INTRODUCTION TO ELECTRICAL ENGINEERING
(ESO 203A)

LABORATORY MANUAL

DEPARTMENT OF ELECTRICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY KANPUR

WHAT IS EXPECTED OF YOU

This laboratory is an integral part of the course **Introduction to Electrical Engineering** (**ESO 203A**). Its objective is to supplement the theoretical knowledge with the practical aspect of the subject matter. Development of experimental skills, the ability to set up and carry out appropriate experiments and draw relevant conclusions are essential in the formation of an engineer. You must carefully consider the following points while preparing and performing each experiment and while reporting the observations.

1. Students must come prepared for each experiment. You should read and understand the theory and the experimental aspects beforehand. You must chalk out a proper plan for carrying out the experiments (such as plan for layout of circuit etc.).
2. Each student must come to the lab with individual lab sheet, calculator, graph sheet etc. Students are required to bring lab sheet with the title of experiment, theory, circuit diagram and observation table already prepared. All the students are required to get the observations/readings verified and get the observation sheets signed by the lab instructors/tutors. Each student has to submit the lab report to the instructor/tutor in the next lab class.
3. The students should wear shoes (not the slippers), while performing the experiments. Students are required to get the connections verified by the lab TAs, before switching on the power supply. Utmost care should be taken while handling the equipments to avoid any damage or electrical shock.
4. Perform all the experiments with care. Otherwise you may damage some expensive equipment. Carefully consider the specifications and limitations of the equipment you are working with.
5. You should pay attention to the accuracy of measurements based on the knowledge of tolerance of circuit elements used and limitations of measuring equipment.
6. Recording of observations, results, and discussions should be well organized from the point of view of clarity and completeness.
7. If you observe any unusual or interesting phenomenon, do try to investigate its nature and discuss it with your instructor.
8. Each student must complete all the experiments. Make-lab will be announced to complete the missed experiments, if any, during the regular lab hours.

Lists of Experiments

Exp. No.	Title
1	Determination of Thevenin equivalent of a given electrical circuit.
2	Power measurement in balanced three-phase circuits.
3	Determination of self and mutual inductances of coils.
4	To study the windings of a transformer and assembling a small transformer.
5	Determination of the equivalent circuit of a single-phase transformer and evaluation of its performance.
6	To study the characteristics of a DC generator.
7	To study the characteristics and speed control of DC motors.
8	Determination of load characteristics of a capacitor run induction motor.

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EXPERIMENT NO. 1: DETERMINATION OF THEVENIN EQUIVALENT OF A GIVEN ELECTRICAL CIRCUIT

The purpose of this experiment is to determine the Thevenin equivalent of a given electrical circuit experimentally and use the equivalent circuit for theoretically predicting the current through a given circuit element appearing across terminals A-B of the circuit. The results must be verified through

(i) Actual test
(ii) Theoretical estimation of Thevenin equivalent of the circuit.
(iii) KVL equations.

Brief Theory

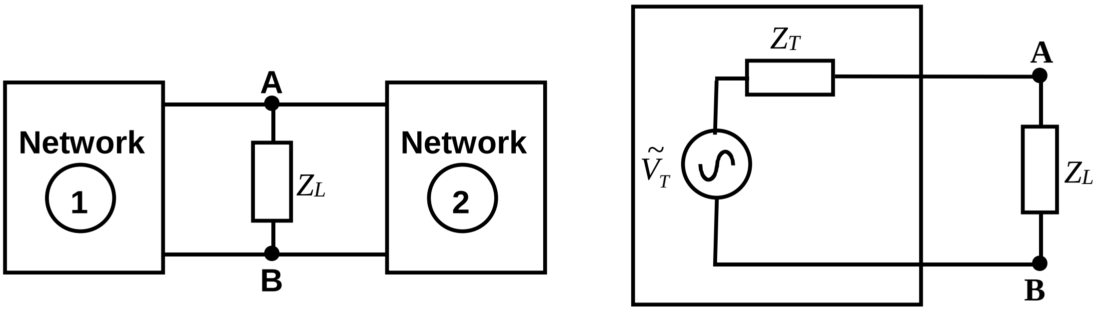
Consider an electrical circuit consisting of active sources and passive elements with no mutual coupling and working at steady state with sinusoidal excitations at the same frequency as shown in Fig. 1.1 (a). In so far as the impedance Z_L across the terminals A-B is concerned, the circuit can be replaced by an equivalent voltage source $\tilde{V}_T$ in series with equivalent source impedance Z_T, when looked at across the terminal A-B from the impedance Z_L. The resulting equivalent circuit is shown in Fig. 1.1 (b), where

$\tilde{V}_T$ = Open circuit voltage appearing across A-B with Z_L removed,
Z_T = Effective impedance of circuit seen across A-B with all sources deactivated and replaced by their internal impedances.

Thevenin's theorem leads to a convenient method of determining the current flow through a part of an interconnected electric circuit, with relative ease, especially while studying the effect of change in a circuit parameter.

Laboratory Work

The electric circuit chosen for experimental validation of Thevenin's theorem is shown schematically in Fig. 1.2, and the experimental set up is depicted in Fig. 1.3. Follow the steps given below.



(a) (b)

Fig. 1.1 (a) Schematic Representation of an Electrical Network and (b) Thevenin Equivalent of the Network of (a) when viewed across terminals A-B.

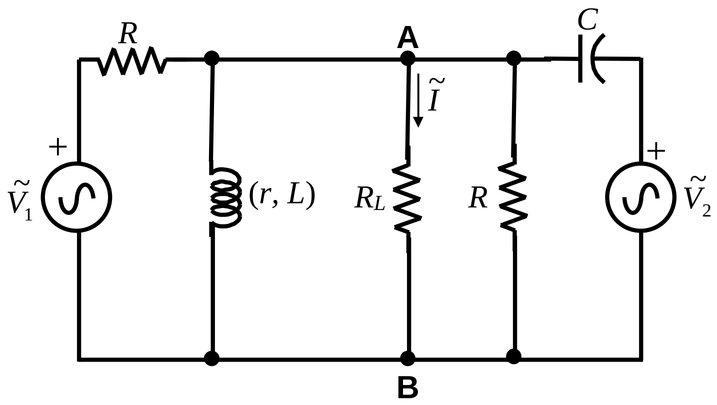
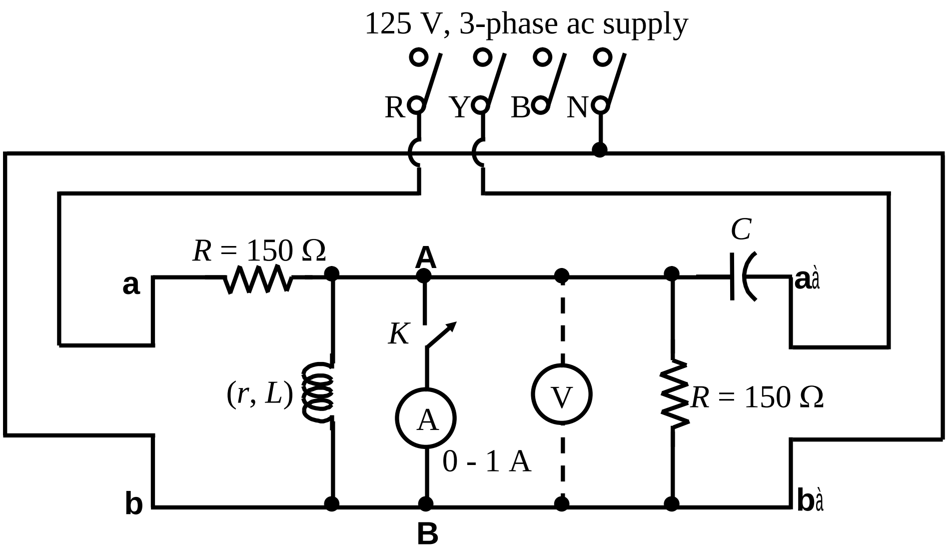


Fig. 1.2 Schematic Circuit Arrangement.



$r = 1.8\Omega$, $L = 0.45$ H and $C = 15$ μF

Fig. 1.3 Connection Diagram.

1. Connect the circuit as per Fig. 1.3 and get it checked by your lab tutor/TA. Voltmeter should not be connected permanently. One terminal of V should be open to measure $|V_{ab}|$,

$|V_{a'b'}|$ and $|V_T|$. (**Precaution**: Use digital multimeter to verify the potentiometer resistances)

2. Place the key K at **open** position, as shown in Fig. 1.3.
3. Switch on the 3-phase ac supply and note down the voltages $|V_{ab}|$ and $|V_{a'b'}|$.
4. Record the reading of the voltmeter,V as $|V_T|$.
5. Close key K, shown in Fig. 1.3.
6. Record the reading of the ammeter A as $|I|$.
7. Switch off the 3-phase ac supply.
8. Replace the original connections across the terminals A-B by a resistance R = 10 ohms and an ammeter, as shown in Fig. 1.4. Get your circuit checked by the lab tutor/TA.
9. Switch on the 3-phase ac supply and record the ammeter reading.
10. Switch off the 3-phase supply.

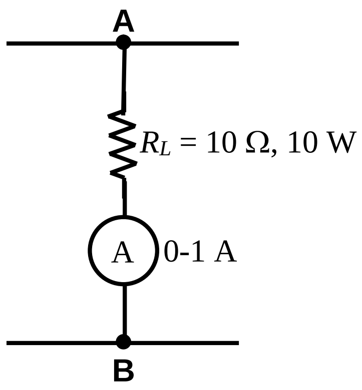


Fig. 1.4 Connection Details for terminals A and B.

Laboratory Report

Your laboratory report should contain the following.

1. Objective of the experiment.
2. List of the components, instruments and equipment (if any) used.
3. Specifications of all the instruments.
4. Circuit diagrams, complete with ranges of meters, parameters of circuit components with suitable titles for easy identification.
5. Laboratory observations in the tabular form as shown in Tables 1.1 to 1.3.

Table 1.1 Open circuit test

$\lvert V_{ab}\rvert$ (Volts)	$\lvert V_{a'b'}\rvert$ (Volts)	$\lvert V_T\rvert$ (Volts)

Table 1.2 Short circuit test

$\lvert V_{ab}\rvert$ (Volts)	$\lvert V_{a'b'}\rvert$ (Volts)	$\lvert I\rvert$ (Amps)

Table 1.3 Load test

$\lvert V_{ab} \rvert$ (Volts)	$\lvert V_{a'b'} \rvert$ (Volts)	$\lvert I \rvert$ through R_L = 10 Ω (Amps)

6. Report the results in the following form.

$\lvert V_T \rvert$ – Experimental	=	Volts
$\lvert Z_T \rvert \left(= \dfrac{\lvert V_T \rvert}{\lvert I \rvert} \right)$ – Experimental	=	Ω
$\lvert V_T \rvert$ – Estimated	=	Volts
$\lvert Z_T \rvert$ – Estimated	=	Ω

Current through resistive element R_L (= 10 ohms)

Experimental $\lvert I \rvert$	=	Amps
Estimated, Thevenin's method $\lvert I \rvert$	=	Amps
Estimated, KVL method $\lvert I \rvert$	=	Amps

7. Your conclusions and comments on the results, including justification of any anomaly between estimated and observed results.
8. Any precautions specific to the experiment.

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EXPERIMENT NO. 2: POWER MEASUREMENT IN BALANCED THREE-PHASE CIRCUITS

Brief Theory

The flow of power in ac circuit can be represented in the following terms

Apparent Power	= VI Volt-Amperes
Active (or real) power	= VI cos ¤ Watts
Reactive power	= VI sin ¤ VAr
Complex power	= $\tilde{V}\tilde{I}^*$

Of these, the active and reactive powers are often of basic interest and methods for measuring their values are of importance.

Active (or real) power in ac circuits is measured with the help of wattmeter. In balanced 3-phase circuits, theoretically it is possible to determine the total power flow from the measurement of power flow per phase by using a single wattmeter. However, it is usually not feasible in practice to do so, since this would necessitates opening of the star or delta connection of the load to insert the wattmeter, which is not possible in most cases. Furthermore, if there are several loads connected to the same supply mains, some in delta and others in star, and we wish to measure the total power drawn by all these loads, we shall be required to use the wattmeters on the supply lines where the possibility of per-phase power measurement may not exist.

Real power in balanced (or unbalanced), 3-phase circuits can be measured by employing two wattmeters in the three lines supplying the load system, irrespective of whether the load is star or delta connected (or a combination of them). The schematic circuit arrangement used for such a measurement is shown in Fig. 3.1. The current coil (cc) of the wattmeters carry line current and the pressure coil (pc) of wattmeter have line voltage impressed across it. In order to verify the possibility of 3-phase power measurement with the help of two wattmeters, let us consider that the load is Y-connected and let the instantaneous voltages and currents in the R, Y and B phases of the load be (v_R, i_R), (v_Y, i_Y)and (v_B, i_B) respectively.

The total instantaneous power flow in the 3-phase load will be given by

$$P_i = v_R i_R + v_Y i_Y + v_B i_B$$

For any Y-connected load with ungrounded neutral, the sum of three phase currents must be zero, i.e., $i_R + i_Y + i_B = 0$, irrespective of whether the load is balanced or not. Therefore we have

$$i_Y = -(i_R + i_B)$$

and hence

$$P_i = (v_R - v_Y)i_R + (v_B - v_Y)i_B$$

Examination of the circuit in Fig. 3.1 will show that the current through the current coil (cc) of W_1 is i_R and the voltage across the pressure coil (pc) of W_1 is $v_R - v_Y$. Similarly, the current through the cc of W_2 is i_B and the voltage across the p.c. of W_2 is $v_B - v_Y$. Hence, at any instant,

$$P_i = pw_1 + pw_2$$

where pw_1 and pw_2 are the instantaneous power readings. The wattmeters, however, measure the average power only, which is by definition, the real power of the circuit. Thus, we conclude that the real power of a 3-phase circuit – balanced or unbalanced can be measured using two wattmeters (provided $I_R + I_Y + I_B = 0$) and is simply given by

$$P = W_1 + W_2$$

where, W_1 and W_2 are the readings of the two wattmeters.

