

Laboratory Manual

EE-380A

**ELECTROMECHANICAL ENERGY
CONVERSION (EMEC) LAB**

LOCATION: WL-112



**DEPARTMENT OF ELECTRICAL
ENGINEERING, IIT KANPUR**

IMPORTANT INSTRUCTIONS FOR STUDENTS

- Wear shoes during the lab experiment.
- Ensure that when you come in the lab you should have lab report, lab manual, pen, pencil, graph paper etc.
- Do not wear loose clothes, when you are doing the experiments on rotating electrical machines.
- Make the connections tightly.
- Connections shall be made so that only necessary meter/equipment is present on the experimental table. These shall be arranged as neatly and clearly as possible
- Before energizing the circuits, please ensure that your connections should be checked by the lab instructor/TA/Lab In charge.
- Use the appropriate rating/range of measuring instruments/meters.
- Please do not touch the machine terminals or the knob of the auto transformer/DSO etc. unnecessarily.
- Increase or decrease the voltage gradually by auto transformer.
- Increase or decrease the load step by step.
- If you have any doubt, ask your lab instructor.
- Handle the lab equipments/measuring instruments carefully.
- Do not use mobile phone, while performing the experiments.
- After completing your experiment, return the measuring instruments to lab persons.

LIST OF EXPERIMENTS

Experiment No. 1A: To conduct Sumpner's test on two identical transformers and to determine their efficiencies at 110%, 100%, 75% and 25% of the full load at unity and 0.8 lagging power factor.

Experiment No. 1B: To separate the hysteresis and eddy current losses in the core of 1-phase transformer under the rated conditions.

Experiment No. 2: To conduct experiment in the High Voltage lab. To observe the Followings.

- (i) Distinction between the types of electrostatic fields.
- (ii) Different stages in gas breakdown.

Experiment No. 3: To connect three 1-phase transformers into 3-phase transformer banks and study the waveforms for various configurations.

Experiment No. 4: To perform the no-load, blocked rotor and load tests on 1-phase induction motor (split phase and capacitor start), and determine its parameters and study its performance.

Experiment No. 5: To perform the no-load, blocked rotor and load tests on a 3-phase squirrel cage induction motor and obtain its equivalent circuit referred to the stator.

Experiment No. 6: To perform open circuit and short circuit tests on a synchronous generator to determine its equivalent circuit parameters. Also conduct load test to study its various performance characteristics.

EXPERIMENT NO. 1A

Objective

To conduct Sumpner's test on two identical transformers and calculate their efficiencies at 110%, 100%, 75% and 25% of full load at unity and 0.8 p.f. lagging.

Theory

Two identical transformers are used in this test. The primaries are connected to the supply. The secondaries are connected together such that the voltage in the loop formed by the secondaries is zero, i.e., the voltages are in phase opposition in the loop. Under this condition, the power taken from the mains equals the sum of the iron losses taking place in the two transformers. If an auxiliary voltage source is now introduced in the loop formed by the secondary windings, it essentially sees a short circuit in the primary winding circuit. As such, a small voltage of this source can be made to circulate short circuit currents through the primary and secondary windings of the two transformers equal to their full load currents. The power delivered by this auxiliary source is essentially equal to the copper losses in the windings of the transformers. The auxiliary voltage source is in the form of a booster transformer. See Fig. 1.1 for details. Since the transformers are identical, we can determine the iron and full load copper losses in each transformer from the readings of the total iron and copper losses. The main advantage of this test is that the power required for operation at any load is only equal to the losses. So, without much expenditure in energy, we can operate the transformers such that the iron and full load copper losses take place in them, and run them in this condition for a long enough time to determine the temperature rise under steady state condition. Such tests are called 'heat run' tests. They are extremely important since power ratings of transformers (for that matter, of any electrical power equipment), are decided by their temperature rise.

