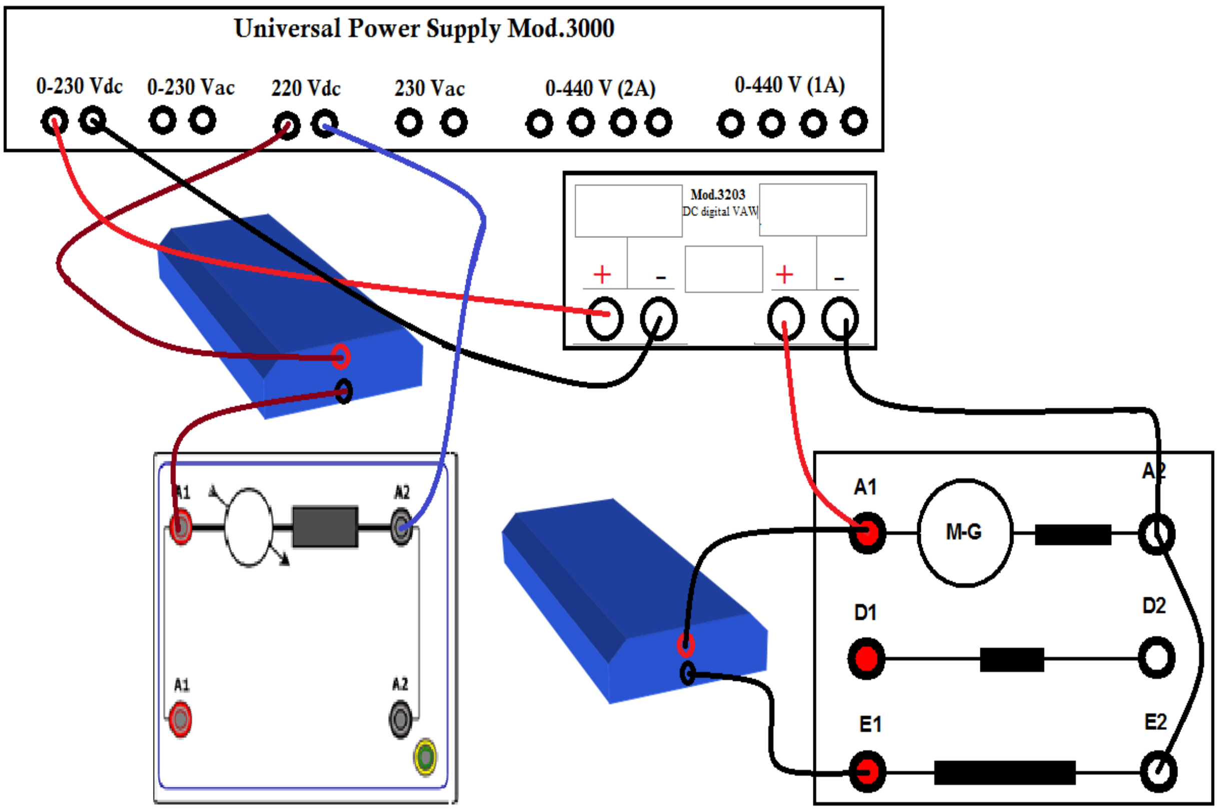


Figure (4)

Part IV-3: Shunt DC Motor (Reversing the direction of rotation)

1. Connect the circuit as shown in the Figure 4 (connection 1) without starting rheostat.
2. Switch on the general switch; Switch on DC and acting on the regulating knob, increase the voltage up to nominal voltage of the motor (230 V).
3. Verify the direction of the motor.
4. Change the connection of the motor as shown in figure 5 (connection 2) and observe the direction of the motor.

Connection	Direction (CW,CCW)
Connection (1)	
Connection (2)	

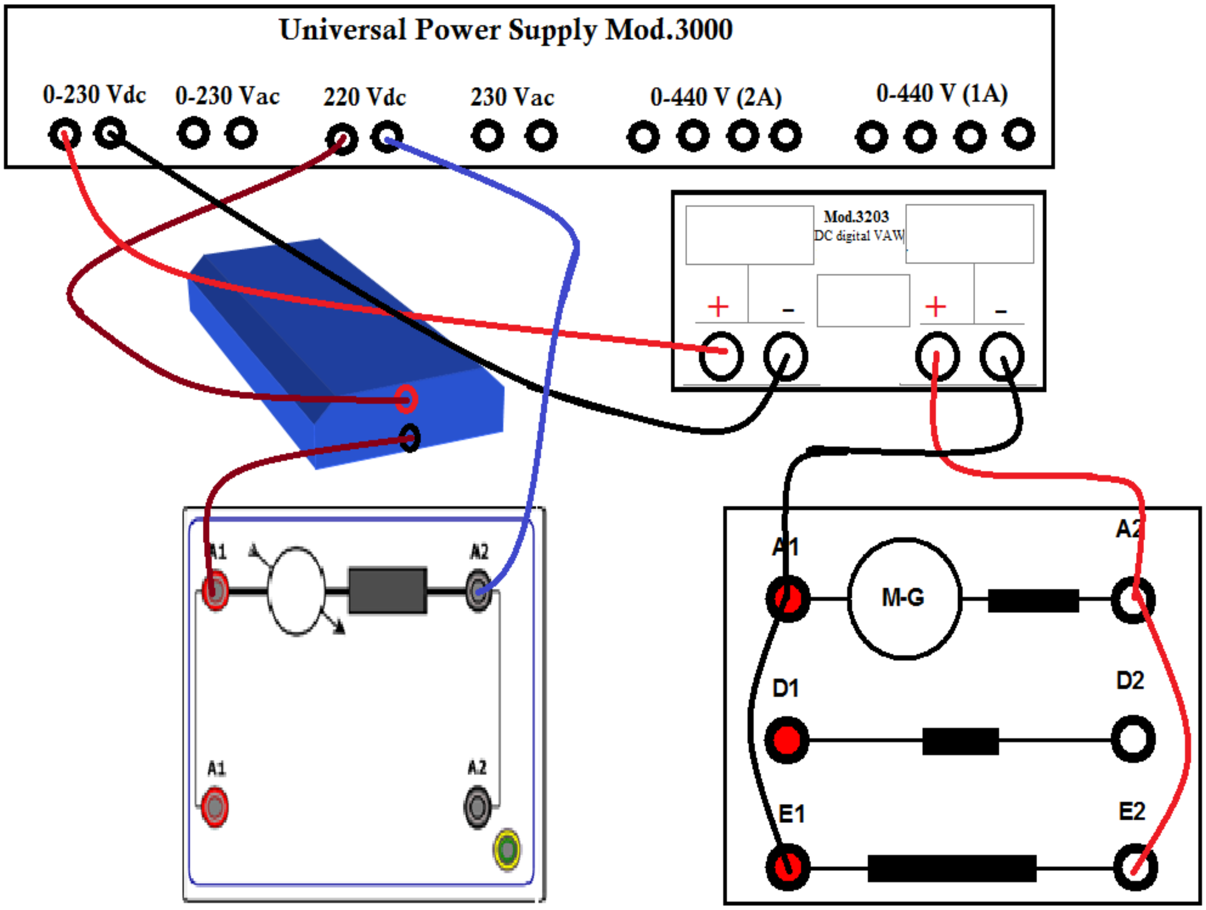


Figure (5)

Part IV-4: External characteristics of the Shunt DC Motor.

1. Make the mechanical coupling between the Shunt DC Motor and break unit.
2. Connect the circuit as shown in Figure 6.
3. Apply a DC voltage of 230-V at the terminals of the Shunt DC Motor and run the motor at no load condition.
4. Vary the meachanical load connected to the shaft of the motor by changing the dc voltage applied to the break unit.
5. Measure the speed, voltage applied to the motor, current and power absorbed by the motor at each value of the load.
6. Calcultae the output power, you may use the following relation:

   Pout = τ (N.m) * ω (rad/sec) = (τ (g.m) *(10/1000)) * (2*3.14*n (rpm)/60))

7. Calculate the efficiency of the motor, you may use the following relation:

   η = Pout/Pin *100%

8. Calculate the Speed regulation of the motor, you may use the following relation:

SR = n_{nl} - n_{fl} / n_{fl} *100%

9. Tabulate the results in the following table.

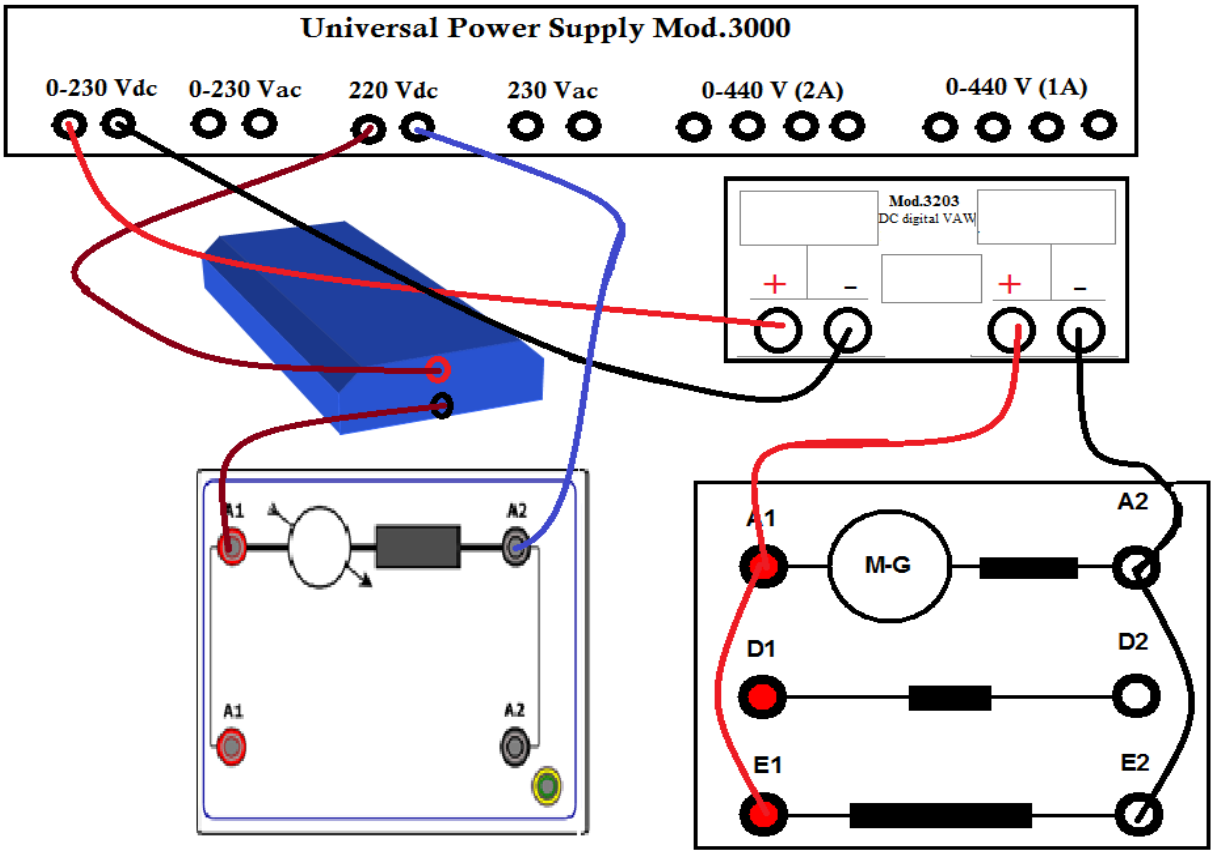


Figure (6)

10. Tabulate the results in the following table.

Motor				**Break unit**	**Calculations**		
Speed (rpm)	Applied Voltage	Absorbed Current	Absorbed Power	Torque (gr.m)	Pout	η	SR
				5			
				10			
				15			
				20			
				25			

11. Plot and explain the **mechanical characteristics** of the Shunt DC Motor.
(Speed (Y-axis) vs Torque (X-axis))

12. Plot and explain the **electromechanical characteristics** of the Shunt DC Motor.
X-axis: Output Power
Relations:
- Efficiency (Y-axis)
- Speed (Y-axis)
- Current (Y-axis)

Part V: Running the Motor as Compound DC Motor under no-load condition.

1. Connect the circuit as shown in the Figure 7.
2. Switch on the general switch; Switch on DC and acting on the regulating knob, increase the voltage up to nominal voltage of the motor (230 V).
3. Measure the speed, voltage applied to the motor, current and power absorbed by the motor under no-load condition.
4. Verify the direction of the motor.
5. Tabulate your results in the following table.

Applied Voltage	Speed (rpm)	Absorbed Current	Absorbed Power	Direction
230				

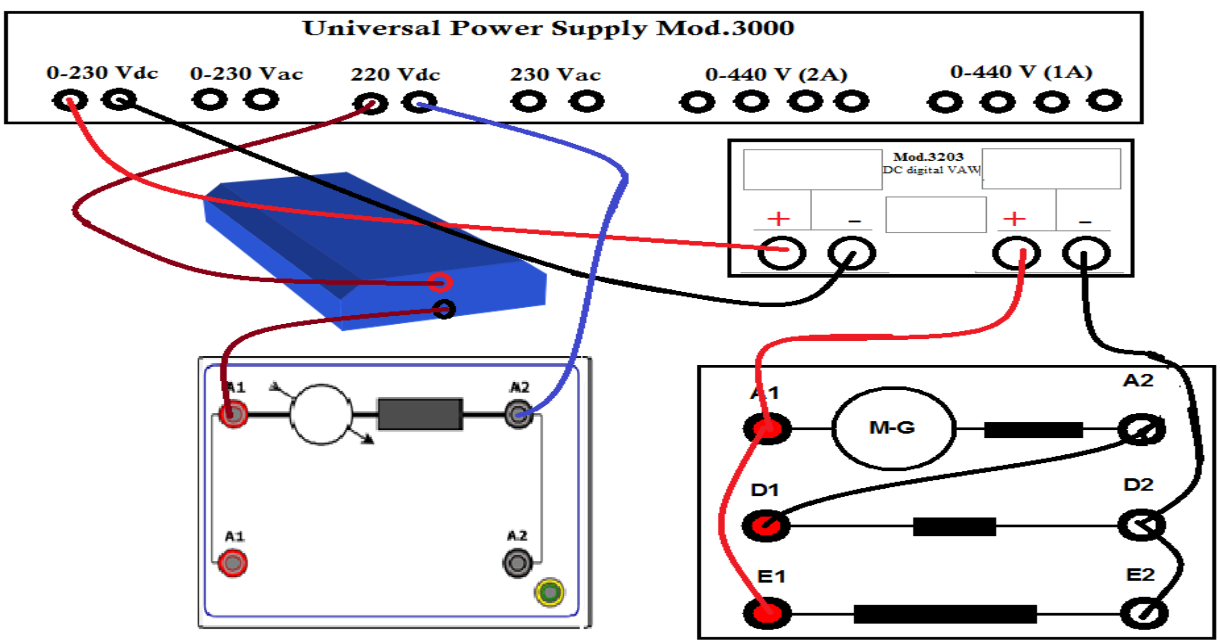


Figure (7)

Part II: Reversing the direction of rotation of the Compound DC Motor

1. Connect the circuit as shown in the Figure 8.
2. Switch on the general switch; Switch on DC and acting on the regulating knob, increase the voltage up to nominal voltage of the motor (230 V).
3. Verify the direction of the motor.
4. Tabulate your results in the following table.