Let us now examine in relation to a balanced system under steady state, what W_1 and W_2 will actually measure. With reference to Fig. 3.2 (b), in which the load is star-connected, W_1 carries a current I_R in its current coil and has a voltage of V_{RY} across its potential coil. Hence,

$$W_1 = V_{RY} I_R \cos\angle\tilde{V}_{RY} \ \& \ \tilde{I}_R$$

Similarly,

$$W_2 = V_{BY} I_B \cos\angle\tilde{V}_{BY} \ \& \ \tilde{I}_B$$

For a balanced system we assume

$$V_R = V_Y = V_B = V \text{ and } I_R = I_Y = I_B = I$$

Therefore

$$V_{RY} = \sqrt{3}\, V \quad \text{and} \quad \angle \tilde{V}_{RY} \;\&\; \tilde{V}_R = 30^\circ$$
$$V_{BY} = \sqrt{3}\, V \quad \text{and} \quad \angle \tilde{V}_{BY} \;\&\; \tilde{V}_B = 30^\circ$$

Then

$$W_1 = \sqrt{3}\, VI \cos(30^\circ + \text{¯}) \,\text{and}\, W_2 = \sqrt{3}\, VI \cos(30^\circ - \text{¯})$$

and hence

$$W_1 + W_2 = 3\, VI\, cos\text{¯}$$

which is the total power of the 3-phase circuit. Note that, if ¯ $> 60^\circ$, *W*, will be negative. In actual power measurement it is possible to encounter such a situation when one of the wattmeters has a negative reading. The point to remember is that the total power in the 3-phase circuit is obtained by ALGEBRAICALLY ADDING the two-wattmeter readings, taking the signs of the reading into account.

It may also be worthwhile to identify the following cases:

(i) When the value of ¯ = 0 (signifying that load is such that current is in phase with the voltage across each of the phases), W_1 = W_2 and both are positive. Such a reading signifies that the load power factor (cos ¯) is unity.

(ii) When the value of ¯ = 60° lag (load pf, cos 60° = 0.5 lagging), W_1 = 0. Similarly, for ¯ = 60° lead (corresponding to load pf =0.5 lead) W_2 = 0.

(iii) When ¯ $> 60^\circ$ (i.e. load pf is less than 0.5 lag or lead) one of the wattmeter readings is negative.

Reference to Fig. 3.2 (b), which depicts the phasor diagram for a balanced delta-connected load system will show similar results. It is left to the students to verify the same.

A simplified version of the circuit arrangement of Fig. 3.1 (a), uses only one wattmeter in conjunction with a reversible double-pole double-throw (DPDT Fig 3.8) switch and a two-way key Fig 3.7 for measuring W_1 and W_2. This is shown in Fig. 3.1 (b). Examination of the circuit shows that when DPDT is thrown to A-B side (refer Fig.3.8) and 2-way key on W_2, the p.c. of the wattmeter has a voltage V_{BY} applied across it, while, with the key on W_1, the corresponding voltage across p.c. of wattmeter is V_{RY}. In both cases, the current through c.c. is $I_{Y,}$, hence, with reference to the phasor diagram of Fig. 3.3, it will be readily seen that,

$$\begin{aligned} W_2 &= \sqrt{3}\, VI\, cos(30^\circ - \text{¯}) \\ W_1 &= \sqrt{3}\, VI\, cos(30^\circ + \text{¯}) \end{aligned} \qquad (3.1)$$

A single wattmeter connection as shown in Fig. 3.6 can be used for measuring reactive power. With reference to the phasor diagram of Fig. 3.3, it can be seen that the c.c. of the wattmeter carried a current of I_Y = (I) (Fig. 3.6) while the voltage across the p.c. of the wattmeter is V_{BR} (when DPDT is on A', B') or V_{RB} when DPDT is on A, B). Hence the wattmeter measures either $\sqrt{3}\,VI\cos(90° - \phi)$ or $\sqrt{3}\,VI\cos(90° + \phi)$. In other words, reading of the wattmeter gives $\pm\sqrt{3}\,VI\sin\phi$. To get the total VAR of the circuit we have only to multiply the wattmeter reading by a factor of √3.

Laboratory Work

You are given balanced ac 50 Hz, 230 V supply. This implies that rms line-to-line voltage is 230 volts. In the first and second parts of your experiment, the load consists of a bank of three lamps. Use 300 W lamp loads for Parts 1, 2 and 3. Each lamp is connected to a pair of terminals as shown in Fig. 3.4 (a).

Part 1

Connect the lamps in star as shown in Fig. 3.4 (b), and connect the wattmeter as per circuit diagram of Fig. 3.1 (b), together with an ac ammeter and an ac voltmeter. Figure out how the ammeter and voltmeter will be connected and draw an appropriate modification of the circuit diagram of Fig. 3.1 (b) to accommodate them in circuit. GET YOUR INSTRUCTOR TO CHECK THE CIRCUIT BEFORE SWITCHING ON. Now switch on the 3-phase supply and note down W_1, W_2, V and I. Switch off supply show that $(W_1 + W_2)$ gives the total power.

It is interesting to note that W_1 and W_2 may be used in estimating the power factor of the load provided that the voltage and current waveforms are sinusoidal. Thus, with reference to expression (3.1)

$$W_2 = \sqrt{3}\,VI\cos(30° - \phi), \quad W_1 = \sqrt{3}\,VI\cos(30° + \phi)$$

Therefore

$$W_2 - W_1 = \sqrt{3}\,VI\sin\phi \text{ and } W_2 + W_1 = 3\,VI\cos\phi$$

Hence,

$$\tan\phi = \frac{W_2 - W_1}{W_1 + W_2}\sqrt{3}$$

From the above expression we get

$$\phi = \tan^{-1}\left\{\sqrt{3}\,\frac{W_2 - W_1}{W_1 + W_2}\right\}$$

and hence the power factor $\cos\phi$ can be calculated.

Measurement of Reactive Volt-Ampere (VAr) in 3-Phase Circuits

From the forgoing discussions, it is seen that

$$W_2 - W_1 = \sqrt{3}\, VI \sin\phi$$

where, V and I are 'phase' quantities. But, by definition, $VI \sin\phi$ is the VAR per phase. For 3-phase, therefore, the total reactive volt-ampere is given by $\sqrt{3}\, VI \sin\phi$. Thus $\sqrt{3}\,(W_2 - W_1)$, will give the value of total volt-ampere reactive for a balanced 3-phase circuit.

An alternative method of measuring this quantity is provided when the wattmeter is connected as shown in Fig. 3.6. With DPDT (Fig 3.8) thrown on the A, B or the A', B' side to get a deflection on the wattmeter.

Part 2

Connect the lamps in delta as per schematic diagram of Fig. 3.4 ©, without disturbing other parts of the circuit. Get the circuit checked by your instructor. Switch on the 3-phase supply. Note down W_1, W_2, V and I. Switch off the supply.

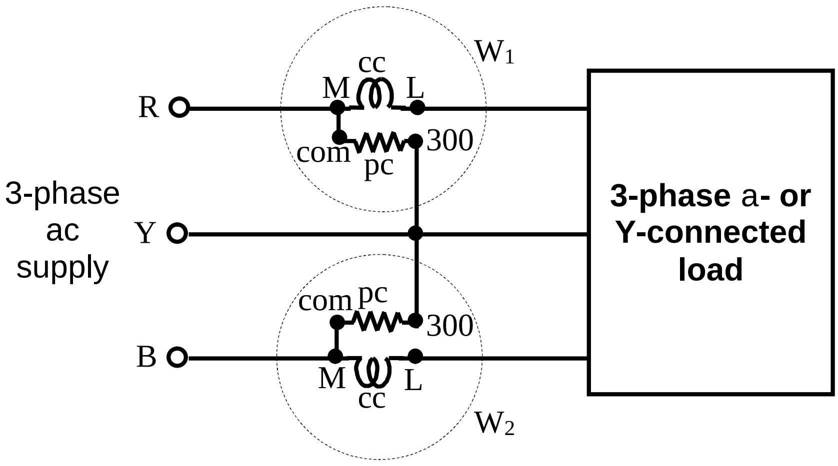
Part 3

Connect each lamp in series with an inductance of value 0.45 H (or two capacitances, each 15 μF, in series) provided. Connect the three series combinations in delta as shown in Fig. 3.5. Connect wattmeter as shown in Fig. 3.1 (b), together with a n ammeter and voltmeter, as you did in Parts 1 and 2 above. You must get your circuit checked by the instructor before switching on the supply. Now switch on the supply. Note down W_1, W_2 taking care to see whether the readings are +ve or –ve, and also V and I. Switch off the supply.

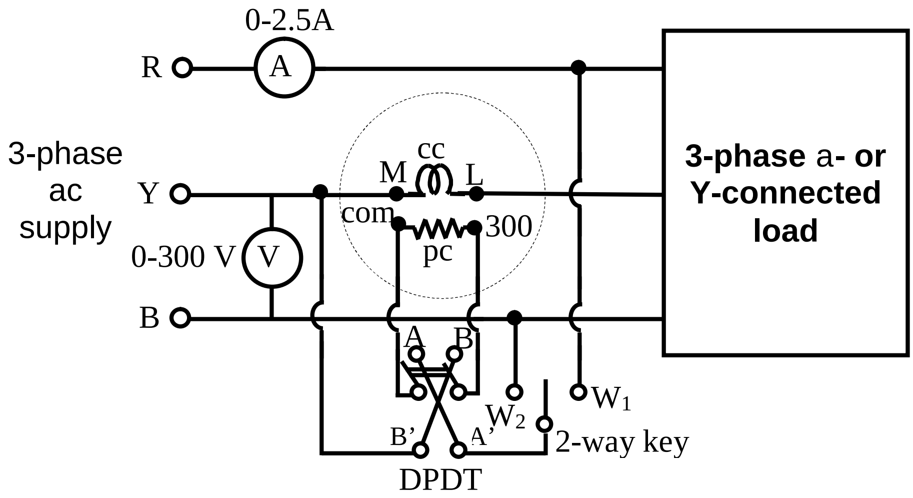
Modify the wattmeter p.c. connection only as per Fig. 3.6. Get the circuit checked, and switch on. Note down the wattmeter reading. Also note the inductor (or capacitor) values used in the circuit.

Report

Determine, for each case, the total active power flow in the circuit in watts, and the circuit power factor. Also calculate the reactive volt-ampere of the circuit in each case. Verify the results with the measured values. Estimate the line and phase currents for each case and cross check with appropriate measured values. Draw the phasor diagram for each case. From the given voltage-power characteristics of the lamps (this is displayed in the laboratory), verify that two-wattmeter method of power measurement yields the real and reactive powers in the circuit in each case.

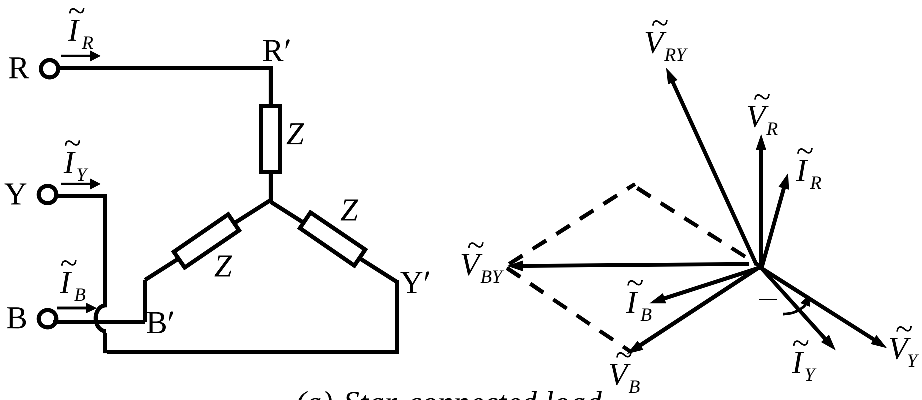


(a) Schematic diagram used for unbalanced load.

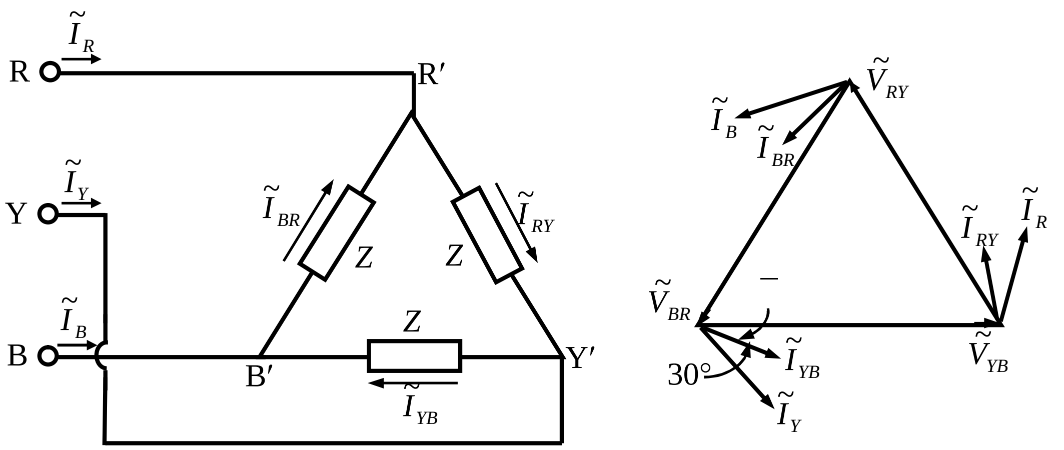


(b) Schematic circuit used only with Balanced Load.

Fig. 3.1 Alternate circuit arrangements for 2-wattmeter method of measuring power in 3-phase ac Circuits.



(a) Star-connected load.



(b) Delta-connected load.

Fig. 3.2 Phasor diagrams of power measurement by 2-wattmeter method.