Laboratory Work

1. Study the circuit and mark the current paths in the primary and secondary of both the transformers under test.
2. Calculate the ranges of the meters required and get these approved. Make the connections as given in Fig. 1.1 and get them checked.
3. Connect the 4 amp variac (connected in primary of transformers) to single phase supply and increase the voltage from zero to the rated voltage of primary of transformers. If the voltmeter (connected in the circuit of the secondary windings of the test transformers), indicates double of secondary voltage i.e., if emfs are additive in the loop, switch off the supply and interchange any one of the secondary windings and again see the voltage. Now if the voltmeter indicates zero, the secondaries are connected back to back. Short circuit the voltmeter by closing the switch, as shown in Fig. 1.1.

4. Connect the supply to the 15 amps variac (connected in secondary side of transformers) as shown in Fig. 1.1 Increase the voltage (start from zero) of the secondary side of transformers through the variac gradually then the current in the secondaries of the test transformers will vary. Take the meter readings and record them in table for 60%, 80%, 100% and 110% of the rated current of the transformers under test.

Sl. No.	W_p	A_p	W_s	A_s

5. Calculate the efficiency of the transformer at unity and at 0.8 p.f. lagging for the various load currents given above and plot them. Also plot efficiency, copper loss and iron loss versus load current.

Precautions

1. Note carefully the rating of the transformers and connect accordingly the wattmeters, ammeters and voltmeters.
2. Do not exceed the currents in the secondaries of the transformers more than its rating except for 110% load. Keep the load on at 110% only for a short time.
3. Before connecting the variac (auto transformers) to the supply, check it should be at zero position.
4. Get your connections checked before connecting it to the mains.
5. The low power factor wattmeter required the additional single phase ac supply for working. The connection cord is provided for the purpose.