Connection	Direction (CW,CCW)
Reversing the direction of rotation	

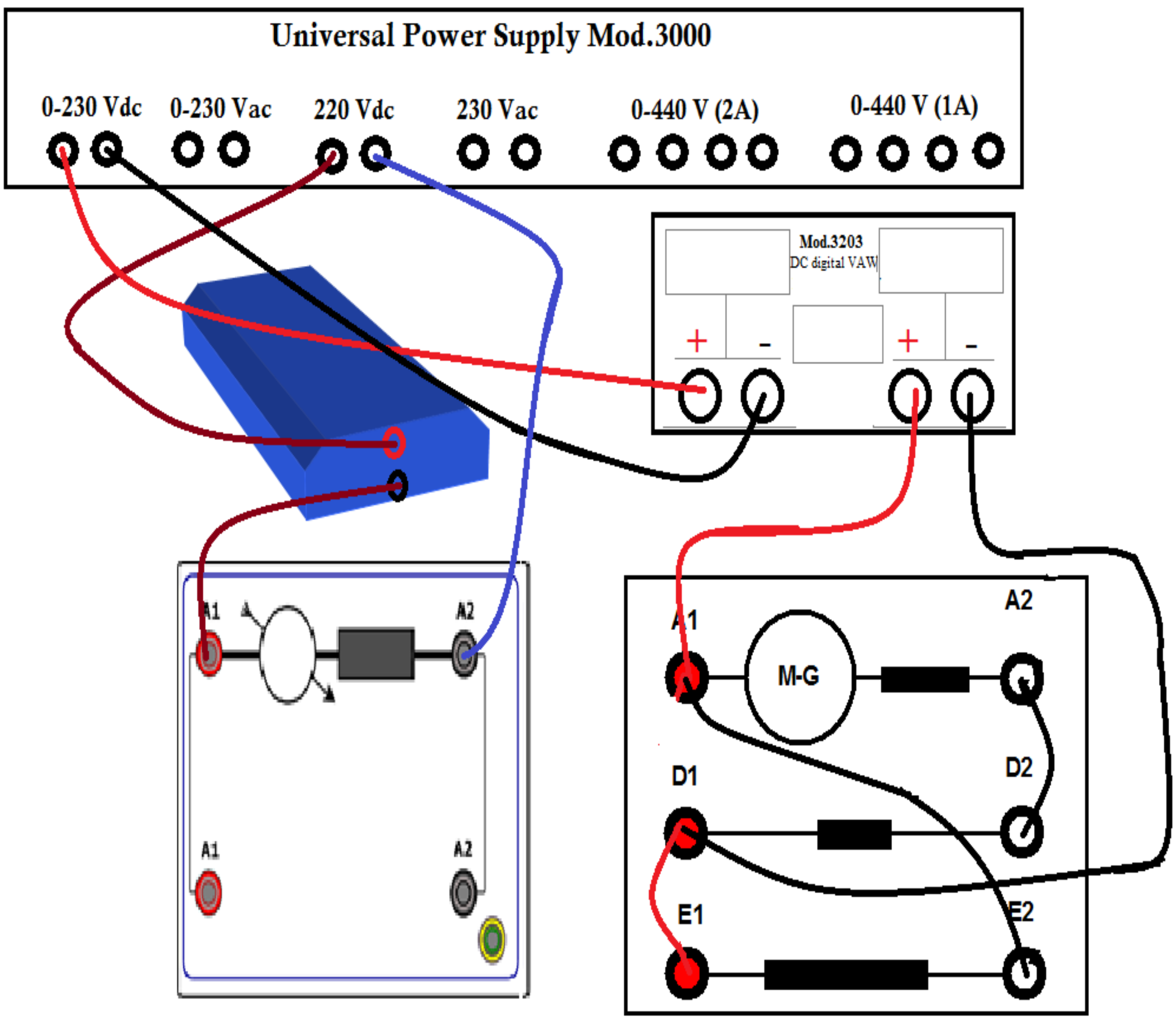


Figure (8)

Part III: External characteristics of the Compound DC Motor with speed control.

1. Make the mechanical coupling between the DC Motor and break unit.
2. Connect the motor as shown in the figure 3.
3. Set the excitation rheostate at $R_E = 0\ \Omega$.
4. Switch on the general switch; Switch on the fixed DC (230 V).
5. Vary the meachanical load connected to the shaft of the motor by changing the dc voltage applied to the break unit.

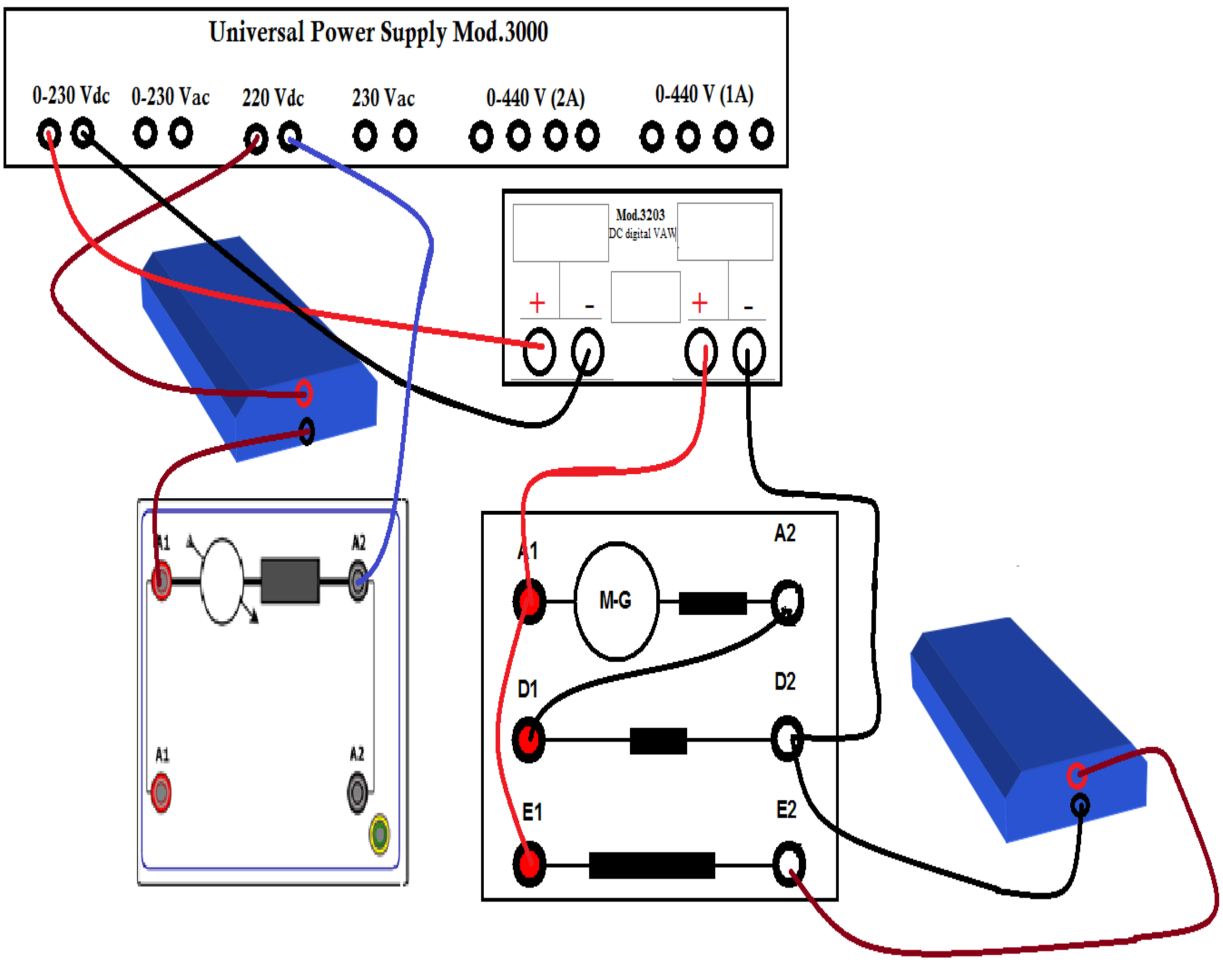


Figure (9)

6. Measure the speed, current, and power absorbed by the motor.
7. Change the excitation rheostat to 500 Ω and then measure the speed, current, and power absorbed by the motor with varying the mechanical load as shown in the table.
8. Change the excitation rheostat to 1000 Ω and then measure the speed, current, and power absorbed by the motor with varying the mechanical load as shown in the table.

9. Calculate the efficiency of the motor, you may use the following relation:

η = Pout/Pin *100%

10. Calculate the Speed regulation of the motor, you may use the following relation:

SR = n_{nl} - n_{fl} / n_{fl} *100%

11. Tabulate the results in the following table.

Motor					**Break unit**	**Calculations**		
R_E	Input voltage	rpm	Current	Pin	Torque gr.m	Pout	η	SR
0					0			
0					20			
0					50			
500					0			
500					20			
500					50			
1000					20			
1000					50			

12. Plot and explain the **mechanical characteristics** of the Compound DC Motor.
(Speed (Y-axis) vs Torque (X-axis))

13. Plot and explain the **electromechanical characteristics** of the Compound DC Motor.
X-axis: Output Power
Relations:

- Efficiency (Y-axis)
- Speed (Y-axis)
- Current (Y-axis)

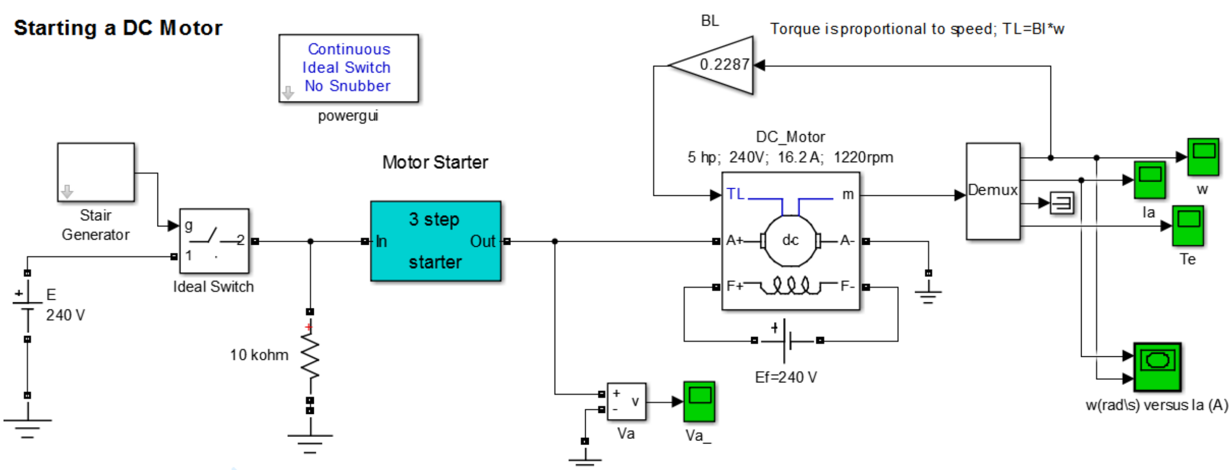
Questions:

1. How can the speed of a shunt dc motor be controlled?
2. What are the principal characteristics of a series dc motor? What are its uses?
3. Why is a starting resistor used in dc motor circuits?
4. What are the principal characteristics of a compound dc motor? What are its uses?

Matlab Section

This model illustrates the starting procedure of a starting of a 5 HP 240V DC motor with a three-step resistance starter.

Describe this model briefly?



Experiment (2)	Self-Excited DC Generator (Shunt and Compound)

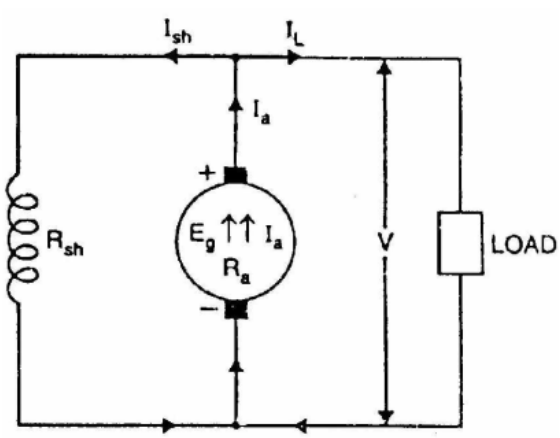
Objectives:

1. To study the no-load characteristics of the DC shunt generator (magnetization).
2. To study the external characteristics of the compound DC generator.
3. To study how to control the output voltage of a DC generator.

Theory and concepts:

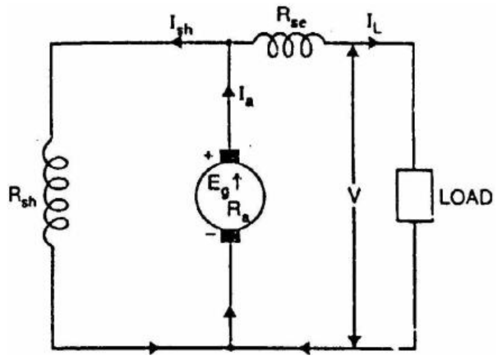
An electric generator is a machine that converts mechanical energy into electrical energy. An electric generator is based on the principle that whenever flux is cut by a conductor, an e.m.f. is induced which will cause a current to flow if the conductor circuit is closed. The d.c. generators and d.c. motors have the same general construction. The e.m.f. generated in the armature winding of a d.c. generator is alternating one. The commutator and brushes cause the alternating e.m.f. of the armature conductors to produce a d.c. always in the same direction between the terminals of the generator.