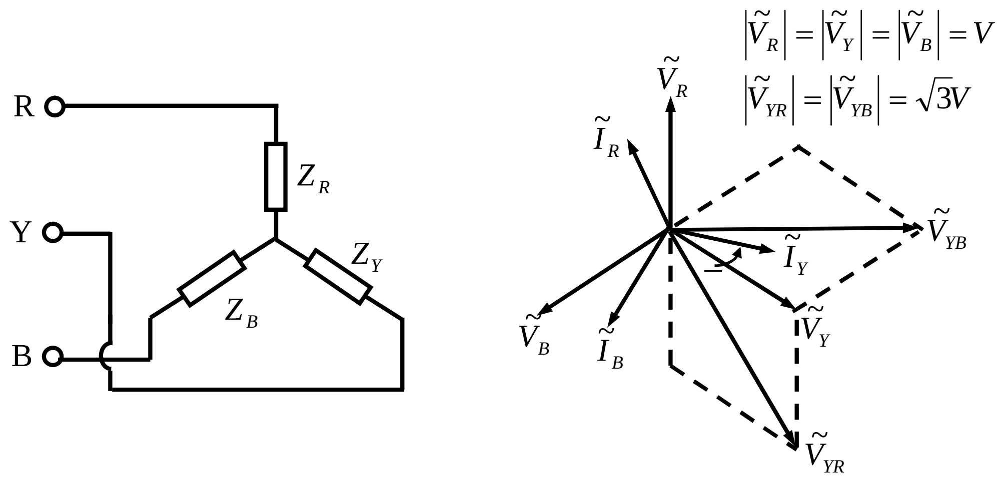
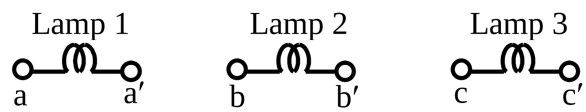
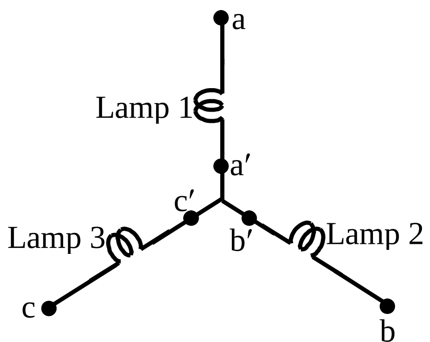
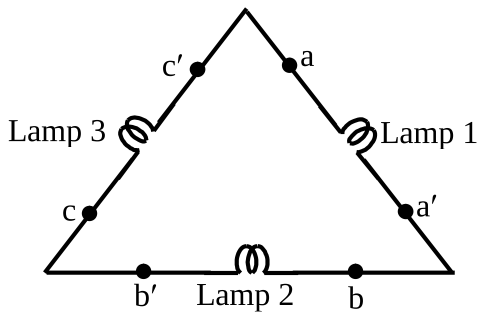


Fig. 3.3 Phasor diagram with star-connected load for power measurement using one wattmeter only for balanced load.



(a) Three-phase lamp board.





(b) Lamp in 3-phase star. *(c) Lamp in 3-phase delta.*

Fig. 3.4. Lamp board and its 3-phase connections.

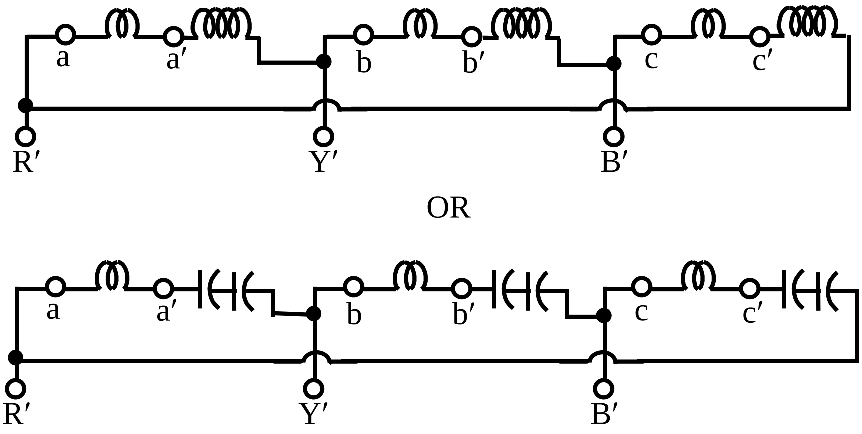


Fig. 3.5 Delta-connection of lamp-inductance OR lamp-capacitance combinations.

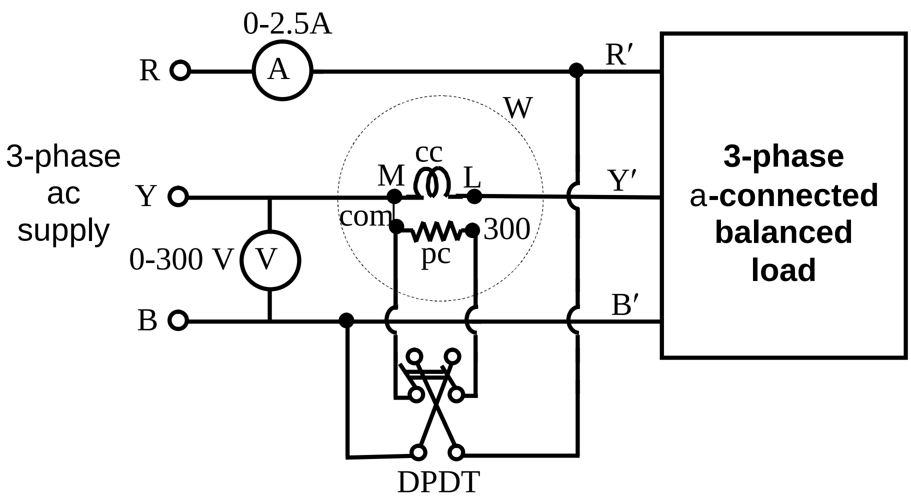


Fig. 3.6 Circuit diagram for measurement of reactive power in balanced 3-phase circuit.

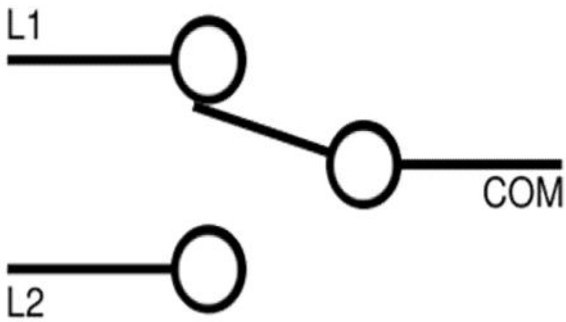


Fig. 3.7 2 Way Key

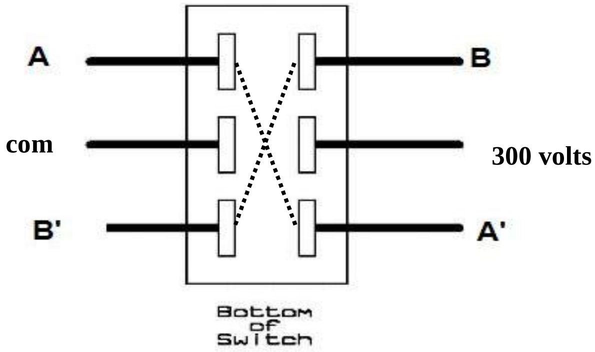


Fig. 3.8 DPDT Switch

NOTE: (1) Always connect A with A' and B with B' contacts of DPDT
(2) Com and 300 volts corresponds to the potential coil ends of the wattmeter.
(3) In case 2 way key, shown in Fig. 3.7, is not provided, keep the wire from the terminal A' of the DPDT switch floating.

Observations:

(a) Measurement of Active Power

	V (V)	I (A)	W1 (Watts)	W2 (Watts)	Total power (W1+W2) Watts
Part-1					
Part-2					
Part-3					

(b) Measurement of Reactive Power

V (V)	I (A)	Wattmeter reading	Reactive power (VAr)

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EXPERIMENT NO. 3: DETERMINATION OF SELF AND MUTUAL INDUCTANCES OF COILS

Objective: To determine experimentally the self and mutual inductance of a given pair of magnetically coupled coils, and to estimate there from the value of the coupling coefficient *K* for the coil. Also determine the polarity of the coils.

Brief Theory

Measurement of self and mutual inductance of a two coil electrical circuit with mutual coupling can be made with reasonable accuracy using static ac tests, provided

a. the test is conducted at the proper level of current and frequency on the two windings
b. the level of magnetization can be suitably maintained while the test is conducted – preferably at unsaturated conditions of the magnetic circuit and
c. the effect of power loss due to hysteresis and eddy currents in the magnetic circuit is suitably accounted for.

Let us consider the schematic circuit of Fig. 4.1, together with a voltmeter, an ammeter and a wattmeter, as shown in Fig.4.1.

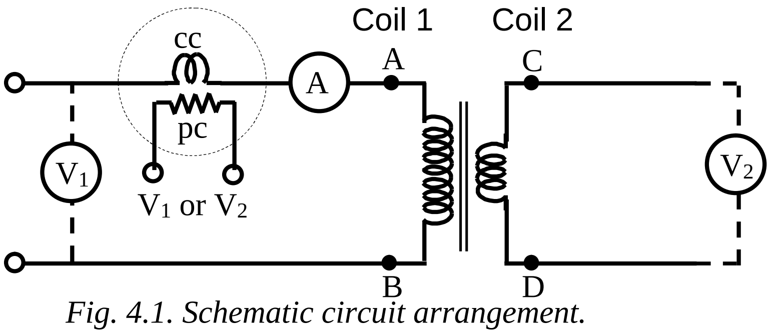

Fig. 4.1. Schematic circuit arrangement.

Let voltage V_1, at a known frequency f_1, be applied across the terminals A-B of coil 1, such that the current flow through the coil does not saturate the magnetic circuit. (While performing the experiment we shall see how this is ascertained). If we connect the voltmeter and the potential coil of the wattmeter in parallel, by temporarily connecting the terminals A-B, we can get the voltmeter reading V_1, wattmeter reading W_1, besides the ammeter reading I_1. With the circuit otherwise undisturbed, let us now remove the contacts of the voltmeter/wattmeter potential coil combination from AB, instead let us now connect it to terminals C-D. We shall obtain new voltmeter reading V_2 and wattmeter reading W_2. By knowing the value of resistance of coil 1 (say R_1), it is possible for us to calculate,

$$W_1' = W_1 - I_2^2 R_1$$

and we shall find that

$$\frac{W_1'}{V_1} \approx \frac{W_2}{V_2}$$

Analysis of the nature of power flow shows that W_1',in fact, is the power fed to account for the hysteresis and eddy current losses of the magnetic circuit responsible for magnetic linkage of the two coils.

We shall see later (while studying transformers) that the circuit under reference can be represented by an equivalent circuit shown in Fig. 4.2, where the actual coil 1 is replaced by a resistance R_1 (of the coil), with an equivalent resistance R_2 parallel to L_1, such that the power consumed by R_2 accounts for the hysteresis and eddy current losses of the magnetic circuit. Taking this to be the equivalent circuit of coil 1 we can readily draw the phasor diagram showing phasor relationship between $\tilde{V}_1$ and $\tilde{I}_1$ and determine therefrom the component of current $\tilde{I}_M$ through the pure inductance L_1. This is shown in Fig. 4.3.

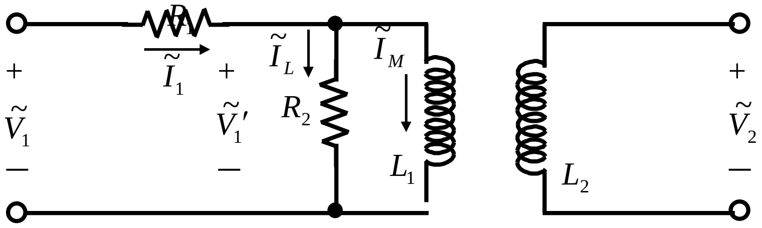

Fig. 4.2 Circuit equivalent of Fig. 4.1 with supply in coil 1 only.

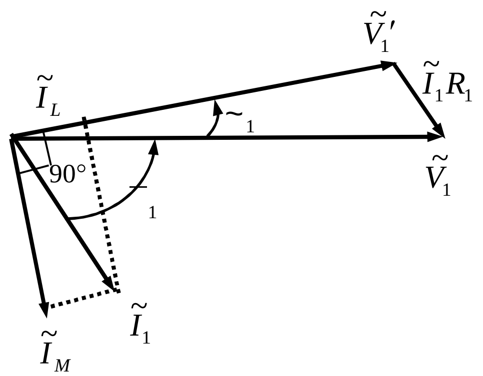

Fig. 4.3 Phasor diagram showing phasor relationship of $\tilde{V}_1$, $\tilde{I}_1$, $\tilde{I}_M$ and $\tilde{I}_L$.

It will be readily seen that,

$$\cos\theta_1 = \frac{W_1}{V_1 \cdot I_1}$$

$$V_1' = \sqrt{\left(V_1 - I_1 R_1 \cos\theta\right)^2 + \left(I_1 R_1 \sin\theta\right)^2}$$

$$\delta_1 = \tan^{-1} \frac{I_1 R_1 \sin\theta_1}{V_1 - I_1 R_1 \cos\theta_1}$$

since I_M will be 90° lagging below V_1', magnitude of I_M is given by

$$I_M = I_1 \sin\left(\theta_1 + \delta_1\right)$$

It is now possible to obtain the values of L_1 and M. These are given by

$$L_1 = \frac{1}{2\pi f} \cdot \frac{V_1'}{I_M} \qquad \text{and} \qquad M = \frac{1}{2\pi f} \cdot \frac{V_2}{I_M}$$

The value of L_2 (and M) can be experimentally obtained by repeating the test with voltage now applied across the terminals C-D of coil 2 and with terminals A-B of coil 1 kept open circuited. The only precaution to be observed is to choose a proper value of applied voltage to coil 2, which should be equal to V_2 measured in the earlier test. This is to ensure that the flux level in the magnetic circuit remains the same for both the tests.

Laboratory Work

Part I: Experimental determination of L_1 and M

1. Choose the coil with higher voltage rating, as coil 1. Set up the circuit as shown in Fig. 4.4 and set the variac to zero output voltage. Get the connections verified by your instructor.
2. Switch on the ac supply.
3. With the voltmeter kept connected across terminals A-B of the coil 1, increase the applied voltage to coil 1 gradually to 180 V.

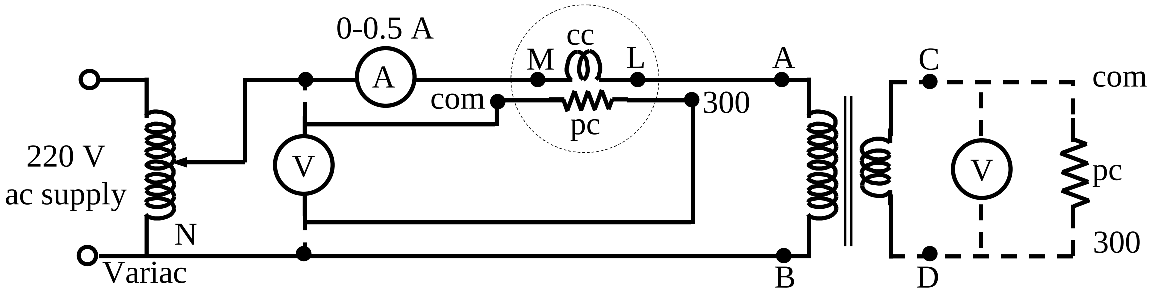

Fig. 4.4 Circuit Diagram for Tests Part 1.

(a) Increase the voltage in steps of 10 V up to 230 V and record the ammeter readings.

(b) Plot V-I. This should come out to be a straight line.