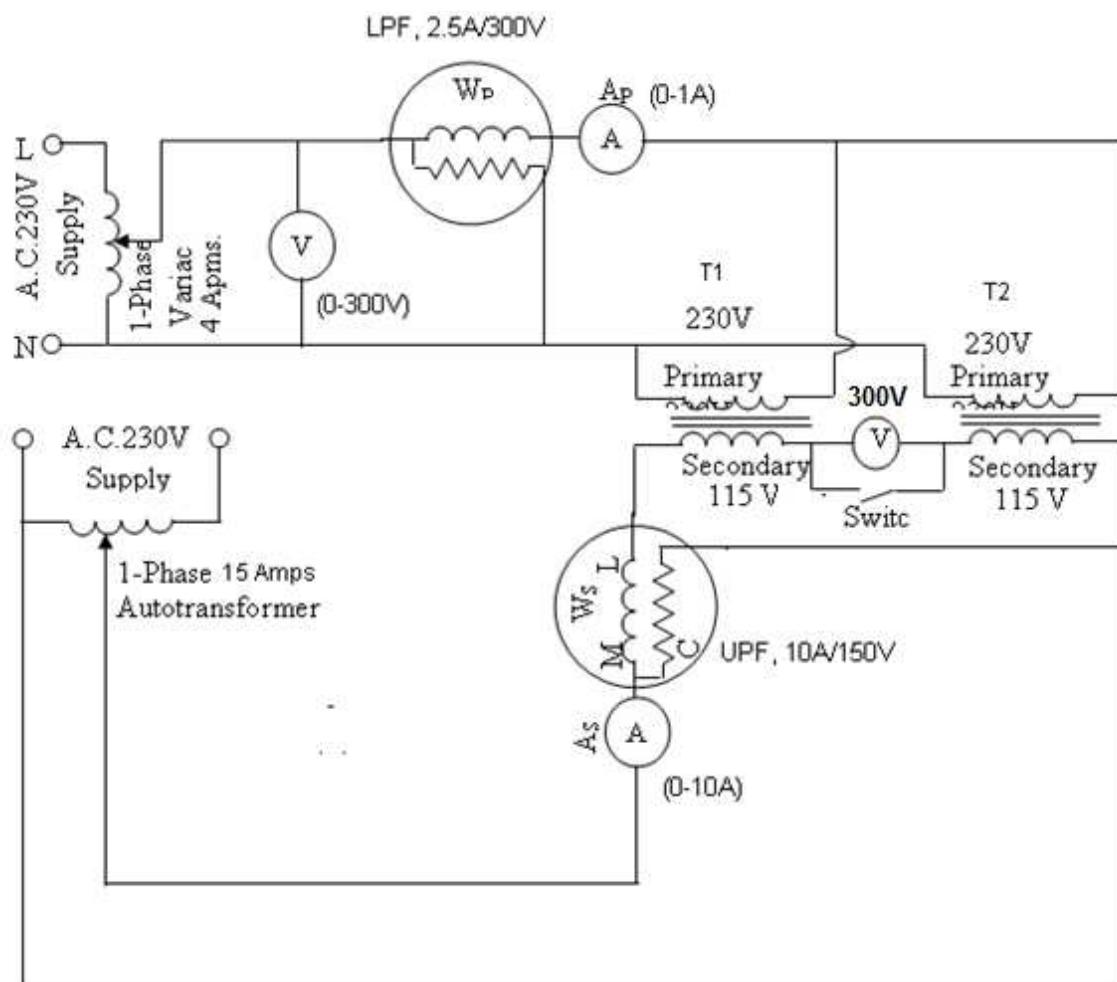


FIG 1.1 Circuit diagram for Sumpner's test.

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EXPERIMENT NO. 1B

Objective

To separate the hysteresis and eddy current losses combined in the core of a 1-phase transformer under the rated conditions.

Theory

At a given flux density, the hysteresis loss is proportional to the frequency, while the eddy current loss is proportional to the square of the frequency. Thus the total core loss P_c in the magnetic circuit of an electric machine can be written as

$$P_c = Hf + Pf^2 \quad (1B.1)$$

Where f is the frequency, and H and P are functions of flux density B . The term Hf represents hysteresis loss and the term Pf^2 represents eddy current loss. If we keep flux density constant, H and P become constant. Dividing both sides of equation (1B.1) by f , we get,

$$\frac{P_c}{f} = H + Pf \quad (1B.2)$$

This relationship is utilized in the separation of hysteresis loss from the eddy current loss. Let the value of total loss P_c be available at a certain flux density at two frequencies f_1 and f_2 .

Writing equation (1B.2) at these two frequencies, we have

$$\frac{P_{c1}}{f_1} = H + Pf_1, \quad (1B.3)$$

$$\frac{P_{c2}}{f_2} = H + Pf_2, \quad (1B.4)$$

Solving the simultaneous equations, P and H can be determined. The individual losses $P_h = Hf$ and $P_e = Pf^2$ can be computed at any frequency. The rated flux density can be obtained at any frequency by keeping the ratio V/f constant and equal to the value obtained at rated voltage and rated frequency. Here V represents the voltage applied to the transformer primary.

Laboratory Work