In a shunt generator, the field winding is connected in parallel with the armature winding so that terminal voltage of the generator is applied across it. The shunt field winding has many turns of fine wire having high resistance. Therefore, only a part of armature current flows through shunt field winding and the rest flows through the load. The following Figure shows the connections of a shunt-wound generator.

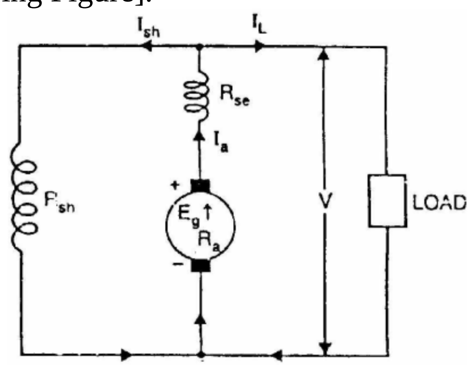


In a compound-wound generator, there are two sets of field windings on each pole—one is in series and the other in parallel with the armature. A compound wound generator may be:

(a) Short Shunt in which only shunt field winding is in parallel with the armature winding [See the following Figure].



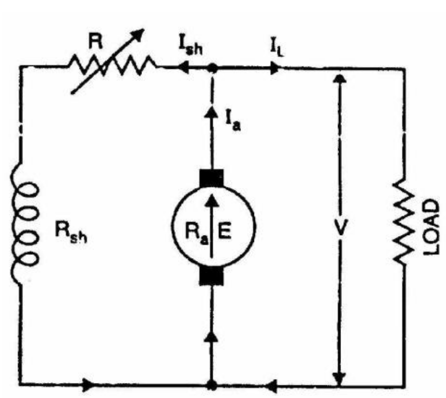
(b) Long Shunt in which shunt field winding is in parallel with both series field and armature winding [See the following Figure].



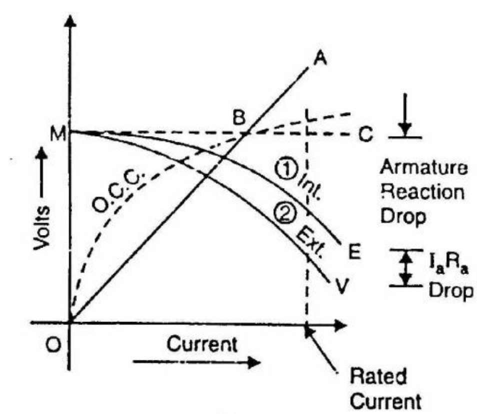
Shunt DC Generator Characteristic

The following Figure shows the connections of a shunt wound generator. The armature current Ia splits up into two parts; a small fraction Ish flowing through shunt field winding while the major part IL goes to the external load.

The line OA represents the shunt field circuit resistance. When the generator is run at normal speed, it will build up a voltage OM. At no-load, the terminal voltage of the generator will be constant (= OM) represented by the horizontal dotted line MC.



(i)



(ii)

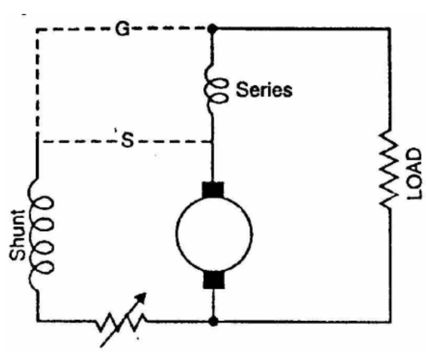
When the generator is loaded, flux per pole is reduced due to armature reaction. Therefore, e.m.f. E generated on load is less than the e.m.f. generated at no load. As a result, the internal characteristic (E/Ia) drops down slightly as shown in Figure (ii).

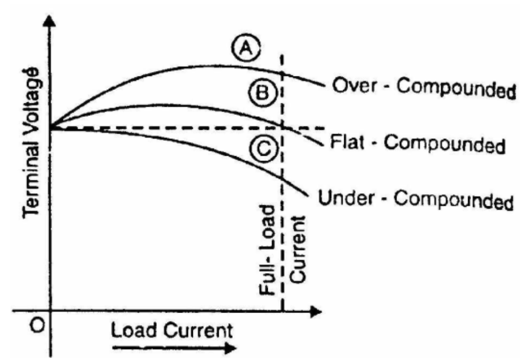
Curve 2 shows the external characteristic of a shunt generator. It gives the relation between terminal voltage V and load current IL. The external characteristic curve will lie below the internal characteristic curve by an amount equal to drop in the armature circuit $(I_L + I_{sh})R_a$ as shown in Figure (ii).

Compound DC Generator Characteristics

In a compound generator, both series and shunt excitation are combined as shown in the following Figure. The shunt winding can be connected either across the armature only (short-shunt connection S) or across armature plus series field (long-shunt connection G). The compound generator can be cumulatively compounded or differentially compounded generator.

The following Figure shows the external characteristics of a cumulatively compounded generator. The series excitation aids the shunt excitation. The degree of compounding depends upon the increase in series excitation with the increase in load current.





Voltage Regulation

The change in terminal voltage of a generator between full and no load (at constant speed) is called the voltage regulation, usually expressed as a percentage of the voltage at full-load:

$$\%\text{Voltage regulation} = \frac{V_{NL} - V_{FL}}{V_{FL}} \times 100$$

Note that voltage regulation of a generator is determined with field circuit and speed held constant. If the voltage regulation of a generator is 10%, it means that terminal voltage increases 10% as the load is changed from full load to no load.

Necessary Material:

1. **Mod.3000:** Universal Power Supply
2. **Mod.x160:** DC Compound Motor
3. **Mod.3180:** Electromagnetic Break
4. **Mod.3203:** DC digital VAW
5. **Mod.3012:** Field Regulator for DC motor.

Experimental Procedures:

Part I: Magnetization characteristics (Open-circuit characteristics) of a DC Generator.

1. Make the mechanical coupling between the DC generator and Induction Motor.
2. Connect the circuit as shown in figure 1.
3. Make sure the terminals are disconnected from all loads and the field current is set to zero.
4. Apply a line voltage of 400-V at the terminals of the three phase induction motor and run the motor to obtain a speed of 2900 rpm (it has to rotate in CCW direction).
5. **Gradually** start to increase the field current in steps to match the requirements of the following table.
6. In each step measure the terminal voltage of the dc generator using voltmeter.
7. Tabulate your results in the following table.
8. Plot the magnetization characteristics of the generator. (induced voltages E_A with respect to field current I_f)

Excitation Current (A)	Output Voltage (V)	Speed (rpm)
0.00		2900
0.04		
0.07		
0.10		
0.12		
0.15		

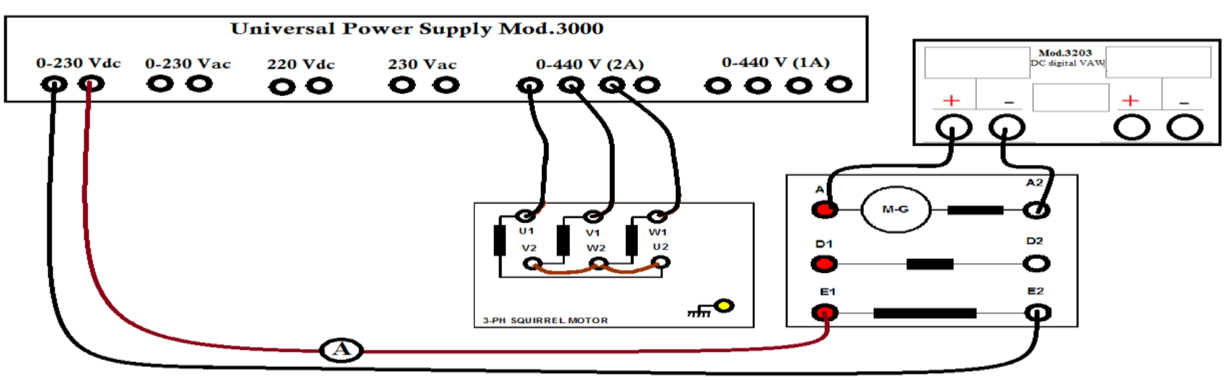


Figure (1)

Part II: External characteristics of Shunt DC Generator.

1. Make the mechanical coupling between the DC generator and Induction Motor.
2. Connect the motor as shown in the figure 3.
3. Supply the power to the prime mover and increase its voltage to 400 V.
4. At no-load measure the terminal voltage of the motor and the speed of the prime mover.
5. Apply the resistive load with steps and then measure the field current, load current, terminal voltage, power consumed by the load and the speed of the prime mover.
6. Calculate the voltage regulation at each load.
7. Tabulate your results in the following table.
8. Plot the external characteritics of the generator.

Load (Ω)	Prime Mover	Shunt DC Generator				Caculations
	Speed (rpm)	Field Current	Load Current	Terminal Voltage	Consumed Power	%VR
0						-
900						
700						
500						
300						
250						

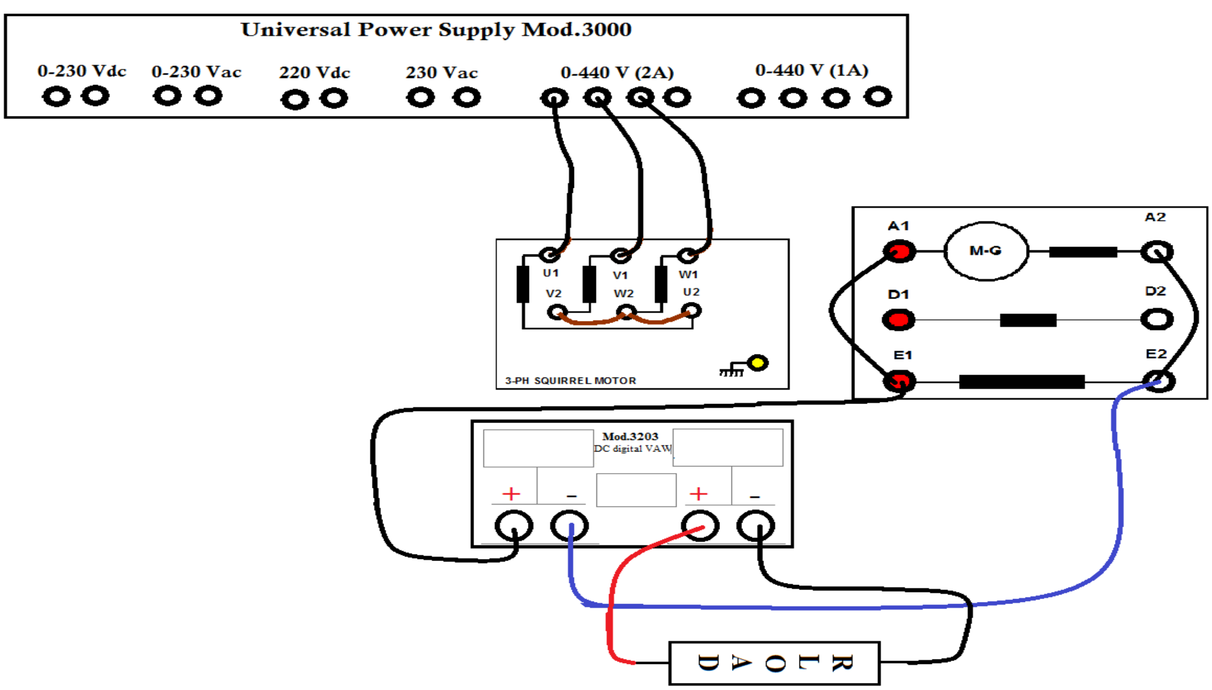


Figure (2)

Part III: External characteristics of Compound DC Generator.

1. Make the mechanical coupling between the DC generator and Induction Motor.
2. Connect the motor as shown in the figure 3.
3. Supply the power to the prime mover and increase its voltage to 400 V.
4. At no-load measure the terminal voltage of the motor and the speed of the prime mover.
5. Apply the resistive load with steps and then measure the field current, load current, terminal voltage, power consumed by the load and the speed of the prime mover.
6. Calculate the voltage regulation at each load.
7. Tabulate your results in the following table.
8. Plot the external characteritics of the generator.

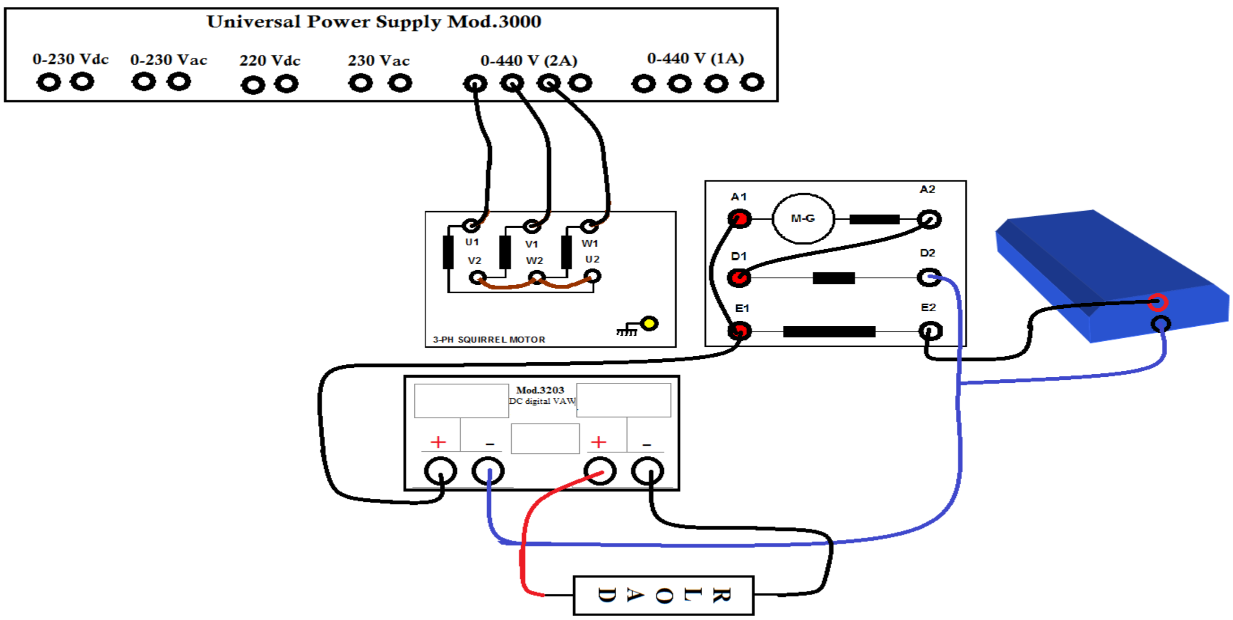


Figure (3)

Load (Ω)	Prime Mover	Compound DC Generator				Caculations
	Speed (rpm)	Field Current	Load Current	Terminal Voltage	Consumed Power	%VR
0						-
700						
400						
190						
150						
130						

Questions:

1. Specify the applications of DC shunt generators.
2. Differentiate between DC shunt Motor and DC shunt generator.
3. What happens if shunt field connections is reversed in the generator?
4. Where you can use DC Compound Generator?