4 Turn the variac control fully in anticlockwise direction to reduce the applied voltage to zero.
5 Now slowly increase the applied voltage by clockwise rotation of variac control, and set the voltage to V_1 = 200 V.
6 With wattmeter potential coil connected in parallel to the voltmeter, connect the terminals of the combination across A-B. Record I_1, V_{11} and W_{11}, respectively.
7 Withdraw the contact of the voltmeter/wattmeter pressure coil combination from terminals A-B without disturbing the voltage setting on variac, connect them to terminals C-D of coil 2. Record V_{21} and W_{21}, respectively.
8 Turn the variac regulating handle to set the voltage to zero. Switch off supply.
9 Open the connections from across terminals A-B of coil 1 and transfer the original connections to terminals C-D.
10 Get the connections checked by your instructor after ensuring that the variac handle is turned fully anti-clockwise (zero voltage position).
11 Switch on ac supply and slowly turn the variac handle to set the applied voltage V_{22} (equal to V_{21} measured in step 7).
12 Record the values of V_{22}, I_2 and W_{22}, respectively.
13 Follow the procedure laid down in step 7 to obtain values of V_{12} and W_{12}. Turn the variac handle to zero voltage and switch off. Disconnect.
14 Given that the resistances of the two coils are (these are indicated on the coil):

$$R_1 \quad \text{for coil } 1 = 3.9\ \Omega$$
$$R_2 \quad \text{for coil } 2 = 1.2\ \Omega$$

Follow the procedure outlined in the 'Theory' to calculate self inductances (L_1, L_2) and the mutual inductance, M. Note that M obtained from the two tests are, for all practical purposes, equal.
15 The value of the coefficient of coupling, K, is given by:

$$K = \frac{M}{\sqrt{L_1 \cdot L_2}}$$

Part II: Determination of Polarities

1 Connect coil 1 and coil 2 in series by joining B and C.
2 Set the circuit through a lamp-board in series as shown in Fig. 4.5. Get the circuit verified by your instructor.
3 Switch on the supply and note the intensity of glow of the lamp.
4 Switch off.
5 Interchange connections between terminals C and D only. This will cause the terminal B to be connected to D and the supply (through the lamp board in series) to be across A and C. check that this is the case.
6 Switch on and note the intensity of glow of the lamp. Note in which case the intensity of glow is more.

Switch off and disconnect.

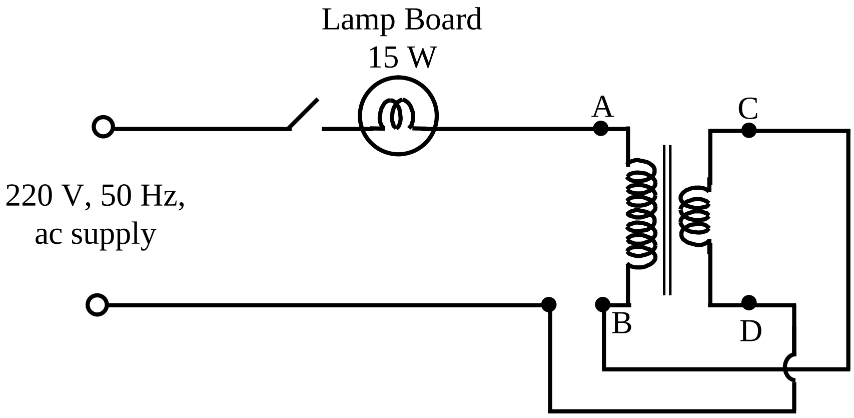

Fig. 4.5 Circuit for checking polarity.

Laboratory Report

Your laboratory report should follow the pattern, set in earlier experiments. Since you are already acquainted with it, you should devise your own method of recording and labeling the experimental data and results.

Note that this experiment has some precautions. Identify them and record them appropriately. Try to comment on the procedure followed and give your comments by answering the following questions:

1. In determining the voltage-current characteristics, why do we choose the coil with higher voltage rating as coil 1?
2. Why do we plot the V/I characteristic for increasing values of the applied voltage?
3. How do we recognize that the series connection, yielding lesser glow of the lamp, is the coil configuration for series addition?
4. Why do we perform tests on the coils connected in series with currents equal to I_1 measured in step 6 of part 1 of tests?
5. If the two coils were not magnetically coupled by an iron core (or core of some other high permeance material) the wattmeter readings W_{21} and W_{21} would have been zero. Can you reason why they show finite values when magnetic core is present?

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INTRODUCTION TO ELECTRICAL ENGINEERING (ESO 203A)

EXPERIMENT NO. 4: TO STUDY THE WINDINGS OF A TRANSFORMER AND ASSEMBLING A SMALL TRANSFORMER

Design Inputs

Given Data:

Primary voltage (E): 230 V
Supply frequency (f) = 50 Hz.
Maximum allowable flux density (B_m) = 1.0 T
Primary turns (N_1) = 1200

Basic Equation

The voltage equation of the transformer is

$$E = 4.44 B_m A_i f N_t$$

where A_i is the cross- sectional area of the iron (CRGO) core.

Design

1. From the given data calculate A_i.
2. Draw the magnetic circuit and the flux path. A_i is the core area perpendicular to the flux path.
3. The stamping dimensions are shown in Fig. 5.1. Calculate the depth (d_i) of the core required.

The iron core is made up of number of laminations which are stacked together to form the core. Each lamination is electrically insulated on the outer surfaces to minimize eddy current flow in the core. Cross section of the stamping is as shown in Fig. 5.2. It is given that

$$\frac{d_{il}}{d_{el}} = 0.87$$

4. Calculate the depth of the core stack.
5. Measure the stack depth in the given transformer and compare with the calculated value.
6. You have to get 6 V at the secondary side. How many secondary turns (N_S) are required?

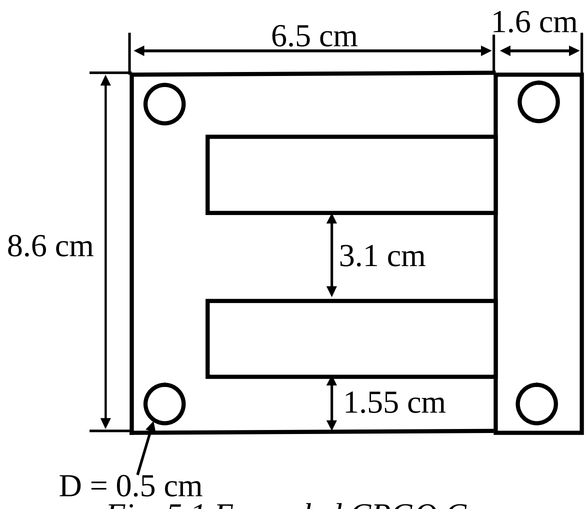

Fig. 5.1 Enameled CRGO Core.

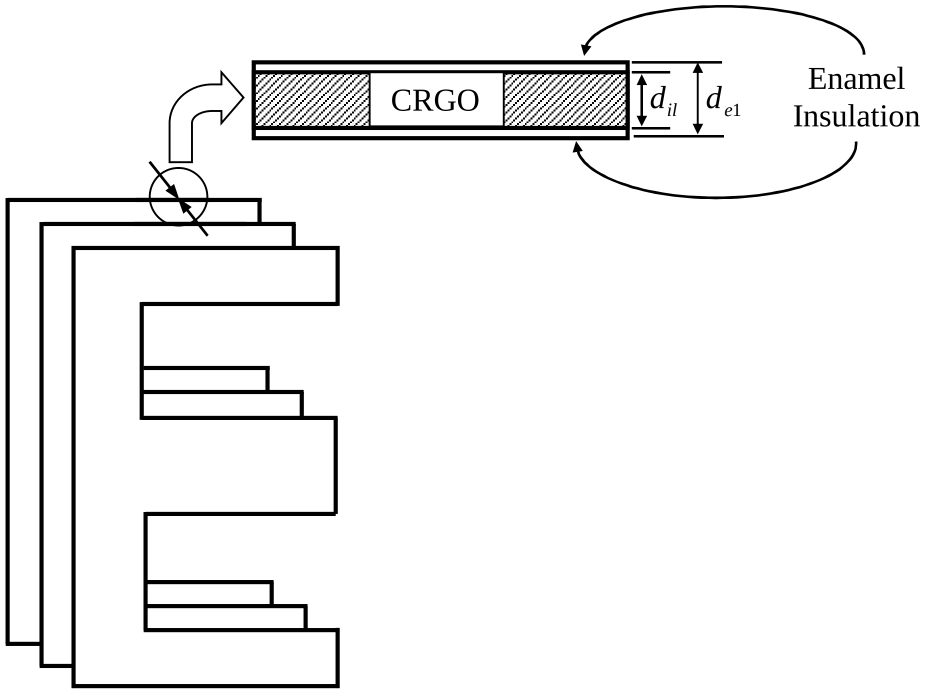

Fig. 5.2 Formation of the core.

Measurement

Connect the primary winding to the variac and adjust the voltage to 230 V. Measure the secondary side output.

Assembly

1. Open the transformer core clamping screws and very carefully remove the stampings. Use the tools given to you. Avoid excessive force on the laminations. Note the manner in which the core is assembled (interleaved). After you finish, you should have a set of E-shaped and a set of l-shaped stampings (such constructions are called E-l cores).

2. Wind another secondary of N_S turns besides the existing secondary winding. Make sure both ends of the new winding are brought out. Mark the Start (S1 and S2) and finish (F1 and F2) of both the secondary windings. Note the sense (Clockwise or Counter-clockwise) in which both secondary windings are wound.
3. Fit the back again, using the tools given. Be careful not to hammer the laminations too hard.

NOTE: Scratch the wires thoroughly to remove insulation, before connecting them.

Testing

1. Connect the primary to the variac and adjust the variac output to 230 V as shown in Fig. 5.3. Note the voltage of the two secondary windings with a multimeter.
2. Connect the secondary windings in series (you will have four combinations) and measure the total output voltage.
3. Readings may be tabulated as shown in Table 5.1.

Interpret the results.

Table 5.1 Tabulate the results in the following format

Connection	**Measurement between**	**Multimeter reading (V)**
S1 and S2	F1 and F2	
S1 and F2	S2 and F1	
F1 and S2	S1 and F2	
F1 and F2	S1 and S2	

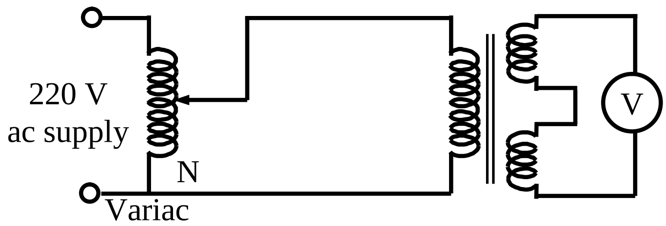

Fig. 5.3 Transformer testing circuit.

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INTRODUCTION TO ELECTRICAL ENGINEERING (ESO 203A)

EXPERIMENT NO. 5: DETERMINATION OF EQUIVALENT CIRCUIT PARAMETERS OF A SINGLE-PHASE TRANSFORMER AND EVALUATION OF ITS PERFORMANCE

Aim

To determine the parameters of the equivalent circuit of a single phase transformer by conducting open and short circuit tests and calculate the efficiency as well as regulation of the transformer are then evaluated at given load conditions.

Theory

Fig. 6.1 shows an equivalent circuit of a single-phase transformer 1,1′ and 2,2′ denote the terminals of the primary and secondary windings, respectively. The resistances and reactances in the circuit are defined below:

R_1	Primary winding resistance
R_2	Secondary winding resistance
X_{L1}	Primary winding leakage reactance
X_{L2}	Secondary winding leakage reactance
R_{M1}	Resistance representing hysteresis and eddy current losses, referred to the primary winding
X_{M1}	Magnetizing reactance referred to primary winding
N_1	Number of turns in the primary winding
N_2	Number of turns in the secondary winding

R_{M1} is a fictitious resistance representing core losses at the rated frequency and applied voltage. The relationship between the magnetic flux in transformer core and the MMF, which establishes it, is nonlinear and is given by the B-H characteristics of the core material. The nonlinearity gives rise to odd harmonics in the magnetizing current. The predominant harmonic is the third. Its magnitude can be as much as 40 % of that of the fundamental. X_{M1} is a reactance to represent the relationship between the fundamental component of the magnetizing current and the magnetic flux.

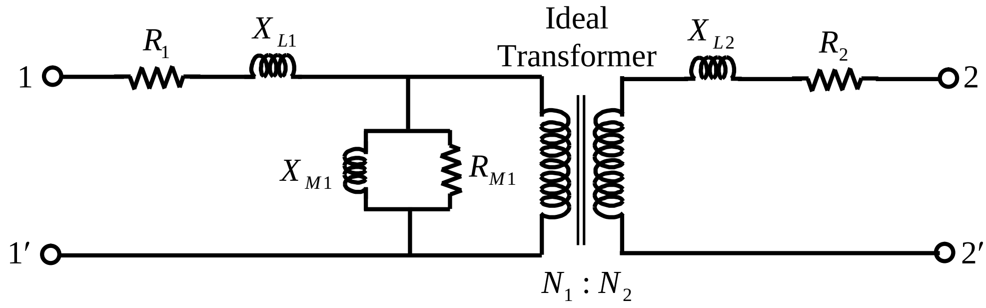


Fig. 6.1 An equivalent circuit of a transformer.

The transformer equivalent circuit parameters are determined through an open circuit test and a short circuit test involving respectively measurement of impedance at one part of the transformer with the other part open and short circuited. Note that:

The open circuit test should be performed at the rated voltage and the short circuit test preferably at the rated current of the transformer. Both tests should be performed at the rated frequency.

The equivalent resistance R_{1eq} and the equivalent leakage reactance X_{1eq} of the transformer windings, both referred to the primary winding, are given by

$$R_{1eq} = R_1 + \left(\frac{N_1}{N_2}\right)^2 R_2 \tag{6.1}$$

$$X_{1eq} = X_{L1} + \left(\frac{N_1}{N_2}\right)^2 X_{L2} \tag{6.2}$$

Noting in Fig. 6.1 that X_{M1} and R_{M1} can be moved to be across points 1,1′ without causing significant error, the equivalent circuit of Fig. 6.1 can be reduced to that shown in Fig. 6.2. The equivalent circuit of Figs. 6.3 (a and b) are approximations to the equivalent circuit of Fig. 6.2 and hold good for conditions of open and short circuit tests, respectively. The open and short circuit impedances, Z_{OC} and Z_{SC}, respectively, can be measured by measuring the applied voltage, input current and power drawn by the transformer under conditions of open and short circuit tests.

Laboratory Work

The experiment is to be performed on a 500 VA, 230/115 V, single phase, 50 Hz transformer.