1. Draw the circuit diagram with the suitable ranges of the meters. Take the help of the circuit diagram shown in Fig 1.1B. Make the connections according to your circuit diagram, as shown by dotted lines. For separation of losses a variable frequency and variable voltage source is needed for which an alternator coupled with a D.C. shunt

motor is used. It can be assumed that the alternator gives a pure sinusoidal voltage waveform at its output.

2. Keep the D.C. motor field resistance to minimum and armature resistance to maximum position at the time of starting the motor.
3. Get your connections checked by the Lab Instructor. Start the D.C. motor by switching on the DC main switch and bring its speed to 1500 rpm by reducing the resistance of armature rheostat. If the rated speed is not attained by this, then slowly increase the resistance of field rheostat of the shunt motor so that you get 50 Hz supply from the alternator (which is a 4-pole machine in our case).

$$Frequency = \frac{RPM \times \text{No. of poles}}{120}$$

$$[\text{Synchronous speed} = \frac{120}{P} f, \text{ where } f \text{ is the frequency of alternator supply}]$$

Core Loss Vs Frequency at Constant Flux Density

4. Keep the field rheostat of alternator to maximum position and then switch on the dc supply of field circuit of alternator.
5. Now switch on the output of alternator and set required voltage, starting from 115 volts and 50 cycles frequency (rated voltage and frequency of transformer), vary the voltage and frequency always in the same proportion, keeping $V/f = 115/50$ in order to separate eddy current and hysteresis losses under rated conditions. Observe wattage (core loss) and frequency at each point.
6. Completing the experiment switch off supply of dc motor.