Experiment (3)	Permanent Magnet DC Motor

Objectives:

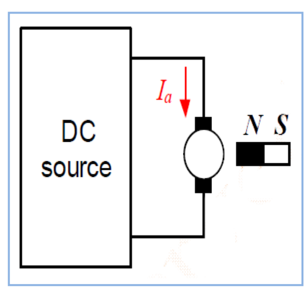
1. To familiarize with Permanent Magnet DC Motors components.
2. To measure the characteristics of a Permanent Magnet DC motors.
3. To demonstrate how to reverse the direction of rotation of PMDC motors.
4. Understand Permanent Magnet DC motors ratings.
5. Understand the techniques used for Permanent Magnet DC motors starting.
6. Understand how the speed of Permanent Magnet DC motors can be controlled.

Theory and concepts:

A permanent-magnet dc (PMDC) motor is a dc motor whose poles are made of permanent magnets. Permanent-magnet dc motors offer a number of benefits compared with shunt dc motors in some applications. Since these motors do not require an external field circuit, they do not have the field circuit copper losses associated with shunt dc motors. Because no field windings are required, they can be smaller than corresponding shunt dc motors. PMDC motors are especially common in smaller fractional and subfractional horsepower sizes, where the expense and space of a separate field circuit cannot be justified.

However, PMDC motors also have disadvantages. Permanent magnets cannot produce as high a flux density as an externally supplied shunt field, so a PMDC motor will have a lower induced torque τ_{ind} per ampere of armature current I_A than a shunt motor of the same size and construction.

With this type of machine the field is not created by an actual coil, but by the insertion of permanent magnets in the stator circuit. PM create a fixed field flux exactly in the same way as if a fixed current flowed in an excitation coil. Permanent Magnet excitation is equivalent to independent /shunt excitation machine with a fixed external excitation. PM excitation allows easy and robust machine construction, but does not allow flux modifications. It is typically used in small DC motors.



A permanent-magnet dc motor is basically the same machine as a shunt dc motor, except that the flux of a PMDC motor is fixed. Therefore, it is not possible to control the speed of a PMDC motor by varying the field current or flux. The only methods of speed control available for a PM DC motor are **armature voltage control** and **armature resistance control.**

Necessary Material:

1. **Mod.3000:** Universal Power Supply
2. **Mod.3142:** Permanent Magnet DC Motor
3. **Mod.3180:** Electromagnetic Break
4. **Mod.3203:** DC digital VAW
5. **Mod.3180C:** Torque and speed meter
6. **Mod.3012:** Field Regulator for DC motor.

Experimental Procedures:

Part I: Specifications of the Permanent Magnet DC Motor.

1. Read the nameplate of the Permanent Magnet DC Motor and then tabulate the rating values of the motor in the following table.

Name Plate of the Permanent Magnet DC Motor Mod.3142.			
Armature Voltage:		Armature Current:	
Power:		Speed:	
Duty Cycle:		Ingress Protection:	
Insulation Class:			

Part II: Measure of the Armature Resistance of the machine.

1. Connect the circuit as shown in figure 1.
2. Measure the Resistance of the armature winding with using ohmmeter.

Winding	Winding Resistance
Armature Winding	

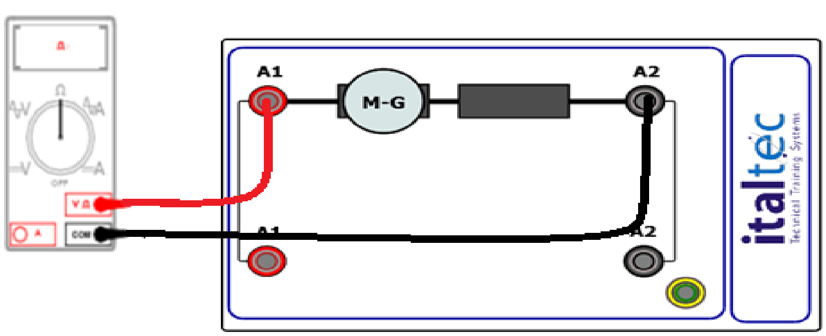


Figure (1)

Part III: Running the Motor Under no-load condition.

1. Connect the circuit as shown in the Figure 2.
2. Switch on the general switch; Switch on DC and acting on the regulating knob, increase the voltage up to 160 V.
3. Measure the speed, voltage applied to the motor, current and power absorbed by the motor under no-load condition.
4. Verify the direction of the motor.
5. Tabulate your results in the following table.

Applied Voltage	Speed (rpm)	Absorbed Current	Absorbed Power	Direction

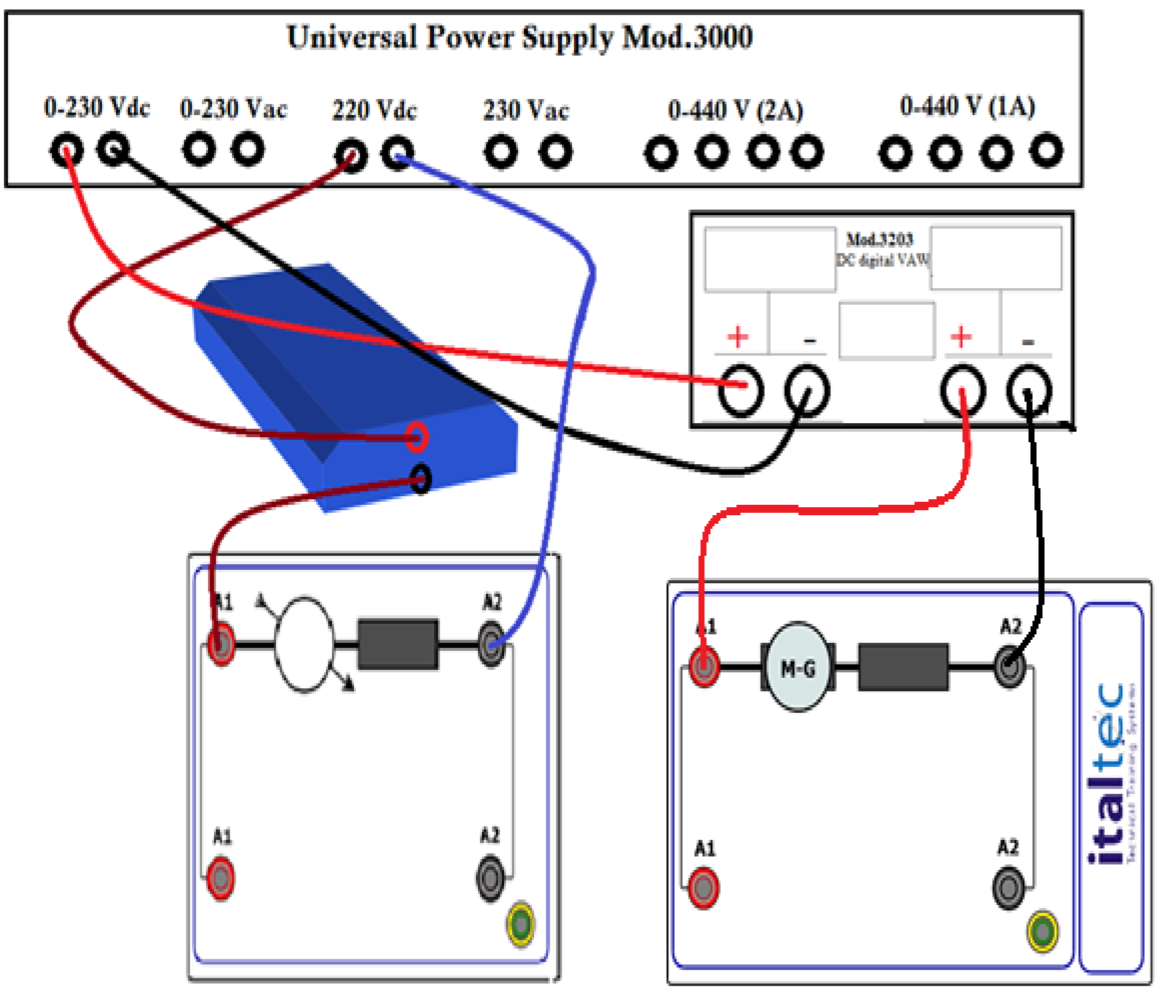


Figure (2)

Part IV: Reversing the direction of rotation of the Permanent Magnet DC Motor

1. Connect the circuit as shown in the Figure 3.
2. Switch on the general switch; Switch on DC and acting on the regulating knob, increase the voltage up to 160 V.
3. Verify the direction of the motor.
4. Tabulate your results in the following table.

Connection	Direction (CW,CCW)
Reversing the direction of rotation	

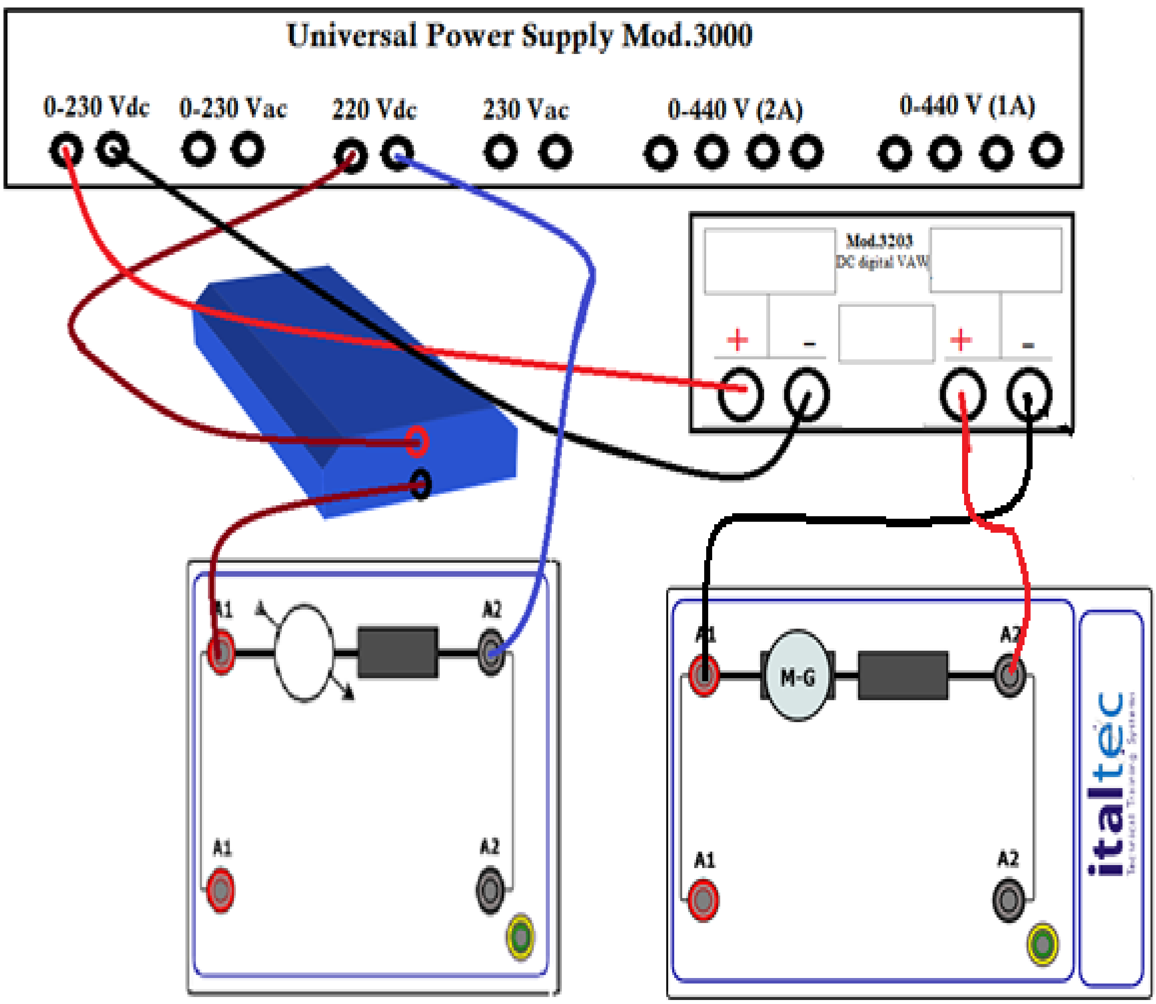


Figure (3)

Part V: Permanent Magnet DC Motor (with Starting rheostat)

1. Connect the circuit as shown in the Figure 4.
2. For starting purpose set the value of Rs to 100 Ω,
3. Switch on the general switch; Switch on DC and acting on the regulating knob, increase the voltage up to nominal voltage of the motor (160 V).
4. Measure the speed, absorbed current and power when the motor is unloaded.
5. Tabulate your results in the following table.