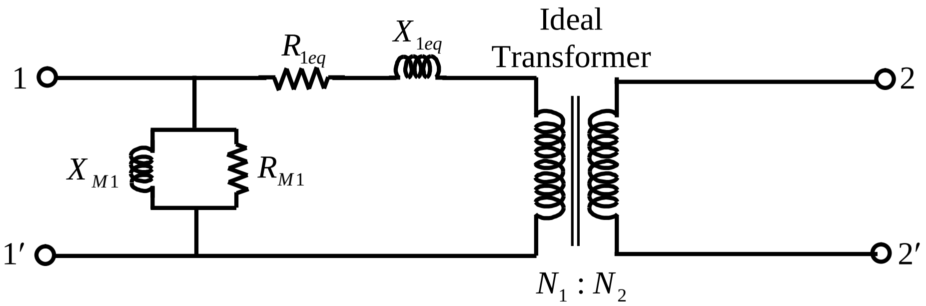
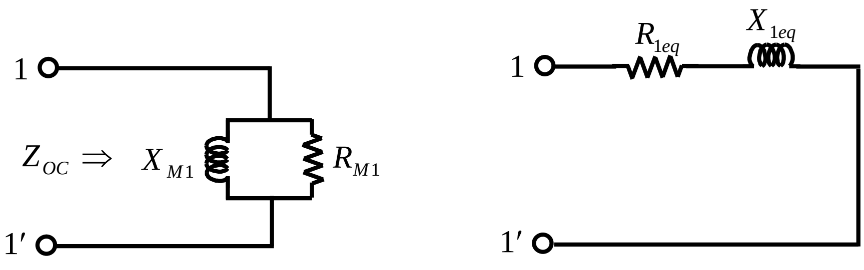


Fig. 6.2 Simplified equivalent circuit of transformer.



(a) (b)

Fig. 6.3 (a) Open-circuit impedance and (b) Short-circuit impedance.

Open Circuit Test

Warning: Do not switch ON the circuit till your instructor has checked it.

Set up the circuit of Fig. 6.4. Note that the secondary terminals 2,2' are left open. Use a 1 A range for ammeter and the current coil of wattmeter, and 300 V range for the potential coil of wattmeter. Adjust the applied voltage to transformer to 230 V using the variac. Note down the meter readings. Let V_{OC}, I_{OC} and W_{OC} be the applied voltage, primary current and input power, respectively. Then

$$R_{M1} = (V_{OC})^2 / W_{OC} \tag{6.3}$$

$$X_{M1} = V_{OC} \Big/ \sqrt{(I_{OC})^2 - (W_{OC}/V_{OC})^2} \tag{6.4}$$

Voltmeter Reading (V_{oc}) Volts	Ammeter Reading (I_{oc}) A	Wattmeter Reading (W_{oc}) Watts

Short Circuit Test

Warning: Do not switch ON the circuit till your instructor has checked it.

Set up the circuit shown in Fig. 6.5. Here, the secondary terminals are shorted. Use appropriate range for current coil of wattmeter, 2.5 A range for ammeter and 150 V range for the potential coil of the wattmeter. **It is very important to note that for this test only a low voltage is to be applied to the primary of the transformer. This is done by setting variac output to zero initially and increasing it very slowly**. If normal voltage is applied to the transformer under short circuit condition, a very large current will flow through it causing damage to the windings, the ammeter and the wattmeter. So you have to be careful and make sure to use small voltage (***maximum of 18 V***) supply to the transformer for the test. Measure the voltage from the dial of the variac/voltmeter.

Adjust the variac to obtain the full load current through the transformer primary. Let V_{SC}, I_{SC}, W_{SC}, be the applied voltage, primary short circuit current and input power, respectively. Then,

$$R_{1eq} = W_{SC} / (I_{SC})^2 \tag{6.5}$$

$$X_{1eq} = \sqrt{(V_{SC}/I_{SC})^2 - (R_{1eq})^2} \tag{6.6}$$

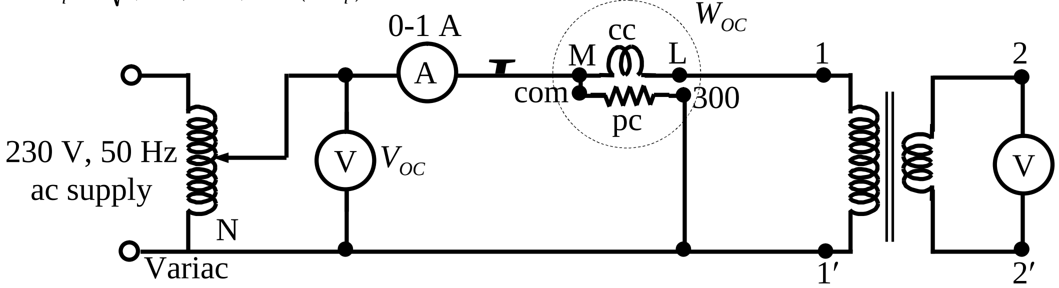


Fig. 6.4 Set-up for open-circuit test.

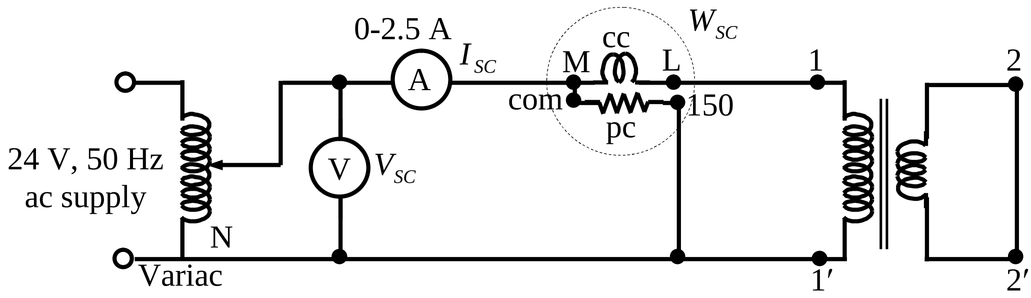


Fig. 6.5 Set-up for short-circuit test.

Voltmeter Reading (V_{sc}) Volts	Ammeter Reading (I_{sc}) A	Wattmeter Reading (W_{sc}) Watts

Note:
In practice, Open Circuit (OC) test for a transformer is done by applying voltage on High Voltage (HV) side of the transformer and Short Circuit (SC) test is performed by applying voltage on Low Voltage (LV) side of the transformer. However, in this experiment, both the OC and SC Tests are performed by applying voltage on HV side of the transformer.

Transformer Performance Evaluation

(a) Efficiency

Using the results of the experiment calculate the efficiency of the transformer when it is supplying full load at 0.8 pf lagging when the rated voltage of 230 V is applied to the primary. Under these conditions, the primary current is I_1 = (500/230) A, (neglecting the magnetizing and core loss components of current), and the copper loss is $(I_1)^2R_{1eq}$. Iron loss is W_{OC} and is given by the open circuit test. The efficiency is then given by the expression

$$(500)(0.8)\big/\left[(500)(0.8)+(500/230)^2 R_{1eq} + W_{OC}\right] \tag{6.7}$$

Calculate also the efficiency when the transformer is supplying half of full load at 0.6 power factor lagging at the rated applied voltage.

(b) Regulation

Calculate the regulation of the transformer for the two conditions given above. Note that regulation is a measure of the voltage drop that takes place in the transformer. Percentage regulation is approximately given by the formula

$$\%\ \text{Regulation} = \left[\frac{\left(I_1 R_{1eq}\cos\phi + I_1 X_{1eq}\sin\phi\right)}{V_{1rated}}\right]\times 100 \tag{6.8}$$

Load Test

Load test on a transformer can be done using the circuit shown in Fig. 6.6. This involves actually loading the transformer and measuring its input and output quantities to determine the performance measures such as voltage regulation and efficiency at various loads, and load power factors. Note that this is not a convenient way of determining transformer performance. The reasons are that

(a) In practice arranging loading equipment which can absorb the power output of the transformer may be difficult, especially in the case of large transformers, and arranging the absorption to take place at stipulated power factors is even more difficult.
(b) The calculation of efficiency by determining input and output powers is bound to be inaccurate since losses would be obtained as the difference between two large and nearly equal numbers. In any case we will perform a load test here at unity power factor to just show the results arrived at, by using the results of the open circuit and the short circuit tests, agree with the actual values.

The experiment setup is shown in Fig. 6.6. Keeping the load switch open, the transformer is switched ON to the mains and the rated voltage applied to the primary. The no load readings of the meters in the primary and secondary sides are taken. Then the transformer is gradually loaded after closing the load switch by putting ON the lamps one by one. Make sure that when you start all the lamps should be OFF. Gradually switch ON the lamps till the rated winding current of the transformer is obtained. For each load, the readings of all the meters on the primary and secondary sides are noted. From the readings, the losses, efficiency and regulation of the transformer are calculated. Draw the plots of efficiency and regulation against load current.

The earlier results for efficiency and regulation using the transformer parameters obtained through open circuit and short circuit test are also drawn on the same graph-sheets and compare the two sets of results.

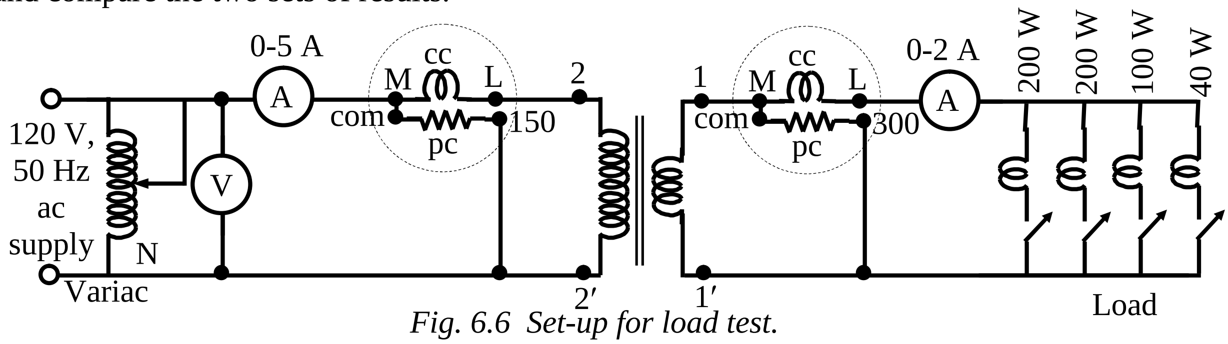


Fig. 6.6 Set-up for load test.

Load Test Observations:

Sl. No.	Lamp Load (Watts)	V_1 (Volts)	I_1 (Ampere)	W1 (Watts)	V_2 (Volts)	I_2 (Ampere)	W_2 (Watts)

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INTRODUCTION TO ELECTRICAL ENGINEERING (ESO 203A)

EXPERIMENT NO. 6: TO DETERMINE THE NO-LOAD AND LOAD CHARACTERISTICS OF A D.C. GENERATOR RUNNING AT CONSTANT SPEED, BOTH FOR SEPARATELY EXCITED AND SHUNT EXCITED MODES OF OPERATION

Brief Theory

In studying the behavior of a d.c. generator, it is usually sufficient to determine experimentally

i. The no-load characteristic
ii. Load characteristic

of the machine at its rated speed. The no-load (or magnetization) characteristic is a plot of the potential difference across the armature terminals against the field current, with no current flowing in the armature circuit and with the armature rotating at a constant speed (usually the rated speed unless some other speed is deliberately chosen). For this test, the machine is operated in the separately excited mode, with the field current supplied form an external source. It is easy to see that this characteristic helps us in knowing about the magnetic circuit of the machine. A typical no-load characteristic, shown in Fig. 7.1, will be readily identified as a part of the hysteresis loop. This suggests an important precaution in the experimental determination of the no-load characteristic. Never reduce the field current when you are determining the no-load characteristic by increasing the current in the field and vice versa.

We already know that the EMF induced in a D.C. machine is given by:

$$E = \left(\frac{2p}{2a}\right) \times Z \times \frac{1}{60} \times \phi N volts$$

where, p – no. of poles, a – no. of parallel paths, Z – no of armature conductors, φ - flux per pole and N- speed of armature in rpm.

Since the no-load characteristic essentially gives us a plot of E against φ, N should be kept constant. This is another important precaution in the determination of the no-load characteristic of the machine.

A d.c. machine, in its shunt excited mode, derives its field excitation from its own armature. This leads to certain basic conditions that the machine must satisfy before self excitation is possible. These are:

I. Existence of residual magnetism in field
II. Direction of rotation and connection of field winding to armature should be such that the excitation derived by the field should aid the residual magnetism.
III. The field circuit resistance should be less than a certain critical value corresponding to each value of operating speed of the machine

IV. The speed of the machine must be more than a certain minimum value, called critical speed of the machine, for which the resistance of the shunt field winding (without any external resistance included in field circuit) becomes the critical field resistance.

In the present experiment, we shall determine the critical field resistance at rated speed and the critical speed of the machine, both experimentally as well as analytically.

The load characteristic, more commonly known as the external characteristic of the generator, is a plot between the terminal voltage and load current, when the machine speed is kept constant (usually at its rated speed) and the armature is electrically loaded. Typical shapes of this characteristic for (a) separately excited mode with fixed excitation and (b) for shunt excited mode are shown in Fig. 7.2. This characteristic gives us important information about the mode of variation of terminal voltage of the generator with increase in current supplied.

It is known from the study of d.c. generators that the EMF induced in the machine will not usually remain constant but will decrease with increasing value of the armature current, even if the field excitation and speed are kept constant. This is because of the effective demagnetization associated with armature reaction. Armature reaction effects are manifested both in the separately excited and the shunt excited machines. A second effect, which causes drop in the terminal voltage with load in both types of machines, is due to armature resistance drop (apart from the voltage drop in the carbon brushes, which is neglected in this experiment).

An additional cause of the change in terminal voltage with load, typical of shunt machines alone, is that the field excitation in such a machine is a function of the terminal voltage itself (which reduces with the increase in the load current). This is responsible for imparting the peculiarity in the shape of the external characteristic of the shunt machines, not observed in case of the separately excited machines. Fig. 7.3 depicts these changes.

Laboratory Work

The experimental setup consists of two identical d.c. machines, mechanically coupled to each other. Each machine is rated for ¼ H.P.(≈ 190 watts), thus signifying that when running as a generator at its rated speed it can deliver to an electrical load of 190 watts at rated voltage. While working as a motor it can deliver rated mechanical power at rated speed for which the armature will require an input power of 190 watts from the supply.

Note the name plate details of each machine. Each machine can function on separately excited or shunt excited mode. The armature and field terminals are brought out on the terminal board of each machine.

In this experiment, we shall use one of the d.c. machines as the prime mover and the other as the d.c. generator. We shall be concerned with the behavior of the latter and use the former to maintain a constant speed.