Record the readings as shown below:

Sl. No.	Motor RPM	Frequency (Hz)	Input Voltage (V)	Wattage (core loss) (W)	Remarks

7. Plot core loss against frequency at rated flux density. Separate eddy current and hysteresis losses and plot them against frequency.

Precautions

1. Keep the rotary switch of alternator rotor field in 'off' position at the time of starting the D.C. shunt motor, and then turn the rotary switch to the position 'D.C. for rotor

field' for excitation to the field winding of the alternator.

2. The voltage limitation to the winding of the transformer is 115 volts. It should not be exceeded.
3. Remember that H.T. (H.V. side) terminals of the transformer are alive the moment A.C. voltage is applied to the L.T. (L.V. side) terminals.
4. Keep the field resistance of D.C. motor to minimum and armature resistance to maximum position at the time of starting the motor.

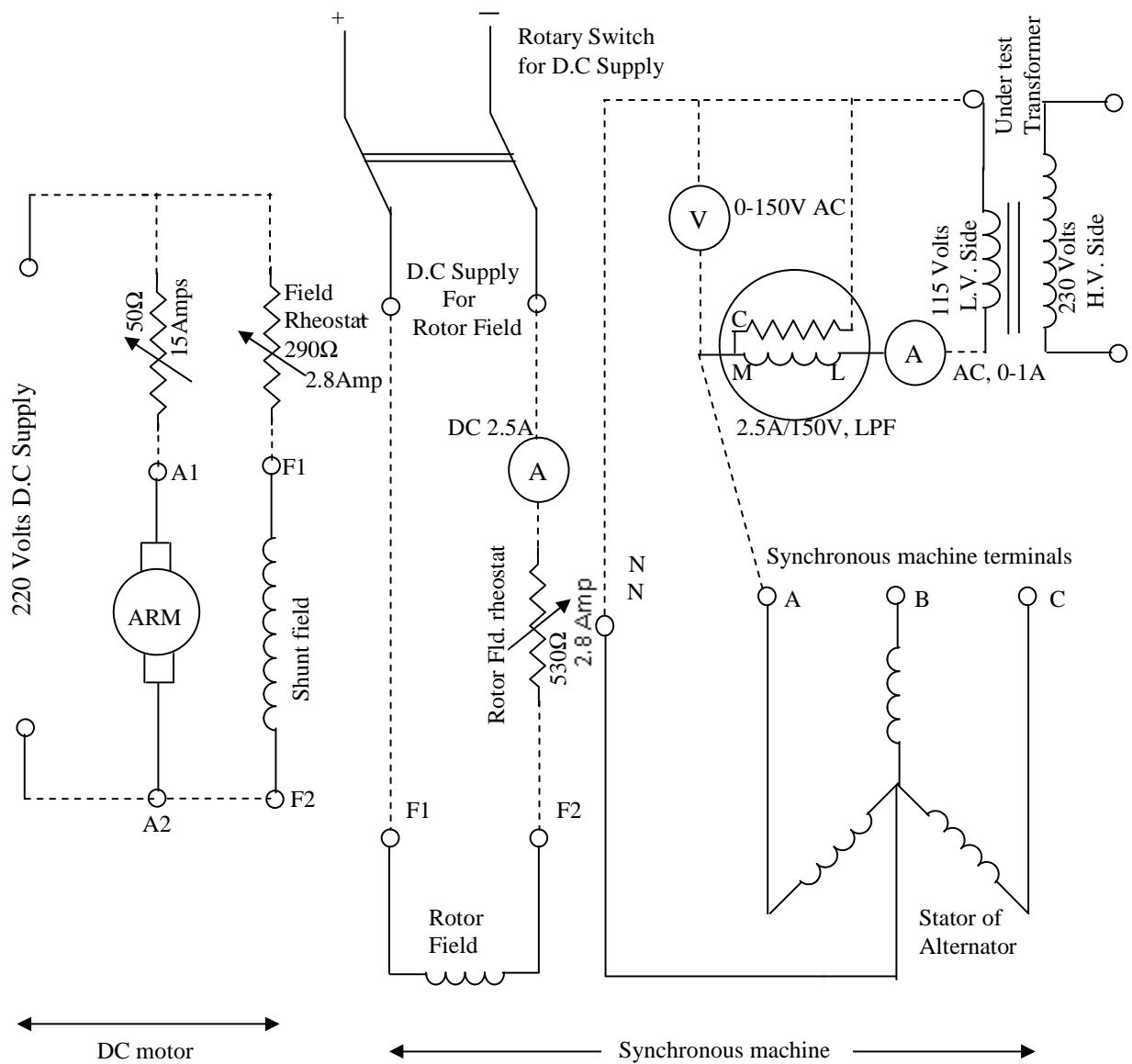


FIG 1.1B Circuit diagram for separation of losses.

EXPERIMENT NO. 2

Objective: To conduct experiment in the High Voltage lab. To observe the following.

- a) Distinction between the types of electrostatic fields.
- b) Different stages in gas breakdown.

Electrostatic field:

For a dielectric material to be used in insulation it should be able to store charge across the material without allowing charges to flow through. The positioning of the charges across the material results in the build-up of electrostatic field. With an increase in demand for electrical energy, transmission level voltages have gone up. In order to keep the size and weight of electrical equipment, the designers are forced to adequately design the insulation. This requires an understanding of the behaviour of the insulating material when exposed to electric fields; the first step towards that is knowledge of electric fields and methods of controlling electric stress.

Electric field E is defined as the force per unit charge. At any point in the field, E is defined as gradient of potential, i.e. $E = -\nabla\phi$

The simplest kind of electric field is **uniform** field. In this case, field is constant within the volume of the dielectric i.e. space independent. This kind of field is very difficult to achieve even with parallel plates. A **non uniform** field is space dependent. In this case, the potential gradient may be very high over a limited region. In a field map representing non-uniform fields, the field lines tend to be concentrated in certain regions but sparsely distributed elsewhere. The extend of non-uniformity may be measured by **field efficiency factor** defined as $\eta = \frac{E_{mean}}{E_{max}}$. It is also called the **Schwaiger factor**. η equals unity for a uniform field and approaches zero with increase of non-uniformity.

The uniformity of a field is predominantly determined by the shapes of the electrodes used.

1. Uniform Fields may be obtained between two parallel plates provided stress control is applied at the ends.
2. Non-uniform Fields with high Schwaiger factor may be obtained between two coaxial cylinders.
3. Non-uniform Field with very low Schwaiger factor may be obtained with a needle - plane geometry, i.e. at any sharp point, edge or a thin wire.