Applied Voltage	R_S (Ω)	Speed (rpm)	Absorbed Current	Absorbed Power	Load (W)
230	100				0

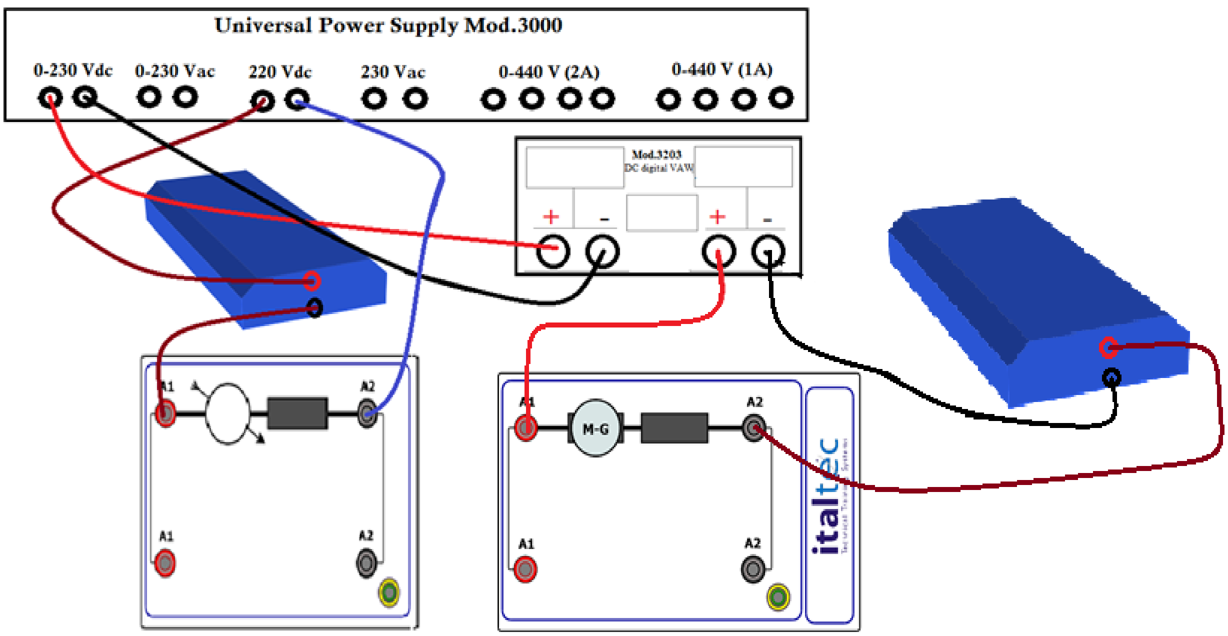


Figure (4)

Part VI: External characteristics of the Permanent Magnet DC Motor.

1. Make the mechanical coupling between the Permanent Magnet DC Motor and break unit.
2. Connect the circuit as shown in Figure 2.
3. Apply a DC voltage of 160-V at the terminals of the Permanent Magnet DC Motor and run the motor at no load condition.
4. Vary the meachanical load connected to the shaft of the motor by changing the dc voltage applied to the break unit.
5. Measure the speed, voltage applied to the motor, current and power absorbed by the motor at each value of the load.

6. Calcultae the output power, you may use the following relation:

Pout = τ (N.m) * ω (rad/sec) = (τ (g.m) *(10/1000)) * (2*3.14*n (rpm)/60))

7. Calculate the efficiency of the motor, you may use the following relation:

η = Pout/Pin *100%

8. Calculate the Speed regulation of the motor, you may use the following relation:

SR = n_{nl} - n_{fl} / n_{fl} *100%

9. Tabulate the results in the following table.

Motor				**Break unit**	**Calculations**		
Speed (rpm)	Applied Voltage	Absorbed Current	Absorbed Power	Torque (gr.m)	Pout	η	SR
				5			
				10			
				15			
				20			
				25			

10. Plot and explain the **mechanical characteristics** of the Permanent Magnet DC Motor. (Speed (Y-axis) vs Torque (X-axis))

11. Plot and explain the **electromechanical characteristics** of the Permanent Magnet DC Motor.
X-axis: Output Power
Relations:
- Efficiency (Y-axis)
- Speed (Y-axis)
- Current (Y-axis)

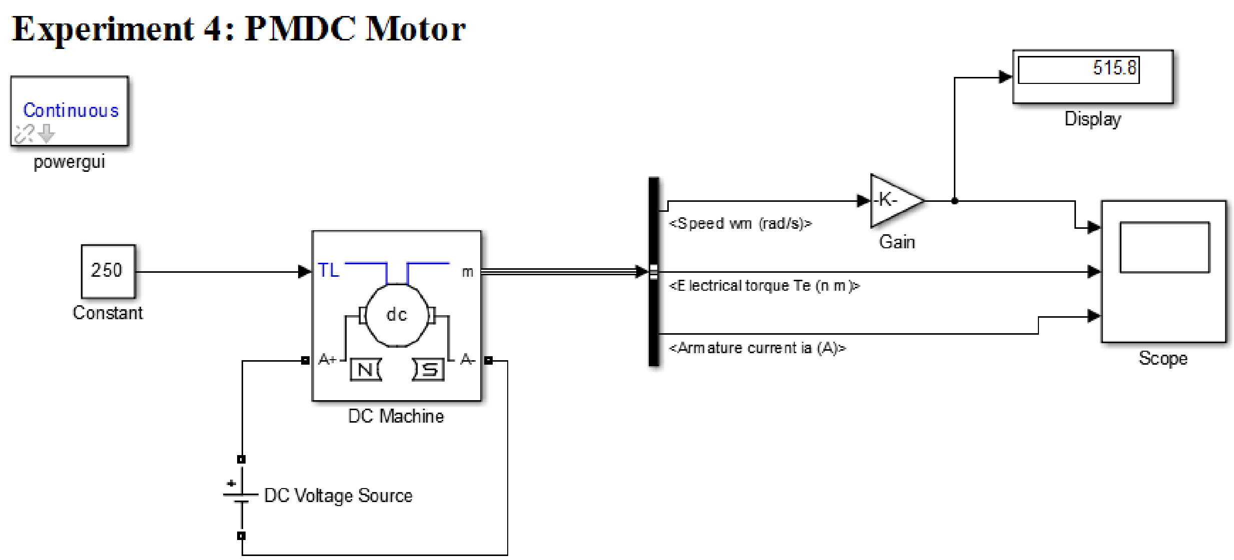
All the relationships should be plotted on the same graph.

Questions:

1. What are the characteristics of a Permanent Magnet DC motor?

Matlab Section

Use **MATLAB SIMULINK** to build the following circuit to simulate a PMDC Motor.



1. Obtain the speed, torque induced and the armature current curves from MATLAB Simulink at load torque equal to 250 and comment on them.
2. Change the load to 400 N.m and describe the changes happen on the speed of the motor.

Chapter 4

Special Machines

Contents

Experiment (1)	Universal Motor

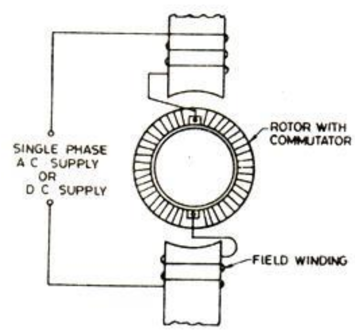
Objectives:

1. To familiarize with Universal Motor components.
2. To measure the characteristics of Universal Motor with operating on AC and on DC.
3. To demonstrate how to reverse the direction of rotation of a Universal Motor.
4. Understand Universal Motor ratings.

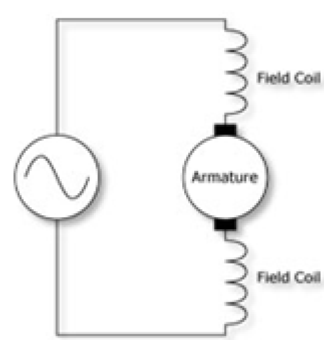
Theory and concepts:

A universal motor is a special type of motor which is designed to run on either DC or single phase AC supply. These motors are series wound (armature and field winding are in series), and hence produce high starting torque.

Most of the universal motors are designed to operate also at higher speeds, exceeding 3000 rpm. They run at lower speed on AC supply than they run on DC supply of same voltage, due to the reactance voltage drop which is present in AC and not in DC.



The universal motor is a commutated series-wound motor where the stator's field coils are connected in series with the rotor windings through a commutator. It is often referred to as an AC series motor. The universal motor is very similar to a DC series motor in construction, but it is modified slightly to allow the motor to operate properly on AC power. This type of electric motor can operate well on AC because the current in both the field coils and the armature (and the resultant magnetic fields) will alternate (reverse polarity) synchronously with the supply. Hence the resulting mechanical force will occur in a consistent direction of rotation, independent of the direction of applied voltage, but determined by the commutator and polarity of the field coils. Because of the commutator mechanism, universal motors are quite noisy, both acoustically and electromagnetically.



An advantage of the universal motor is that AC supplies may be used on motors which have some characteristics more common in DC motors, specifically high starting torque and very compact design if high running speeds are used.

Torque-Speed Characteristics

Series wound electric motors respond to increased load by slowing down; the current increases and the torque rises in proportion to the square of the current since the same current flows in both the armature and the field windings. If the motor is stalled, the current is limited only by the total resistance of the windings and the torque can be very high, and there is a danger of the windings becoming overheated. The counter-EMF aids the armature resistance to limit the current through the armature.

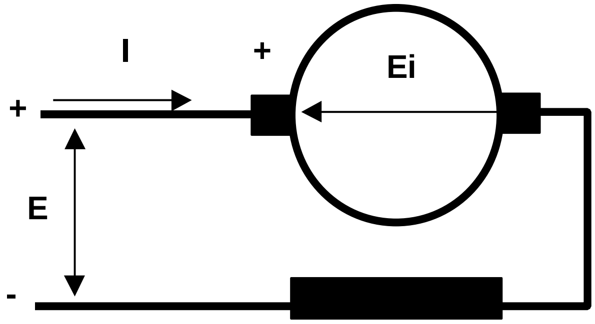
When power is first applied to a motor, the armature does not rotate. At that instant, the counter-EMF is zero and the only factor limiting the armature current is the armature resistance. Usually the armature resistance of a motor is low; therefore the current through the armature would be very large when the power is applied. Therefore the need can arise for an additional resistance in series with the armature to limit the current until the motor rotation can build up the counter-EMF. As the motor rotation builds up, the resistance is gradually cut out. Alternatively it would be useful to feed the motor with a variable voltage from a few initial volts to the working voltage.

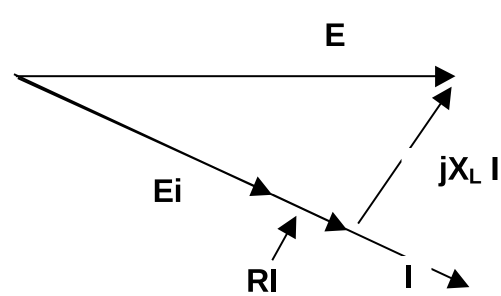
The speed-torque characteristic is an almost perfectly straight line between the stall torque and the no-load speed. This suits large inertial loads as the speed will drop until the motor slowly starts to rotate and these motors have a very high stalling torque.

Motor damage may occur from over-speeding (running at a rotational speed in excess of design limits of about 4000 rpm) if the unit is operated with no significant mechanical load. Sudden loss of load is to be avoided.

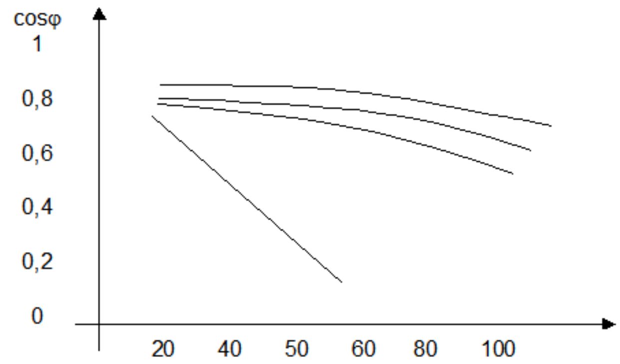
The fan blade attached to the shaft acts as a small artificial load to limit a bit the motor speed to a safe level, as well as a means to circulate cooling air flow over the armature and field windings. If there were no mechanical limits placed on a universal motor it could theoretically speed out of control in the same way any series-wound DC motor can.

In order to improve power factor it is useful to reduce as possible the reactance of the total electrical circuit (armature and inductor). As showed the power factor increases when there is an increase of the motor's speed, as Ei.

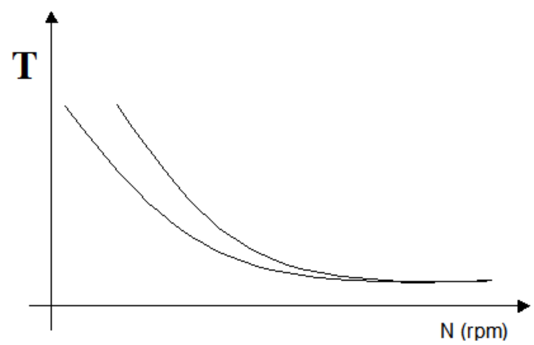




As the speed increases, because of the inductance of the rotor, the ideal commutating point changes.



The mechanical characteristics of the motor with segment commutator series type (supplied with alternating current) are the same of the motor supplied with DC current. The motor series with a great power can be used for the traction and in some equipment for the lifting (crane and goods-lift).



The motor series with little power can be used in different electrical household appliances (polisher, vacuum cleaner, whisk, and ventilator). We can call this motor also universal motor as it can operate both with DC direct current and with AC current.

The power developed by the motor with the alternating current is inferior to the one developed with direct current; the same thing happened with the starting couple

Ts = 2,5 to 4 *Tn with AC;   Ts = 4 to 6 * Tn with DC.

Necessary Material:

1. **Mod.3000:** Universal Power Supply
2. **Mod.3130:** Universal Motor
3. **Mod.3180:** Electromagnetic Break
4. **Mod.3203:** DC digital VAW
5. **Mod.3180C:** Torque and speed meter

Experimental Procedures:

Part I: Specifications of the Universal Motor.

1. Read the nameplate of the Universal Motor and then tabulate the rating values of the motor in the following table.

Name Plate of the Universal Motor Mod.3130.				
Voltage:	DC		AC	
Current:	DC		AC	
Power:	DC		AC	
Speed:	DC		AC	
Frequency:			Duty Cycle:	
Ingress Protection:			Insulation Class:	

Part II: Running the Motor Under no-load condition (AC-Operation).

1. Connect the circuit as shown in the Figure 1.
2. Switch on the general switch; Switch on AC and acting on the regulating knob, increase the voltage up to 110-V.