Part I : Experimental determination of the no-load (magnetization) characteristic of separately excited d.c. generator:

1. Set up the circuit as per circuit diagram of Fig. 7.4 (switch off all the loads).
2. Set the rheostat RM to MAX. position and set RFG so that it produces zero field current.

3. Before switching on, get your circuit checked by the instructor.
4. Switch On the d.c. supply. Gradually cut out the resistance RM from the motor circuit. The speed of the set will increase. By controlling RM, adjust the speed to the rated speed of the machine.
5. By controlling the value of RFG, increase the value of If in steps. TAKING CARE THAT THROUGH RM the speed of the set remains constant. Record E for each value of If, in suitable tabular form. Plot E vs. If. Switch off the d.c. supply.
6. Extend the initial linear part of the E/If curve plotted. The slope of this straight line gives you the value of critical field resistance of the machine at the rated speed.

Part II : Load test – Determination of external characteristic. (Seperately excited)

7. Connect the circuit as per Fig. 7.6(a).
8. Set RM to max. RFM to zero, get your circuit checked by the instructor.
9. Switch On the circuit and control RM to attain rated speed.
10. Control RFG to obtain rated voltage across generator terminals at no-load.
11. Switch On the load (lamps) in steps, and for each load setting, adjust the speed to the original value by controlling RM or RFM as the case may be. Record the value of VM, IM, VG and IG for each load setting. Switch Off the d.c. supply.
12. Refer to the curves in Fig. 7.7 to read the efficiency ηm of the drive motor for each value of IM. The motor output in watts (which equals the generator input) is then given by (VMIMηm). The efficiency of the generator is given by ηg= (VGIG/VMIM. ηm). Plot the ηg vs. IG characteristic for the generator, at its rated speed.
13. Plot VG against IG (including VG at IG = 0). This gives the load characteristic of the separately excited d.c. generator at the rated speed.

Part III : Determination of no-load terminal voltage of shunt generator and its critical speed.

14. Modify the circuit to conform to the circuit diagram of Fig. 7.5. Switch Off all the loads. Set RM to maximum resistance position and RFM to zero resistance position. Get your circuit checked before switching on the d.c. supply.
15. Set RFG to maximum resistance position.
16. Switch On the d.c. supply. The set will start rotating at a slow speed. Now, gradually cut out resistance RM. The speed of the set will increase. Cut RM till the set attains its rated speed. If you cannot attain the rated speed even after RM is fully cut out, slowly increase RFM till the rated speed is attained.
17. Stop controlling RM or RFM(as the case may be). Note that the reading of the voltmeter across the generator armature is very small. With the set running at its rated speed, slowly cut the resistance RFG till the voltmeter reading begins to increase. Stop controlling RFG. Switch Off the d.c. supply. Isolate the terminals C-FF and measure the resistance. Compare the result with that obtained as critical field resistance in Part I.
18. Now reset the resistance RM to max., RFM to zero and RFG to zero value. Reconnect C to A and FF to AA through the ammeter as before in Fig. 7.5.

19. Switch On the d.c. supply and repeat step 16 above. You should observe a substantial reading in the voltmeter. Slowly increase the resistance of the field circuit by controlling RFG, till the rated terminal voltage is read on the C-FF and measure the resistance.
20. Take the plot of E/If obtained in Part I. Mark the rated voltage point on the curve and join it to the origin. Determine the slope of the straight line. Compare its value with the value of the field circuit resistance measured in step 19.
21. Reset RM to max., RFM to zero and RFG to zero. Reconnect C to A and FF to AA through the ammeter as before to reassemble circuit diagram of Fig. 7.5.
22. Switch On the d.c. supply. VERY SLOWLY cut out the resistance RM keeping an eye on the voltmeter. Stop controlling RM as soon as the voltmeter reading begins to increase fast. Measure the speed of the set. This is the value of the critical speed. Switch off the d.c. supply.
23. Verify the value of critical speed from the knowledge of the value of the field resistance and the E/If characteristic you determined in Part I.

Part IV : Load test – Determination of External Characteristics (Shunt gen.)

24. Reconnect the generator circuit of the machine as per Fig. 7.6(b), and repeat steps 8 through 13. The plot of VG against IG (including VG at IG = 0) gives the external characteristic of d.c. shunt generator at its rated speed.

Report

In your report you should include, besides the usual information already known from previous report writing, all plots discussed in the lab. Work together with important precautions and report your comments/observations based on comparisons already outlined.

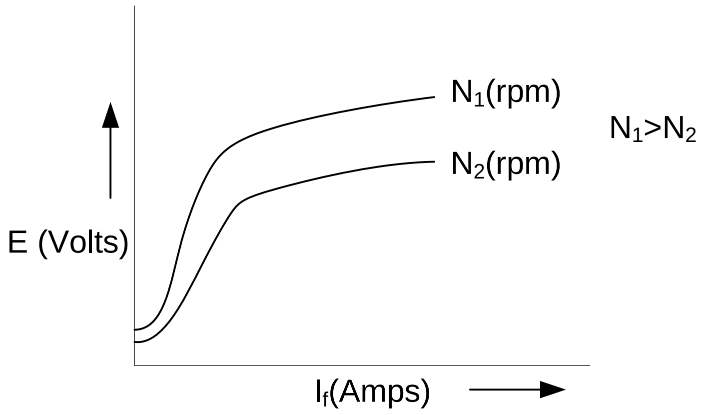


Fig 7.1: No-Load characteristics of D.C. Generator

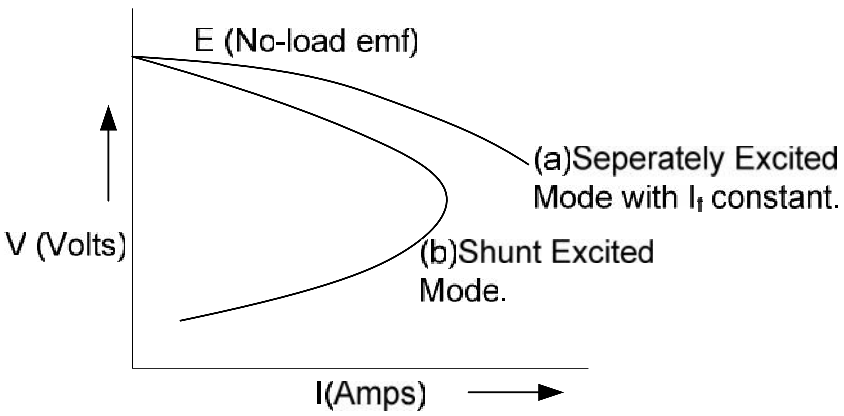


Fig 7.2: Load Characteristics of D.C. Generator Operating at Constant Speed

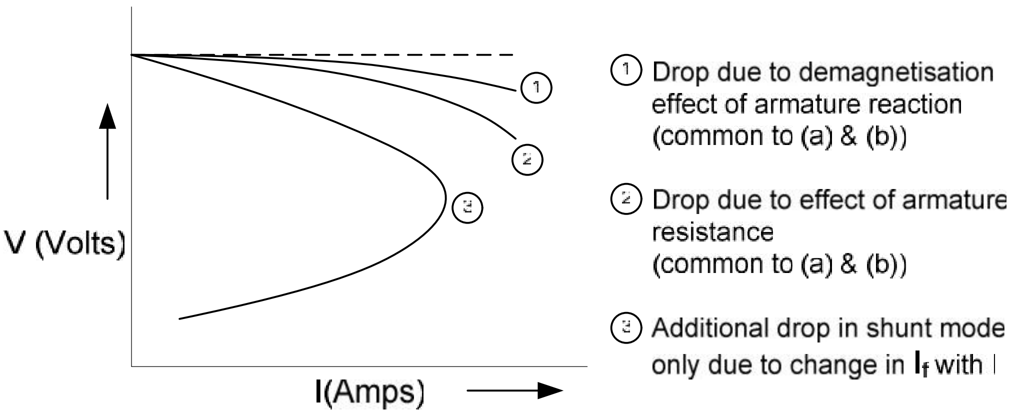


Fig 7.3 : Identification of Causes Leading to the Shape of Load Characteristics in D.C. Generator

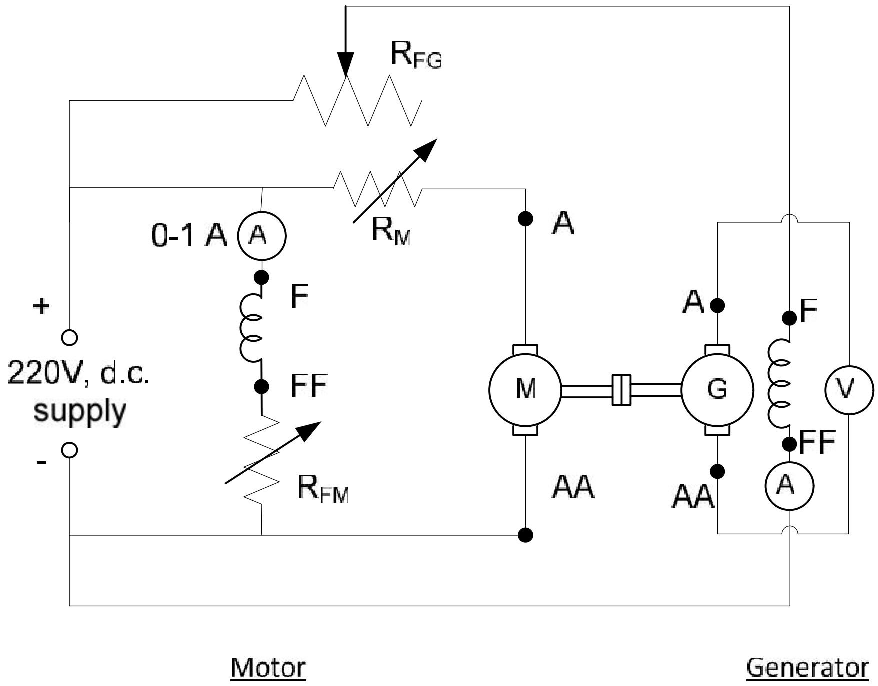


Fig 7.4 : Circuit Diagram for No-Load Test of Separately Excited D.C. Generator

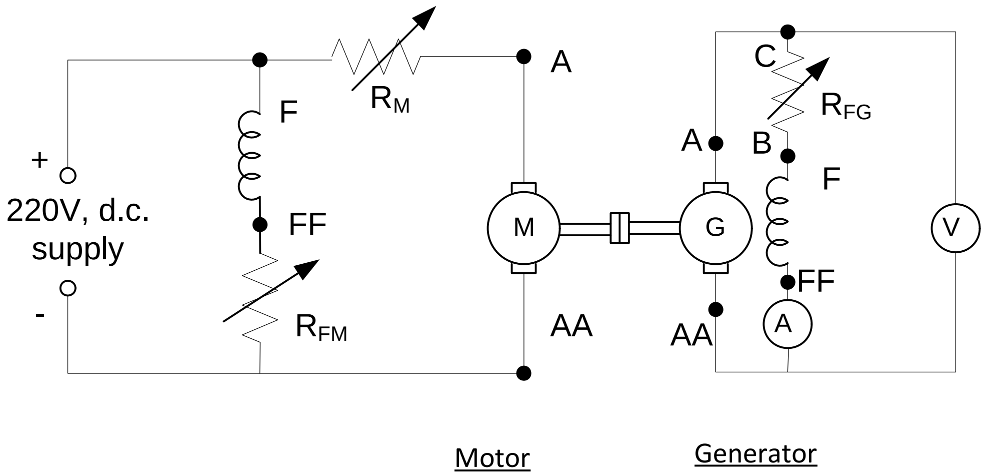


Fig 7.5 Circuit Diagram for Shunt Excited D.C. Generator.