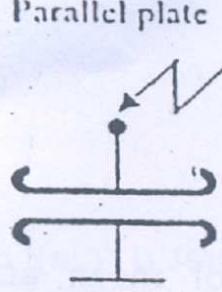
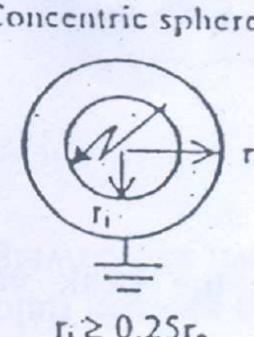
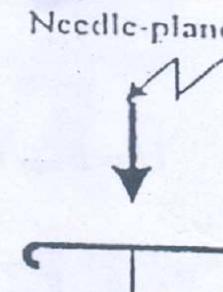
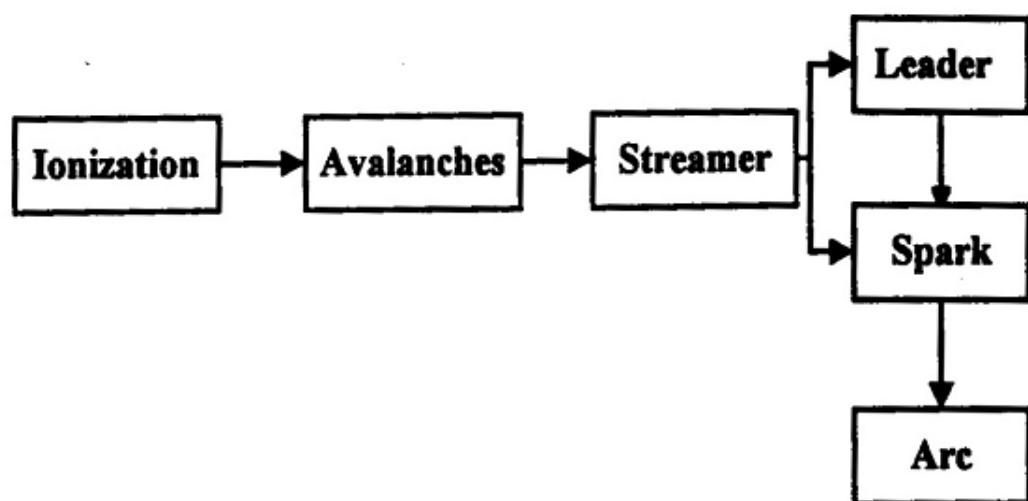
Field Classification	Uniform	Non-Uniform Field with high Schwaiger factor	Extremely Non-uniform (with low Schwaiger factor)
Electrode Configuration	Parallel plate 	Concentric spheres  $r_i \geq 0.25r_o$	Needle-plane 
η	1.0	0.25 for air	<<0.01

Fig.2.1: Typical electrodes configurations

As the voltage across uniform field increases, the applied field exceeds a critical value E_b the dielectric breakdown strength of the material. This is characteristic of the dielectric material. When field across the material exposed to uniform field exceeds the dielectric breakdown strength of the material, **breakdown** occurs i.e. the material loses its insulating property and allows conduction of high current. In a material exposed to non-uniform fields, only a small region may be stressed above the dielectric breakdown strength of the material, while the field elsewhere remains within safe bounds. This may result in localised breakdown of the material (only in the region of maximum field), which then becomes conducting without the conducting path being able to bridge the opposite electrodes. This is called **partial discharge**. Partial discharge in open air is called corona. Other forms of partial discharges occurring within materials or along gas-solid surfaces are internal discharges, tracking, surface flashover, etc.



Stages in Discharge Development:

The visual nature of the corona can change according to the nature of the field. Some or all of the following different stages in the development of the discharge may be witnessed depending upon the field configuration.