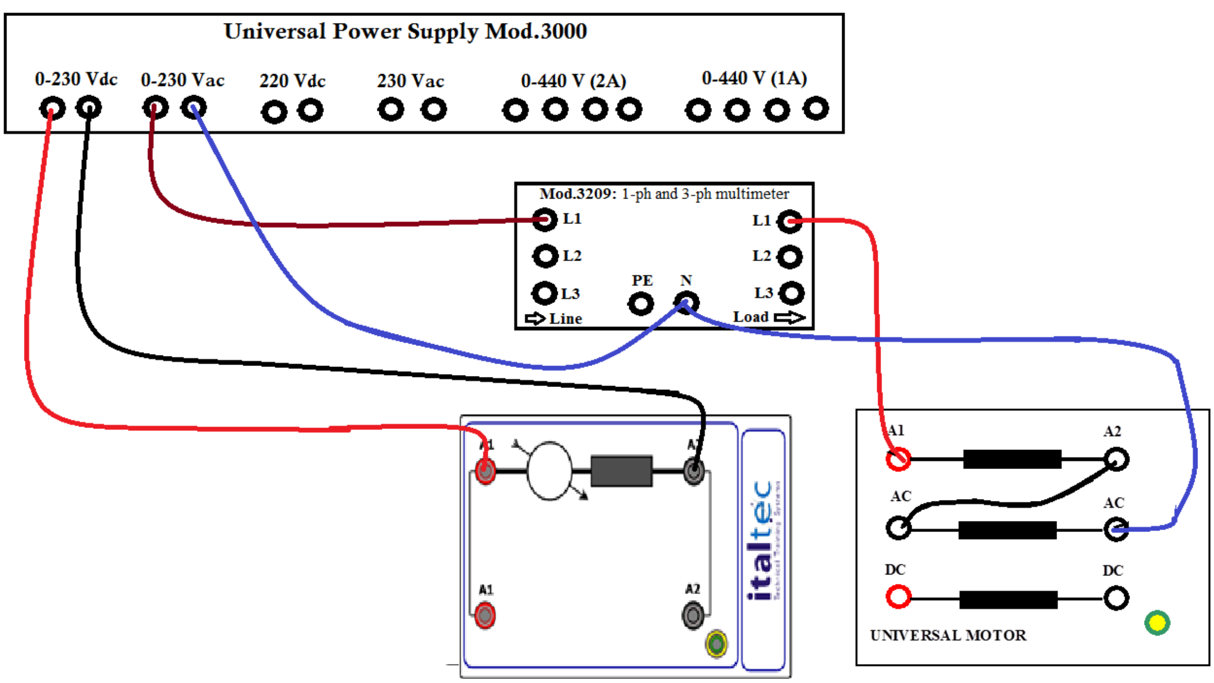


Figure (1)

3. Measure the speed, voltage applied to the motor, current and power absorbed by the motor under no-load condition.
4. Verify the direction of the motor.
5. Tabulate your results in the following table.

Applied Voltage	Speed (rpm)	Absorbed Current	Absorbed Power	Direction

Part III: Running the Motor Under no-load condition (DC-Operation).

1. Connect the circuit as shown in the Figure 2.
2. Switch on the general switch; Switch on DC and acting on the regulating knob, increase the voltage up to 110-V.
3. Measure the speed, voltage applied to the motor, current and power absorbed by the motor under no-load condition.
4. Verify the direction of the motor.
5. Tabulate your results in the following table.

Applied Voltage	Speed (rpm)	Absorbed Current	Absorbed Power	Direction

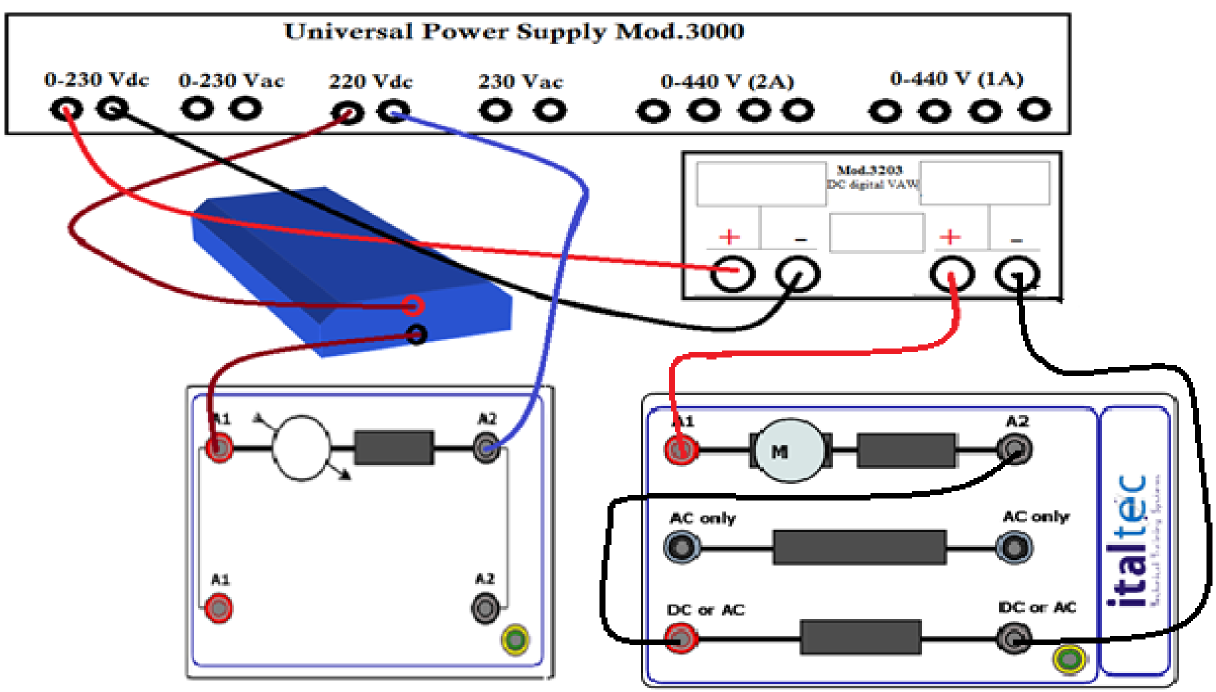


Figure (2)

Part IV: Reversing the direction of rotation of the Universal Motor (AC Operation).

1. Connect the circuit as shown in the Figure 3.
2. Switch on the general switch; Switch on AC and acting on the regulating knob, increase the voltage up to (110 V).
3. Verify the direction of the motor.
4. Tabulate your results in the following table.

Connection	Direction (CW,CCW)
Reversing the direction of rotation	

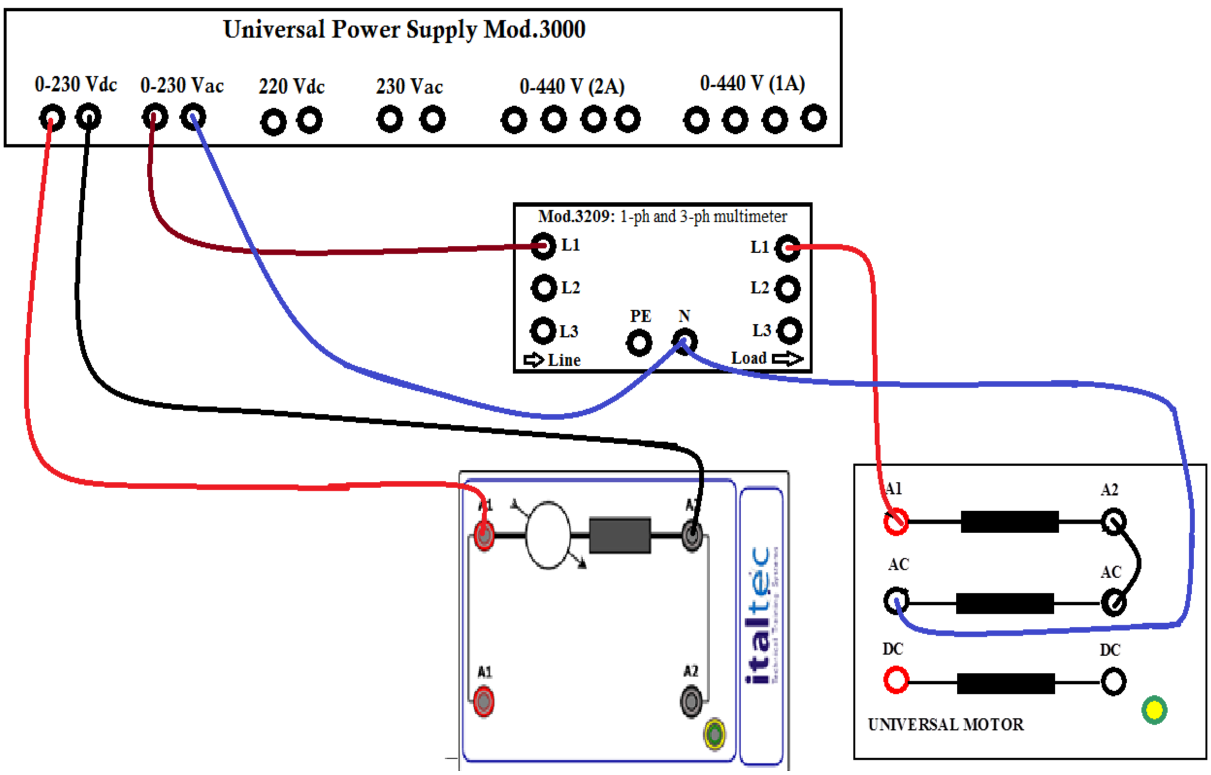


Figure (3)

Part IV: Reversing the direction of rotation of the Universal Motor (DC Operation).

1. Connect the circuit as shown in the Figure 4.
2. Switch on the general switch; Switch on DC and acting on the regulating knob, increase the voltage up to (110 V).
3. Verify the direction of the motor.

4. Tabulate your results in the following table.

Connection	Direction (CW,CCW)
Reversing the direction of rotation	

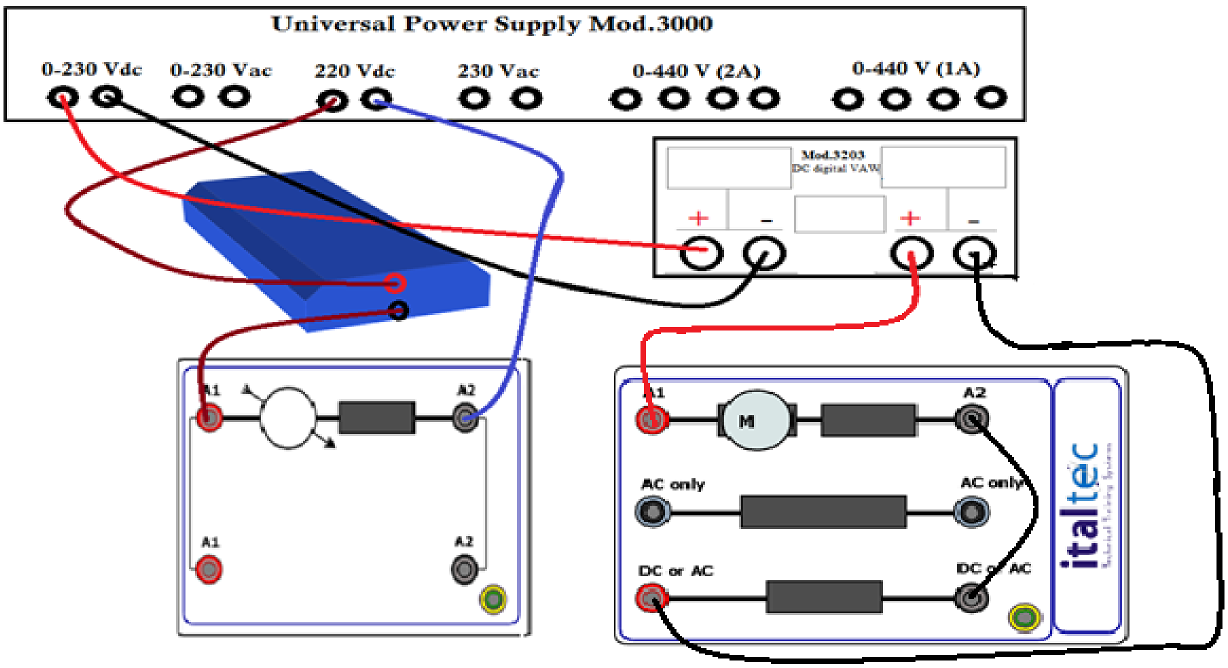


Figure (4)

Part VI: External characteristics of the Universal Motor (AC Operation).

1. Make the mechanical coupling between the Universal Motor and break unit.
2. Connect the circuit as shown in Figure 1.
3. Apply an AC voltage at the terminals of the Universal Motor and run the motor at no load condition.
4. Vary the meachanical load connected to the shaft of the motor by changing the dc voltage applied to the break unit.
5. Measure the speed, voltage applied to the motor, current and power absorbed by the motor and the Power Factor at each value of the load.
6. Calcultae the output power, you may use the following relation:

Pout = τ (N.m) * ω (rad/sec) = (τ (g.m) *(10/1000)) * (2*3.14*n (rpm)/60))

7. Calculate the efficiency of the motor, you may use the following relation:

η = Pout/Pin *100%

8. Calculate the Speed regulation of the motor, you may use the following relation:

   SR = n_{nl} - n_{fl} / n_{fl} *100%

9. Tabulate the results in the following table.

Motor					Break unit	Calculations		
Speed (rpm)	Applied Voltage	Absorbed Current	Absorbed Power	PF	Torque (gr.m)	Pout	η	SR
	144				5			
	151				10			
	168				15			
	186				20			
	188				25			

10. Plot and explain the **mechanical characteristics** of the Universal Motor.
    (Speed (Y-axis) vs Torque (X-axis))

11. Plot and explain the **electromechanical characteristics** of the Universal Motor.
    X-axis: Output Power
    Relations:
    - Efficiency (Y-axis)
    - Speed (Y-axis)
    - Current (Y-axis)
    - PF (Y-axis)

All the relationships should be plotted on the same graph.

Questions:

1. What changes are necessary in a series dc motor to adapt it for operation from an ac power source?

2. Why is the torque-speed characteristic of a Universal motor on an ac source different from the torque-speed characteristic of the same motor on a dc source?

Experiment (2)	Repulsion Motor

Objectives:

1. To familiarize with Repulsion motor components.
2. To study the relationship between speed and brush angle of the rotor.
3. To understand and familiarize with the working of Repulsion Motor.
4. To investigate different characteristics (torque, speed, current, power, power factor and efficiency) of the repulsion motor.
5. To understand Repulsion motors ratings.

Theory and concepts:

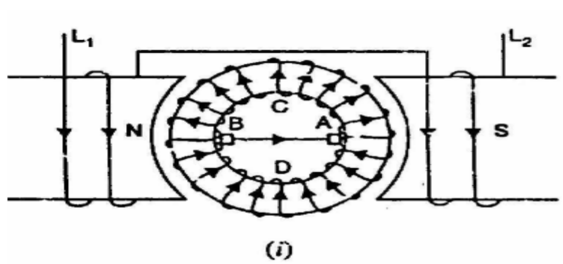
A repulsion motor is a type of electric motors which runs on alternating current (AC). Repulsion motors are classified under single phase motors. In repulsion motors the stator windings are connected directly to the AC power supply and the rotor is connected to a commutator and brush assembly, similar to that of a direct current (DC) motor.