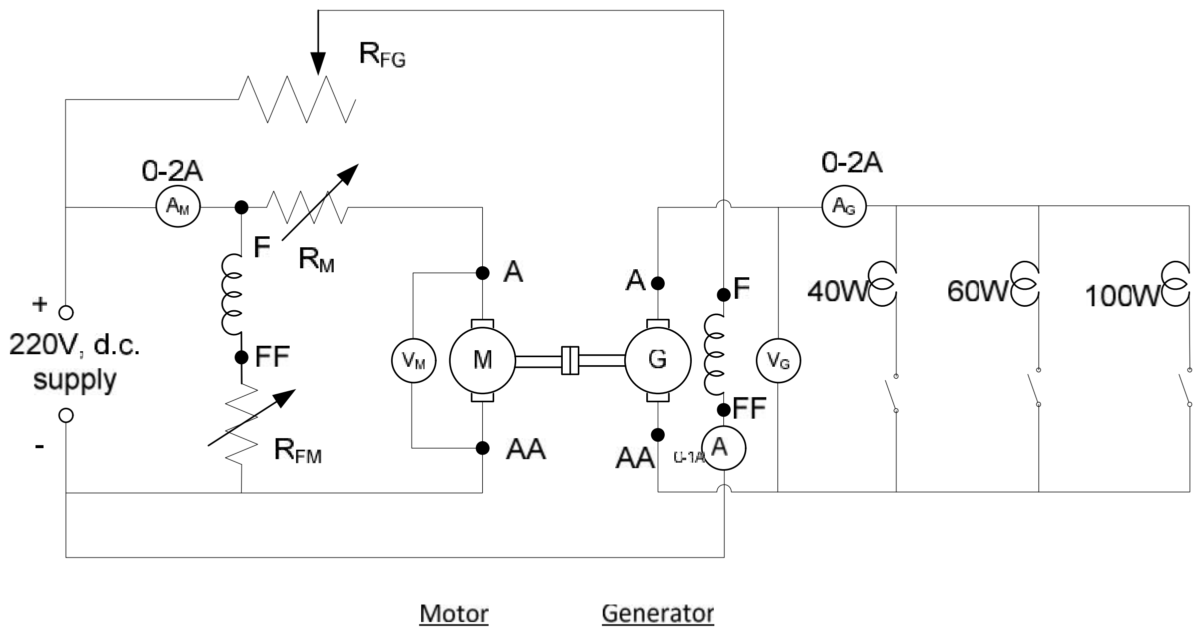


Fig 7.6 (a) : Circuit Diagram for Load Test on Separately Excited D.C. Generator

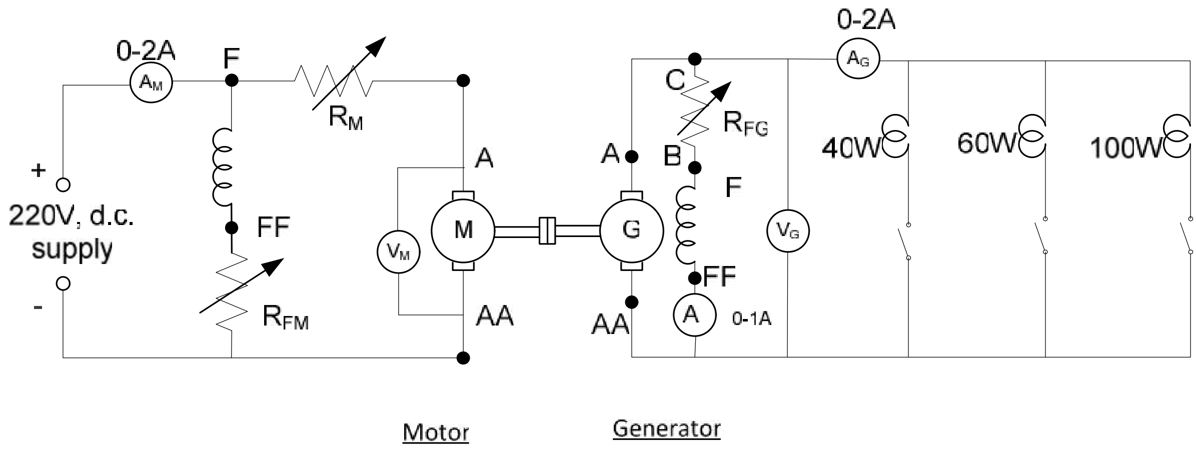


Fig 7.6(b): Circuit Diagram for Load Test on Shunt Excited D.C. Generator

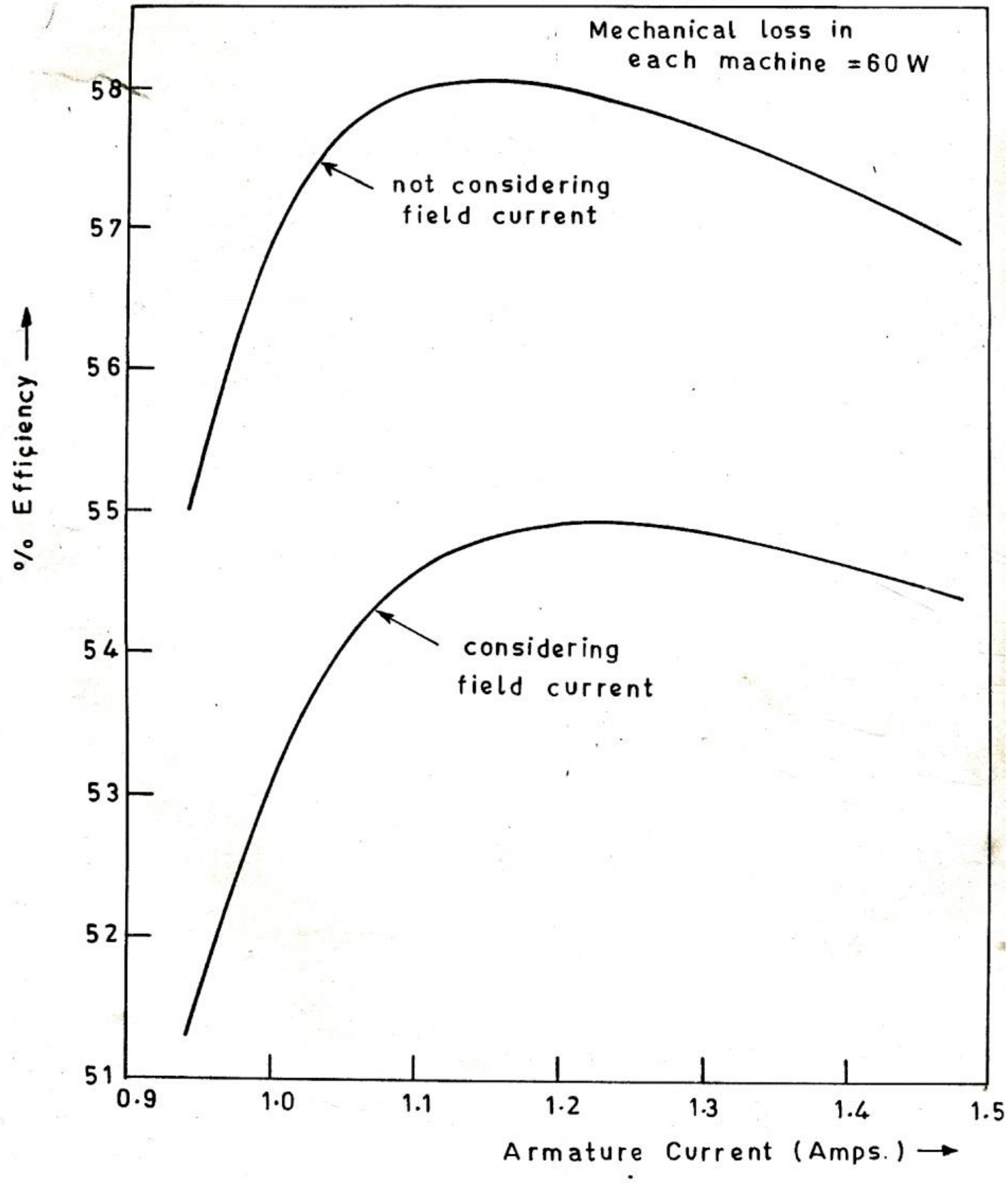


Fig 7.7: Efficiency Curves

INDIAN INSTITUTE OF TECHNOLOGY KANPUR
DEPARTMENT OF ELECTRICAL ENGINEERING

INTRODUCTION TO ELECTRICAL ENGINEERING (ESO 203A)

EXPERIMENT NO. 7: TO STUDY (a) LOAD CHARACTERISTICS OF A DC SHUNT MOTOR, AND (b) THE SPEED CONROL METHODS FOR A SEPERATELY EXCITED DC MOTOR

Brief Theory

One of the unique features of a dc motor, which has helped it maintain its supremacy over other electric drive systems for specific applications in industry, is its ability to provide smooth, wide range of speed control with relative ease. As we already know, the basic equations governing the steady-state operation of a dc motor are given by

$$V - E = I_a \ R_a \qquad (8.1)$$

where, *E*, the back induced emf, is of the form

$$E = \left(\frac{Z \times p}{60 \times a} \right) ¤ N = K ¤ \mu \qquad (8.2)$$

where 'N' and 'ω' are the rotor speed in rpm and rad/sec, respectively and, the constant '*K*', is given by

$$K = \left(\frac{Z \times p}{2 ® a} \right).$$

With no shaft load applied on the motor, the torque developed is only for overcoming the rotational losses. Since the shunt motor operates at essentially a constant flux, a small armature current, I_a, is only required as compared with the rated current of the machine to meet the rotational losses. When a load demanding rated torque is applied to the motor shaft, the applied load torque causes the motor to assume that value of speed, which yields an armature current I_a, sufficient to overcome the load torque and the rotational losses. Hence, the relation between speed-torque is an important characteristic of the d.c. motor.

Various schemes available for the speed control of d.c. motor can also be deduced from the relation given in (8.2).
V and *E*, in (8.1) are of the same order, so that, on a first degree of approximation, $V \approx E$ and thus

$$V \approx K ¤ \mu$$

This gives

$$\mu \propto \frac{V}{¤} \qquad (8.3)$$

Expression (8.3) suggests that there can be two alternative strategies for achieving speed control:

1) By controlling the voltage applied across the armature terminals of the machine.
2) By controlling the field flux of the machine.

Let us consider the practical implications of the above alternatives. Equation (8.3) shows that

(a) The speed (for a given torque supplied by the motor) changes linearly with applied voltage. Since the torque developed by the motor is given by T = K¤I_a, a motor working with a constant field excitation and delivering a constant torque will draw a constant current I_a whose value will be independent of the value of the applied voltage V. This points to the fact that armature voltage control leads to
   - smooth linear control of motor speed
   - control of speed without directly affecting the torque developed by the motor.

(b) The speed of the motor will change in inverse proportion to the field flux or field excitation. Also, in motors, working with constant armature voltage, controlling of field flux will tend to change the torque developed by the motor at a given value of armature current, thus suggesting that field control leads to
   - non-linear inverse speed control of motor speed
   - changed value of torque production for a given armature current.

(c) Although dc machines are designed to operate with given maximum values of armature voltage and field excitation, there exists a minimum permissible value of field current, below which the armature current of the machine may attain dangerously high values during normal operation.

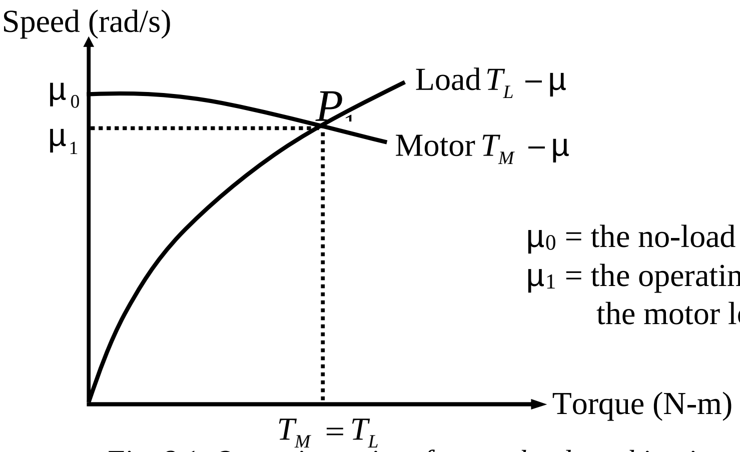
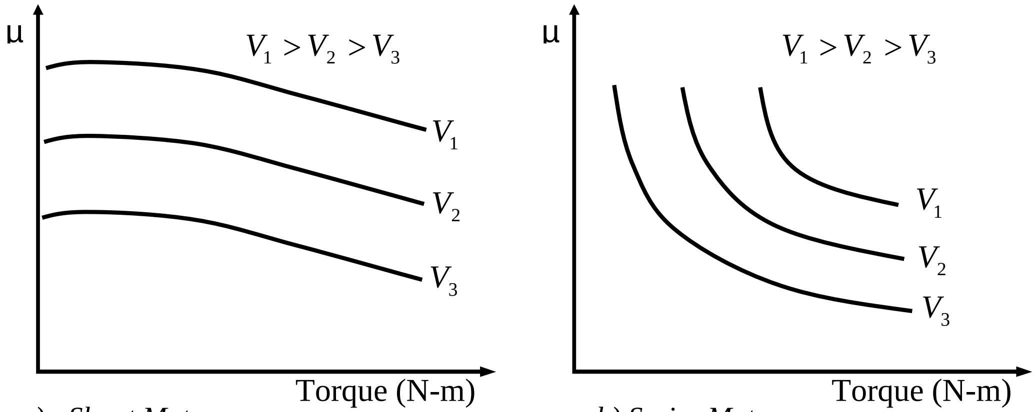


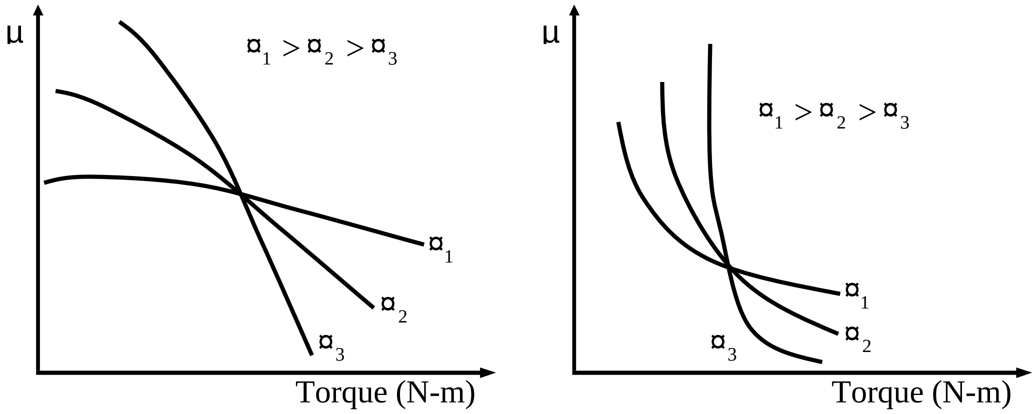
Fig. 8.1. Operating point of motor-load combination.

The speed of operation of a motor driving a load is determined by point of intersection between the motor and the load torque/speed characteristics. This is shown in Fig. 8.1 (point P_1). Control of armature voltage effectively changes the motor torque – speed characteristics without changing their slopes as shown in Figs. 8.2 (a) and (b). Control of field excitation, on the other hand, renders changes in the slopes of the characteristics as shown in Figs. 8.3 (a) and (b). It can, therefore, be seen that, while armature voltage control will invariably lead to proportional control of speed of the motor-load combination, field control, under certain specific load conditions, may NOT yield the expected results (see Fig. 8.4).



a) Shunt Motor *b) Series Motor.*

Fig. 8.2. Variation of characteristics of dc motor with armature voltages at constant field currents.



a) Shunt Motor *b) Series Motor.*

Fig. 8.3. Variation of characteristics of dc motor with field fluxes at constant armature voltage.

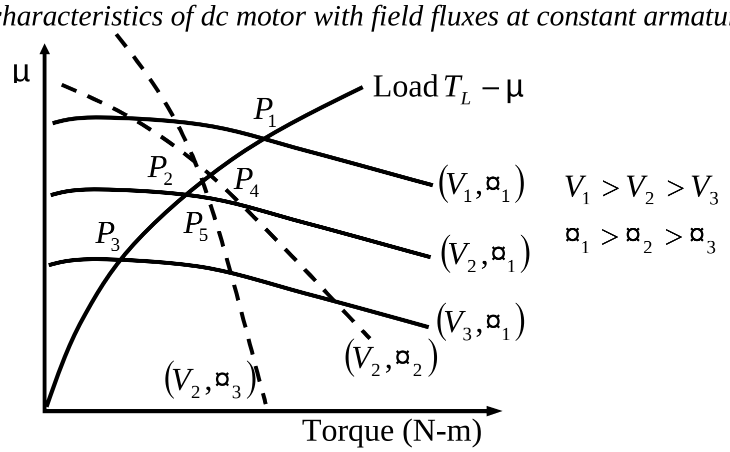


Fig. 8.4. Determination of operating points of motor-load combination with armature voltage and field excitation controls.

Thus, armature voltage control strategy is superior to the field control methodology. However, realization of armature voltage control in practice is more expensive.