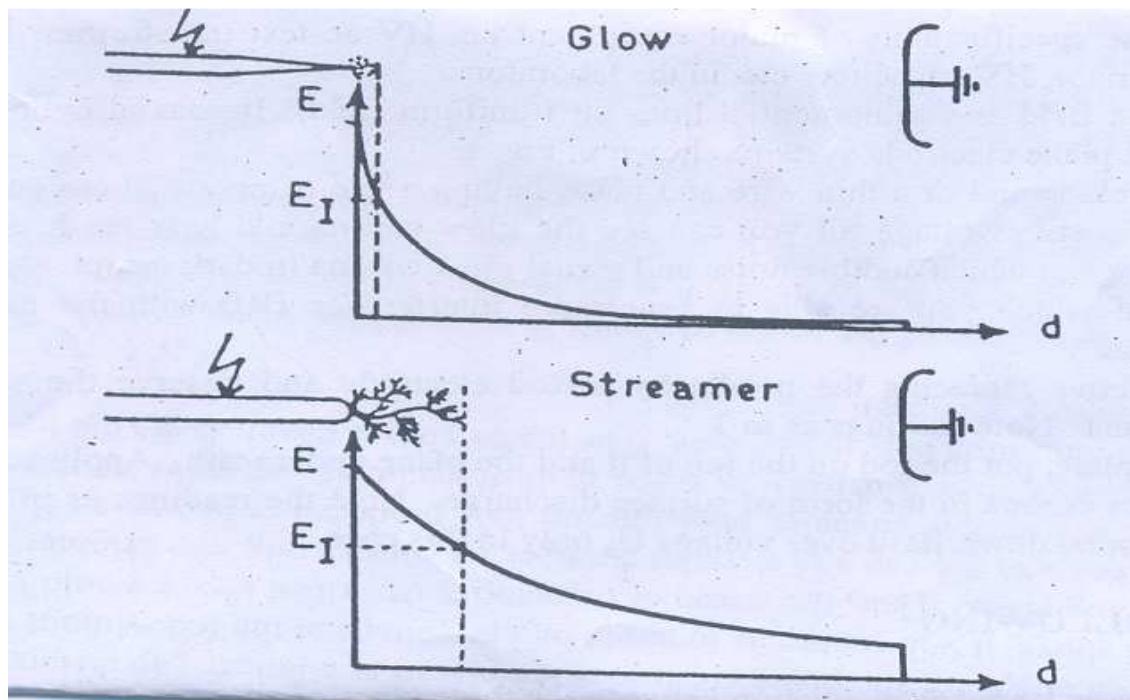
Electric discharges develop due to ionization of atoms and molecules in regions of high electric field. With the production of a large number of electrons, electron avalanches are created. The following steps may occur next, depending on the nature of the field, and hence the electrode configurations.

1. Glow

In highly non-uniform fields, where only a small region near the tip of an electrodes exceeds the breakdown strength of air, the PD is localised within a limited region close to the tip of the electrode. Depth of this region is so small that the ionization of air is not sufficient to create avalanches with a critical amplification. The optical impression of such a partial discharge process is a weak, bluish “Glow”, seen adjacent to the sharp electrode. The electrons at high energy levels emit quantum of light and fall back to the original state of lower energy level. It appears in dark like a star at the tip of any point electrode.

2. Streamer

If the non-uniform field exceeding the breakdown strength of air extends over a larger region, electron avalanches may be produced which progress from the tip of the electrode in steps towards the other electrode. The visual impression is similar to that of lightning. Streamers are essentially electron avalanches, typically lasting a few nanoseconds. Streamers redistribute charge within the surrounding gas.



Where E_I is the minimum field intensity required for impact ionization.

Fig.2.2: Variation of field intensity at needle and rod – plane electrode configurations.

3. Leader

Streamers can lead to the development of a single leader channel. The projecting channel of hot plasma is called a leader and it can have electrical conductivity approaching that of an arc. The function of a leader is similar to introducing a short length of wire into a gap. The Leaders are the brightest channels and produce a “cracking” audible noise. A leader channel arises from the stem of the discharge where the gas is heated to the maximum by the total current flowing in from all streamer bursts. The total streamer current provides the leader its power, heats it and maintains the plasma conductivity. In our laboratory the Leader corona discharge is produced in the form of “Surface Discharge” on a glass plate to the limitation of the magnitude of HV available.

Sometimes this may develop into a spark or an arc. A **spark** is a discharge capable of passing high current typical of short circuit conditions. The final spark stage is the **arc** flash. After this breakdown is generally complete.