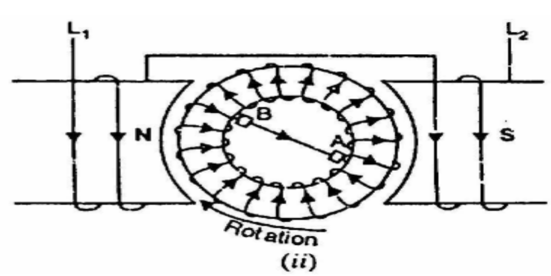
Construction

The field of stator winding is wound like the main winding of a split-phase motor and it is connected directly to a single-phase source. The armature or rotor is similar to a DC motor armature with drum type winding connected to a commutator. However, the brushes are not connected to supply but are connected to each other or short-circuited. Short-circuiting the brushes effectively makes the rotor into a type of squirrel cage. The major difficulty with an ordinary single-phase induction motor is the low starting torque. By using a commutator motor with brushes short-circuited, it is possible to vary the starting torque by changing the brush axis. It has also better power factor than the conventional single-phase motor.

Principle of operation

The principle of operation is illustrated in Figure (1) which shows a two-pole repulsion motor with its two short-circuited brushes.



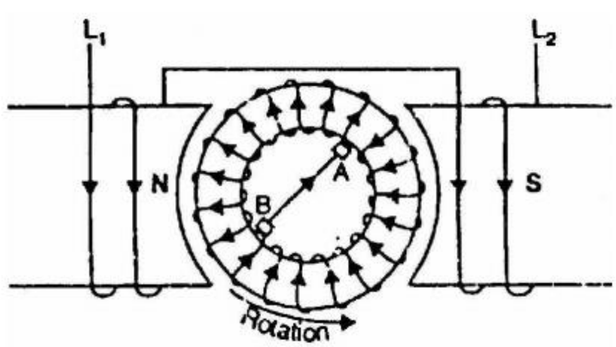


The two drawings of Figure (1) represent a time at which the field current is increasing in the direction shown so that the left-hand pole is N-pole and the right-hand pole is S-pole at the instant shown.

- In Figure (1-i), the brush axis is parallel to the stator field. When the stator winding is energized from single-phase supply, e.m.f. is induced in the armature conductors (rotor) by induction. By Lenz's law, the direction of the e.m.f. is such that the magnetic effect of the resulting armature currents will oppose the increase in flux. The direction of current in armature conductors will be as shown in Fig. (1-i). With the brush axis in the position shown in Fig. (1-i), current will flow from brush B to brush A where it enters the armature and flows back to brush B through the two paths ACB and ADB. With brushes set in this position, half of the armature conductors under the N-pole carry current inward and half carry current outward. The same is true under S-pole. **Therefore, as much torque is developed in one direction as in the other and the armature remains stationary.** The armature will also remain stationary if the brush axis is perpendicular to the stator field axis. It is because even then **net torque is zero**.

- If the brush axis is at some angle other than 0° or 90° to the axis of the stator field, a net torque is developed on the rotor and the rotor accelerates to its final speed. Figure (1-ii) represents the motor at the same instant as that in Figure (1-i) but the brushes have been shifted clockwise through some angle from the stator field axis. Now e.m.f. is still induced in the direction indicated in Figure (1-i) and current flows through the two paths of the armature winding from brush A to brush B. However, because of the new brush positions, the greater part of the conductors under the N pole carry current in one direction while the greater part of conductors under S-pole carry current in the opposite direction. With brushes in the position shown in Figure (1-ii), **torque is developed in the clockwise direction and the rotor quickly attains the final speed**.

- The direction of rotation of the rotor depends upon the direction in which the brushes are shifted, if the brushes are shifted in clockwise direction from the stator field axis, the net torque acts in the clockwise direction and the rotor accelerates in the clockwise direction. If the brushes are shifted in anti-clockwise direction as in Figure (2) the armature current under the pole faces is Reversed and the net torque is developed in the anti-clockwise direction. **Thus, a repulsion motor may be made to rotate in either direction depending upon the direction in which the brushes are shifted.**



- **The total armature torque in a repulsion motor can be shown to be**

  $T_a \propto \sin 2\alpha$

  Where α = angle between brush axis and stator field axis

  For *maximum torque*, 2α = 90° or **α = 45°.**

  Thus adjusting α to 45° at starting, maximum torque can be obtained during the starting period. However, α has to be adjusted to give a suitable running speed.

Characteristics of the motor:

1. It has a high starting torque and a high speed at no load.
2. The speed which the repulsion motor develops for any given load will depend upon the position of the brushes.
3. In comparing with other single-phase motors, the repulsion motor has a high starring torque and relatively low starting current.

Necessary Material:

1. **Mod.3000:** Universal Power Supply
2. **Mod.3100:** Repulsion Motor
3. **Mod.3180:** Electromagnetic Break
4. **Mod.3203:** DC digital VAW
5. **Mod.3209:** 1-ph and 3-ph multimeter
6. **Mod.3180C:** Torque and speed meter

Experimental Procedures:

Part I: Specifications of the Repulsion Motor.

1. Read the nameplate of the Repulsion Motor then tabulate the rating values of the motor in the following table:

Name Plate of the Repulsion Motor Mod.3090					
Voltage:		Power:		PF	
Frequency:		Speed:			
Current:		Duty Cycle:			
Ingress Protection:		Insulation Class:			

Part II: Running the motor under no-load condition, reversing the direction of the repulsion motor and study the relationship between speed and brush angle of the rotor.

1. Connect the circuit as shown in figure 1.
2. Apply a phase voltage of 220-V (rated voltage of the motor) at the terminals of the repulsion motor and run the motor.
3. Adjust the brush moving arm (speed regulation and inversion) in the two directions and observe the change in the speed and the direction of rotation, tabulate your result in the following table:

Brush moving arm	Speed	Direction
Case 1: up direction (90^o)		
Case 2: arm goes to CW direction		
Case 3: arm goes to CCW direction		

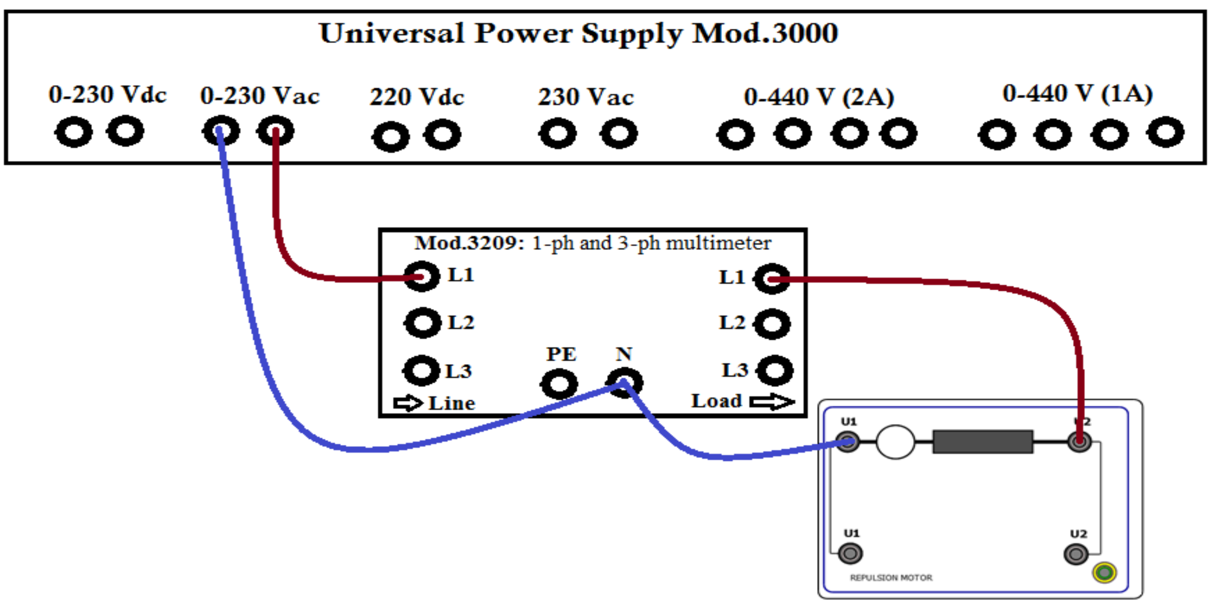


Figure (1)

Part II: External characteristics of the Repulsion Motor.

1. Make the mechanical coupling between the repulsion motor and break unit.
2. Connect the circuit as shown in figure 2.
3. Apply a phase voltage of 220-V at the terminals of the induction motor and run the motor at no load condition.

4. Vary the meachanical load connected to the shaft of the motor by changing the dc voltage applied to the break unit.
5. Measure the speed, voltage applied to the motor, current and power absorbed by the motor and the Power Factor at each value of the torque of the load.
6. Calcultae the output power, you may use the following relation:

Pout = τ (N.m) * ω (rad/sec) = (τ (g.m) *(10/1000)) * (2*3.14*n (rpm)/60))

7. Calculate the efficiency of the motor, you may use the following relation:

η = Pout/Pin *100%

8. Calculate the Speed regulation of the motor, you may use the following relation:

SR = n_{nl} - n_{fl} / n_{fl} *100%

9. Tabulate the results in the following table.

Motor					Break unit	Calculations		
Speed (rpm)	Line Voltage	Line Current	Pin	PF	Torque (gr.m)	Pout	η	SR
	220				0			
	220				6			
	220				8			
	220				10			
	220				12			
	220				16			

10. Plot and explain the mechanical characteristics of the Repulsion Motor.
Plot (Torque (Y-axis) vs Speed (X-axis))

11. Plot and explain the electromechanical characteristics of the Repulsion Motor.
X-axis: Output Power
Relations:
- Efficiency (Y-axis)
- Speed (Y-axis)
- Current (Y-axis)
- PF (Y-axis)

All the relationships should be plotted on the same graph.

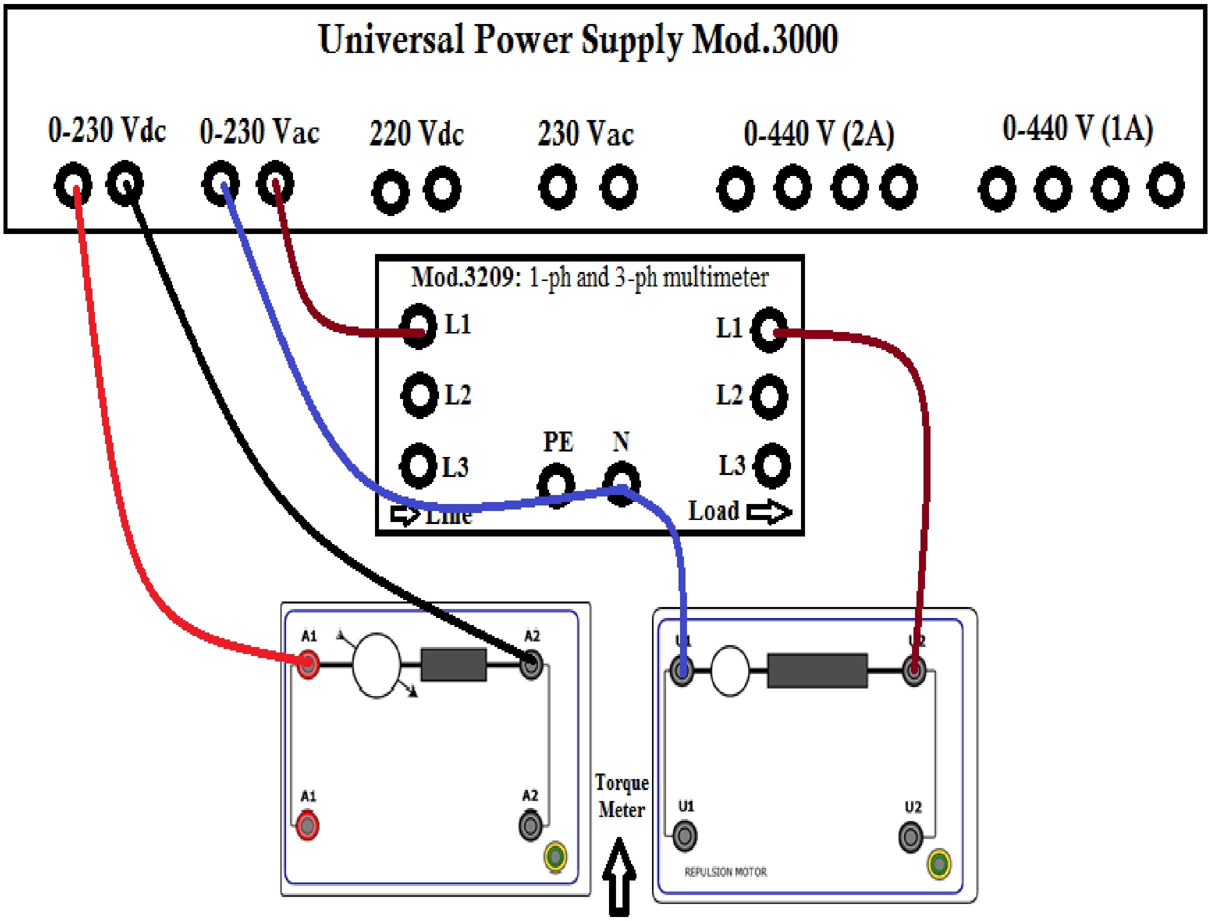


Figure (2)

Questions:

1. Explain the effect of the brush angle of the rotor on the speed and torque of repulsion motor?

2. How can the direction of rotation of the repulsion motor be reversed?

Experiment (3)	Three Phase Synchronous Reluctance Motor

Objectives:

1. To familiarize with Synchronous Reluctance Motor components.
2. To investigate different characteristics (torque, speed, current, power, power factor and efficiency) of the Synchronous Reluctance Motor.
3. To understand Synchronous Reluctance Motor ratings.

Theory and concepts:

A reluctance motor is a motor which depends on reluctance torque for its operation. Reluctance torque is the torque induced in an iron object (such as a pin) in the presence of an external magnetic field, which causes the object to line up with the external magnetic field. This torque occurs because the external field induces an internal magnetic field in the iron of the object, and a torque appears between the two fields, twisting the object around to line up with the external field. In order for a reluctance torque to be produced in an object, it must be elongated along axes at angles corresponding to the angles between adjacent poles of the external magnetic field.