Part - A: Experimental Determination of the Load Characteristics of a D.C. Shunt Motor

As in the case of expt. 7, the experimental setup consists of two identical d.c. machines, mechanically coupled to each other. Note the name plate details of each machine. Each machine can function on separately excited or shunt excited mode. The armature and field terminals are brought out on the terminal board of each machine. In this experiment, we shall use one of the d.c. machines as the d.c. motor and the other one as the load on the first machine. We will be evaluating the speed-torque characteristics and speed control strategies for the first machine and the second one acts as a d.c. generator through which the first machine is loaded. Electrical load is connected to the second machine (d.c. generator).

Laboratory Work

1. Connect the circuit as per Fig. 8.5. Set R_M to maximum resistance position and R_{FM} to zero resistance position. Switch Off all the lamps. ***Get the circuit checked by the instructor***.
2. Switch On the dc supply and gradually reduce R_M so that the voltmeter V_M reads around 200 Volts. Adjust R_{FM} so that ammeter A_{m1} reads a suitable value. Let this value be I_{FM}. Record the speed of the motor, I_{FM}, V_M, I_M and the voltage V_G across the generator terminals.
3. Keeping the values of V_M and I_{FM} constant, load the generator in steps using lamps and record the new values of speed, V_G, I_G and I_M.
4. Switch Off all the lamps. Reduce R_M so that the voltmeter V_M reads around 220V. Adjust R_{FM} so that the current in the motor field is maintained to the original value (I_{FM}). Record the speed of the motor, I_{FM}, V_M, I_M and the voltage V_G across the generator terminals.
5. Repeat step no. 3 and record the observations in a separate table.
6. Now set I_{FM} to some other suitable value and V_M = 220 V and take another set of readings.
7. <u>Procedure to plot torque-speed characteristics</u>

   $$\text{Input to the generator} = V_G I_G + I_A^2 R_A + I_F^2 R_F + \text{Mechanical loss}$$
   where $I_A = I_G + V_G / R_F$, R_F = 550 Ω, R_A = 45.2 Ω, Mechanical loss = 60 W
   Power developed by the motor = Input to the generator + 60 W
   $$\text{Developed torque} = \text{Power developed} / \mu_M \ \text{N - m}$$

8. Plot the torque -speed characteristics for each set of observations and label them suitably by indicating the values of V_M and I_{FM}.
9. Also plot speed–input current (I_M) characteristics for each set of observations. A typical characteristic is shown in Fig. 8.6.

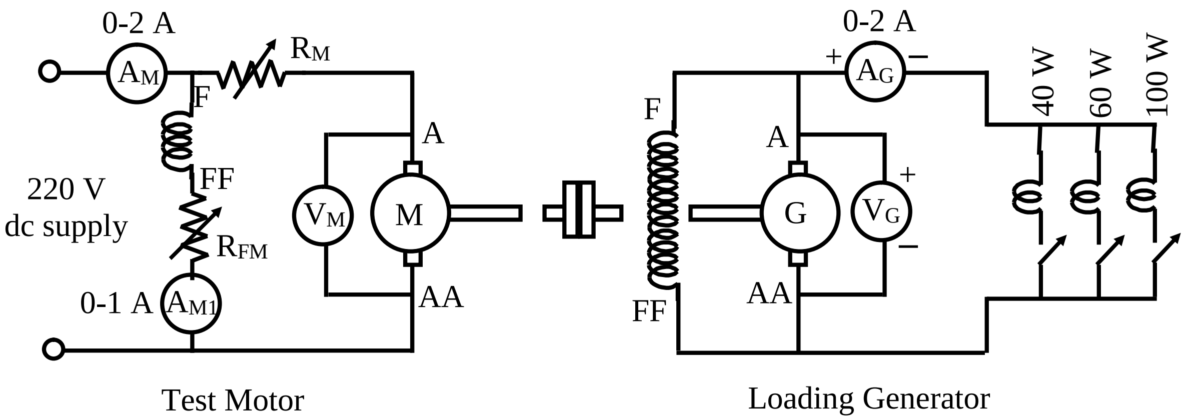


Fig.8.5. Circuit diagram for obtaining speed-torque characteristics.

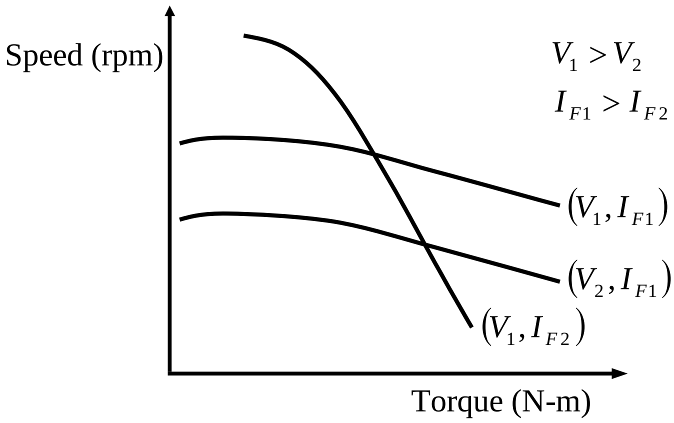


Fig.8.6. Torque-Speed characteristics of dc shunt (or separately excited) motor.

NOTE: Take as many readings (with different combinations of load) as possible. This will help in plotting the graph.

Part -B: Speed Control of a Separately Excited D.C. Motor

Laboratory Work

Set up the circuit as per Fig. 8.7. Get your connections checked by the instructor. Now switch On the dc 220 V supply and control resistance R_{F1} to set he field circuit current to a specific value.

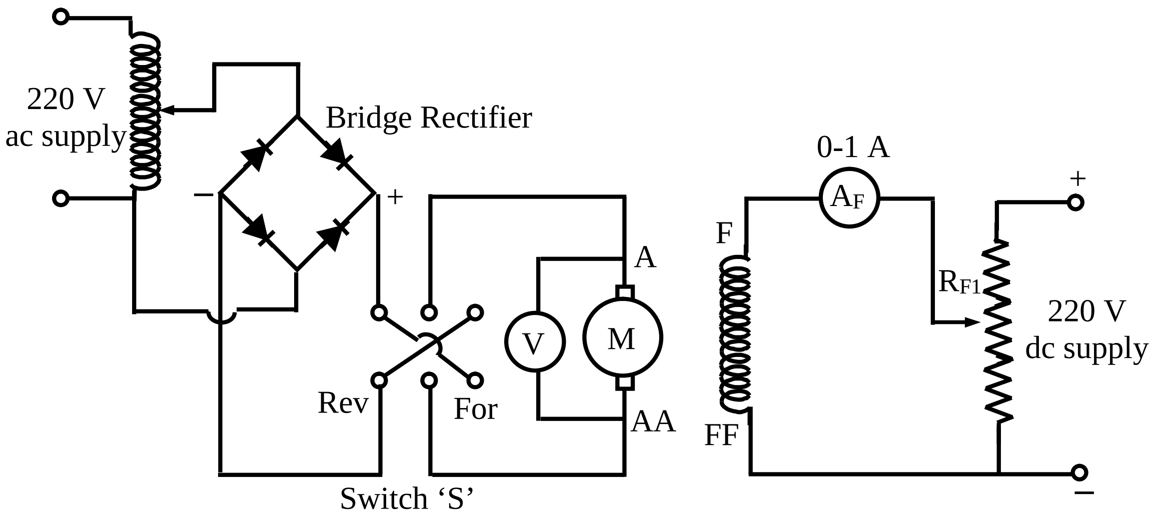


Fig. 8.7. The circuit arrangement.

Ensure that the variac is set to yield zero voltage across its output terminals. Close the switch. Switch On the 1-phase ac supply. Note that the dc motor does not rotate. Now gradually increase the applied voltage to the armature of the machine till the voltmeter *V* reads the rated voltage of the motor. The motor will start and run up to a suitable value of speed. Read speed of motor, applied voltage across motor armature and field current (reading of ammeter A_F, 0 – 1 A). Keeping field current constant at the value originally set, vary the applied voltage in steps by controlling the variac. For each step setting, record the magnitude of applied voltage, across motor armature; and the motor speed.

When the reading of voltmeter *V* is zero, reverse the polarity of the applied voltage by closing the switch in the reverse direction. Now, increase the applied voltage to armature in steps as before, till the voltmeter *V* reads the rated voltage of the motor, and, for each step setting, record the reading of voltmeter *V* and the speed. Make sure that the field excitation remains constant all through this part of the experiment. Note the reversal of direction of rotation. Repeat your experiment for two additional settings of the field excitation.

Reset the variac so that the voltmeter *V* reads zero voltage. Reset the switch to original closed position (Forward). Adjust the resistance R_{F1} so that the value of field excitation (reading of ammeter A_F) is maximum. Control the variac handle so that the applied voltage across motor armature is 150 volts. (This is read by voltmeter *V*). Keeping this voltage constant, gradually control the field resistance R_{F1} such that the field excitation is reduced in steps. For each step setting, record the value of the field current and motor speed. In this part of the test, take the precaution to ensure that the motor speed does not exceed 2000 rpm.

Repeat the experiment for two new settings of armature applied voltage, e.g., 190 V and 220 V.

Laboratory Report

1. Record all your observations in appropriate tabular form, to include all relevant information pertaining to each test.
2. Plot $V - \mu$ characteristics of the three settings of field excitation chosen, on the same graph sheet and label each curve suitably.
3. Plot $I_F - \mu$ characteristics for the three settings of armature applied voltage on the same graph sheet and clearly specify each curve. Record your conclusions about the speed control methodologies based on the above characteristics.
4. Also mention all precautions pertinent to this experiment.

INDIAN INSTITUTE OF TECHNOLOGY KANPUR
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INTRODUCTION TO ELECTRICAL ENGINEERING (ESO 203A)

EXPERIMENT NO. 8: DETERMINATION OF LOAD CHARACTERISTICS OF A SINGLE PHASE CAPACITOR RUN INDUCTION MOTOR

Brief Theory

Single-phase ac induction motors are generally built in the fractional- horse power range and are found in numerous applications at home, offices etc. These motors usually consist of a distributed stator winding and a squirrel-cage rotor. The a.c. voltage applied to the stator winding creates a field distribution. Since there is a single coil carrying an alternating current, air-gap flux is fixed in space, but alternating in magnitude. So, unlike poly phase induction motor, single phase motors do not have a starting torque. Hence, it is necessary to provide a circuit to start rotation of the motor.

For small motors of a few watts, the starting is achieved by means of a single turn of heavy copper wire around one corner of the pole(known as shaded pole construction). The current induced in the single turn is out of phase with the supply current and, hence, causes an out-of-phase component in the magnetic field, which develops torque to start the motor. Starting torque in such construction is very low and efficiency is also less. Such shaded-pole motors are typically used in low-power applications with low starting torque requirement, such as desk fans and record players. Larger size motors are provided with a second stator winding which is fed with an out-of-phase current to create a rotating magnetic field. The out-of-phase current may be derived by feeding the winding through a capacitor, or it may be derived from the winding having different values of inductance and resistance from the main winding. In some designs the second winding is disconnected once the motor achieves certain speed. In other design, the second winding is continuously kept energised during running, which improves running torque. This experiment is on a capacitor run induction motor.

Like in the case of d.c motors, torque-speed characteristics is an important characteristics in the case of single phase induction motors also. Load torque, T_L , is given by

$$T_L = \frac{W_{in}}{\mu_m} \text{ N-m where}$$

where $\mu_m = 2\text{®}n/60$, n is the speed in r.p.m. and W_{in} is the input power supplied to the d.c. generator, which is used for loading the induction motor.

Laboratory Work

1. Connect the circuit as per Fig. 9.1. Ensure that the variac control knob is in zero position. Switch Off all the lamps. Get your circuit checked by the instructor.
2. Switch On the 230 V, 50 Hz, single phase A.C. supply and gradually increase the applied voltage to the motor to 230 V. Measure the input voltage V_M, input current I_M, input power (read by the wattmeter) W, terminal voltage V_G, load current I_G and the speed (since all the switches are open, load current of the generator is zero). Record the observations.
3. Load the D.C. generator in steps using lamps and, for each load setting, adjust the variac so that the input voltage to the motor is 230 V. Record all the meter readings and the speed.
4. Plot load torque T_L (N-m) versus speed, n (rpm) and percentage efficiency versus T_L characteristics.

Calculation:-

Input power supplied by the motor to the D.C. Generator

$$W_{in} = V_G I_G + I_G^2 R_A + \text{Mechanical Loss (W)}$$

Take $R_A = 160\ \Omega$, Mech. Loss = 60 W.

a) Load torque, $T_L = \dfrac{W_{in}}{\omega_m}$ N - m where $\omega_m = 2\pi n/60$ and

b) % Efficiency $= \dfrac{W_{in} * 100}{\text{Input Power to the Motor}}$

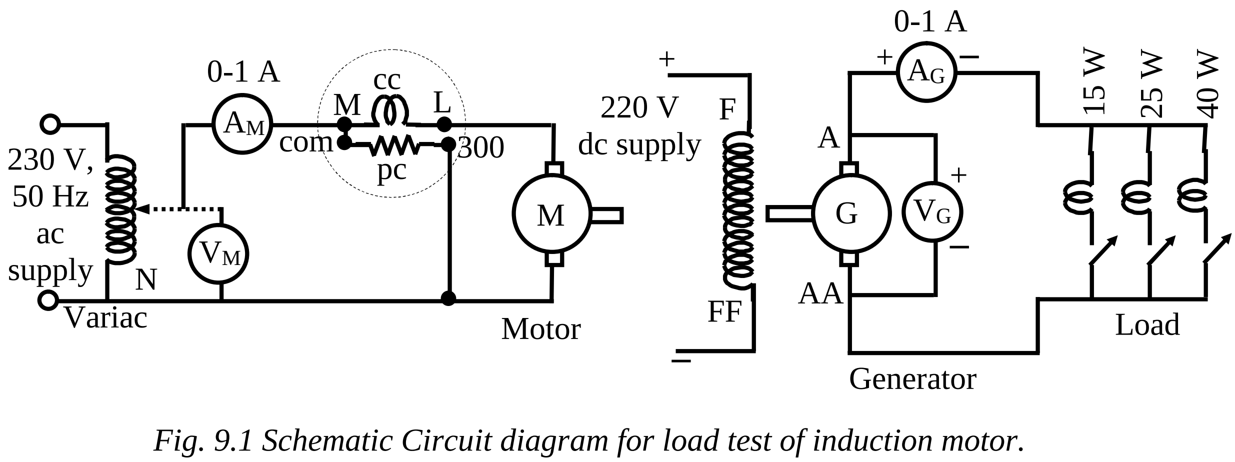

Fig. 9.1 Schematic Circuit diagram for load test of induction motor.

NOTE: Take as much reading (with different combinations of load) as possible, this will help in plotting the graph.