A self-starting reluctance motor that will operate at synchronous speed until its maximum reluctance torque is exceeded can be built by modifying the rotor of an induction motor as shown in Figure 1. In this figure, the rotor has salient poles for steady-state operation as a reluctance motor and also has cage or amortisseur windings for starting. current.

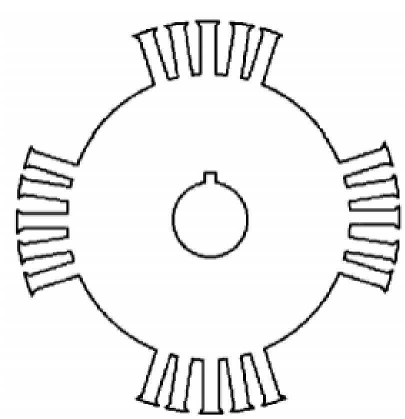
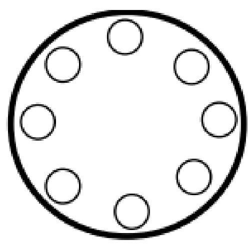


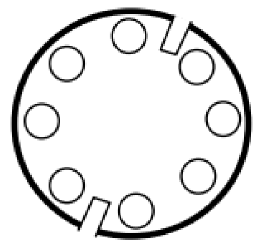
Fig 1: Rotor design of a synchronus relactance motor.

The rotor of this motor is shown in Figure 2. It uses "flux guides" to increase the coupling between adjacent pole faces and therefore to increase the maximum Reluctance Torque of the motor. With these flux guides, the maximum-reluctance torque is increased to about 150 percent of the rated torque, as compared to just over 100 percent of the rated torque for a conventional reluctance motor.

The rotor of the cage motor is milled in an appropriate way and in opposed position to obtain a shape such as it is indicated in the next picture.



Rotor of a cage motor



Rotor of a reluctance motor

This modification change value in the magnetic field in the motor and it creates a zone of reluctance which attracts quickly the poles of the motor that put on speed and synchronise itself near the speed of synchronism. The synchronism is maintained for the shape which has the protruding poles of the rotor because a different reluctance in the air gap is created. The reluctance motors are made for particular applications in which a number of constant revolutions are required, for example: cinema field and in the sector of the textile machines.

Necessary Material:

1. **Mod.3000:** Universal Power Supply
2. **Mod.3080:** Three Phase Reluctance Motor
3. **Mod.3180:** Electromagnetic Break
4. **Mod.3203:** DC digital VAW
5. **Mod.3209:** 1-ph and 3-ph multimeter
6. **Mod.3180C:** Torque and speed meter

Experimental Procedures:

Part I: Specifications of the Reluctance Motor.

1. Read the nameplate of the Repulsion Motor then tabulate the rating values of the motor in the following table:

<table>
<tr><td colspan="7">Name Plate of the Three-Phase Reluctance Motor Mod.3080</td></tr>
<tr><td>Voltage:</td><td>Y</td><td></td><td>Δ</td><td></td><td>Power:</td><td></td></tr>
<tr><td>Current:</td><td>Y</td><td></td><td>Δ</td><td></td><td>Speed:</td><td></td></tr>
<tr><td>Frequency:</td><td colspan="2"></td><td>Poles:</td><td></td><td>PF:</td><td></td></tr>
<tr><td>Duty Cycle:</td><td colspan="4"></td><td>Ingress Protection:</td><td></td></tr>
<tr><td colspan="5">Insulation Class:</td><td colspan="2"></td></tr>
</table>

Part II: Running the motor under no-load condition with Star connection.

1. Connect the circuit as shown in figure 1.
2. Apply a 3-phase voltage of 400-V at the terminals of the induction motor and run the motor.
3. Measure the speed at no-load condition, the starting current and the steady state current drawn by the motor.
4. Tabulate your results in the following table.

Condition	Speed	Starting Current	Steady State Current
No-load (Y-connection)			

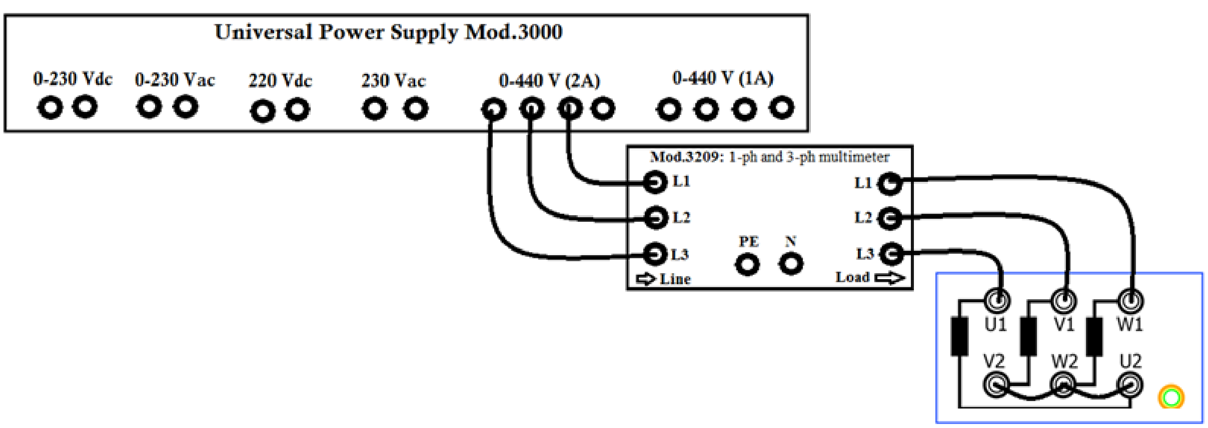


Figure (1)

Part III: Running the motor under no-load condition with Delta connection.

1. Connect the circuit as shown in figure 2.
2. Apply a 3-phase voltage of 230-V at the terminals of the induction motor and run the motor.
3. Measure the speed at no-load condition, the starting current and the steady state current drawn by the motor.
4. Tabulate your results in the following table.

Condition	Speed	Starting Current	Steady State Current
No-load (Δ-connection)			

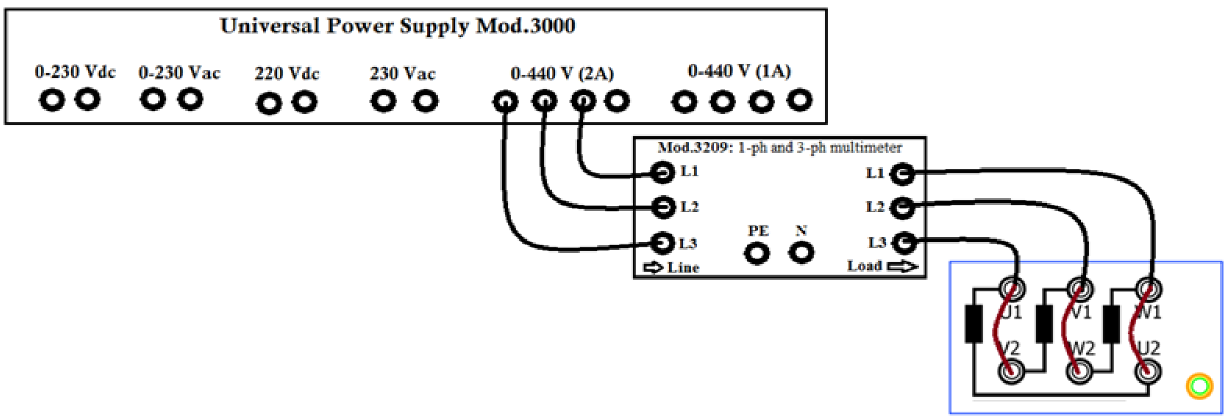


Figure (2)

Part VI: Reversing the direction of the Three-Phase Slip Ring Induction Motor.

1. Connect the circuit as shown in figure 3.
2. Apply a 3-phase voltage of 400-V at the terminals of the induction motor and run the motor, Observe the direction of rotation of the motor.
3. Now with two phases interchanged L2 and L3, Observe the direction of rotation of the motor.
4. Tabulate your result in the following table.

Lines			Direction (CW,CCW)
L1	L2	L3	
L1	L3	L2	

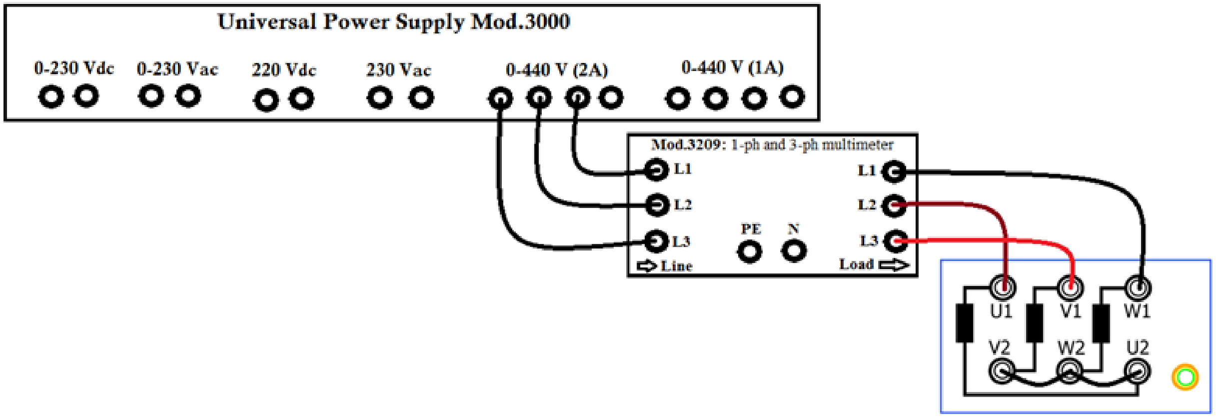


Figure (3)

Part VI: External characteristics of the Three-Phase Reluctance Motor.

1. Make the mechanical coupling between the Slip Ring Induction Motor and break unit.
2. Connect the circuit as shown in Figure 4.
3. Apply a line voltage of 400-V at the terminals of the induction motor and run the motor at no load condition.
4. Vary the meachanical load connected to the shaft of the motor by changing the dc voltage applied to the break unit.

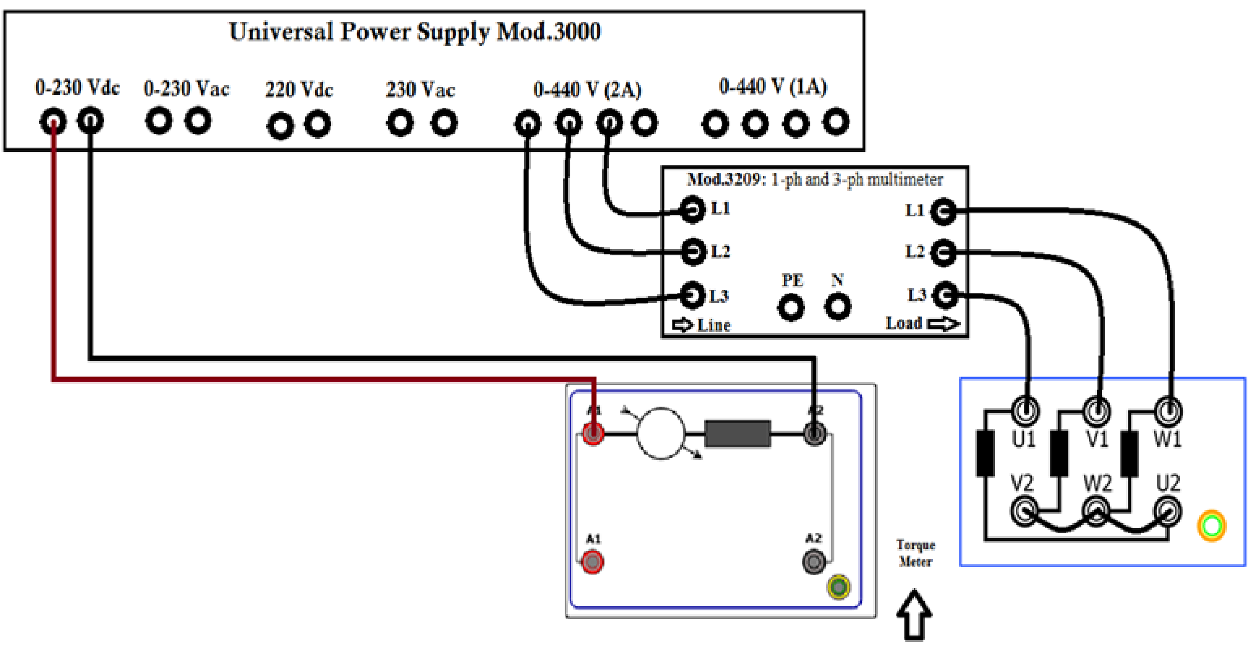


Figure (4)

5. Measure the speed, voltage applied to the motor, current and power absorbed by the motor and the Power Factor at each value of the torque of the load use ItalTec Software.

6. Calcultae the output power, you may use the following relation:

   Pout = τ (N.m) * ω (rad/sec) = (τ (g.m) *(10/1000)) * (2*3.14*n (rpm)/60))

7. Calculate the efficiency of the motor, you may use the following relation:

   η = Pout/Pin *100%

8. Calculate the Speed regulation of the motor, you may use the following relation:

   SR = n_{nl} - n_{fl} / n_{fl} *100%

9. Tabulate the results in the following table.

Motor					**Break unit**	**Calculations**		
Speed (rpm)	Line Voltage	Line Current	Pin	PF	Torque (gr.m)	Pout	η	SR
	400				5			
	400				10			
	400				20			
	400				30			
	400				40			
	400				50			
	400				60			
	400				70			
	400				80			
	400				90			
	400				100			

10. Plot and explain the **mechanical characteristics** of the 3-ph Slip Ring IM.
    (Torque (Y-axis) vs Speed (X-axis))

11. Plot and explain the **electromechanical characteristics** of the 3-ph Slip Ring IM.
    X-axis: Output Power
    Relations:
    - Efficiency (Y-axis)
    - Speed (Y-axis)
    - Current (Y-axis)
    - PF (Y-axis)

Questions:

1. Discuss why Synchronous reluctance motors are now considered superior to induction motors.

2. Compare between the following motors in terms of:

Term	**Reluctance Motor**	**Synchronous Motor**
Rotor Type		
Starting		
Speed		