Laboratory work:

1. Note down the specifications of major equipment i.e. HV ac test transformer, Impulse Voltage Generator (IVG), HV capacitors etc. in the laboratory.
2. Sketch electric field and equipotential lines on (i) Uniform Field, (ii) Coaxial cylinder, and (iii) needle and plane electrode systems shown in Fig.1.
3. Take Needle-Plane and or a thin wire and plane having a gap of about 20 cm and apply ac, power frequency voltage till you can see the Glow Corona and hear the HISS sound. Note the voltage at which audible noise and visual Glow Corona in dark incert. Also note the voltage at which you are able to hear radio interference (RI) with the help of a transistor radio.
4. Repeat the above replacing the needle by a rod electrode and observe the same for Streamer Corona. Note readings as in 3.
5. Take a glass plate and put the rod on the top of it and the plane underneath. Apply voltage to observe Leader Corona in the form of Surface Discharge. Note the readings as in 3. Also measure the breakdown/flash over voltage U_b only in this case.

Answer the Following:

1. Describe the various stages in a discharge.
2. What are the various ways to detect corona.
3. How may corona be reduced?

EXPERIMENT NO. 3

Objective

To connect three single phase transformers into three-phase transformers banks and study the waveforms for various configurations.

Theory

Three phase transformers are required both at generation and distribution ends of a power system network to transform three phase power from one voltage level to another level. The primary and secondary windings of three phase transformers can be connected in a number of ways such as Star, Mesh (Delta), Zigzag or Vee connections. However the most common ones are the Star-Star, Star-Delta and Delta-Delta connections. Their principal features have been described below.

Polarity:

Before any of the transformer connections are made, it is absolutely necessary to determine the polarity of each single phase transformer unit. Each of the two primary terminals of a transformer is alternately positive and negative with respect to the other. Same is true with secondary terminals. When two terminals, one from the primary and the other from the secondary are either both positive or both negative, simultaneously, are said to have same polarity. A pair of terminals having same polarity is usually symbolized by dots.

Star-Star Connection:

Star connection is formed on each side of a transformer bank by connecting together undotted terminals on both sides of the bank as shown in Fig. 3.2 This connection provides zero degree phase shift between the corresponding line voltages/currents on the primary and secondary sides. For this reason it is called a 0° connection. However if the winding connection on the secondary side is reversed i.e. dotted ends are connected together, the corresponding line voltages/currents become out of phase resulting in 180° connection. Further if the phase transformation ratio of each single phase unit is $x:1$, the line transformation ratio of the bank is also $x:1$.

This is the most economical connection for small, high voltage transformers, as number of turns per phase and the amount of insulation required is minimal. Star-Star connected transformers are normally provided with a tertiary winding connected in delta. This winding helps in minimizing the third harmonic content in line currents and stabilizing the neutral of the fundamental frequency voltage. Sometimes the tertiary winding can also be used to feed auxiliary loads of the sub-stations/power stations.

Star-Delta Connection:

Star-Delta connection is formed as shown in Fig. 3.3A. If connected with correct polarity, the phasor diagram should reveal that the sum of voltages around delta is zero. This is a must as otherwise a closed delta would mean a short circuit. This connection can provide $\pm 30^\circ$ and $180 \pm 30^\circ$ connections depending on how the secondary windings are connected. 0° connection is not possible here. Further if the phase transformation ratio of each single phase unit is $x:1$, the line transformation ratio of the bank is $\sqrt{3} x:1$.

This is the most common arrangement for power supply transformers. It has the advantage of a star point for mixed loading and a delta winding to carry third harmonic currents, which stabilizes the star point potential.

Delta-Delta Connection:

Delta-Delta connection is formed as shown in Fig. 3.4. The 0° or 180° connection is possible here. Further if the phase transformation ratio of each single phase unit is $x : 1$, the line transformation ratio of the bank is $x : 1$.

This is an economical connection for a large low voltage transformer in which insulation problem is not important, as it increases the number of turns per phase and reduces the necessary sectional area of conductors. Large unbalance of loads may be met without difficulty, while the closed mesh serves to damp out third harmonic voltage. This, however, is not usually practicable with three-phase units as the absence of a star point may be disadvantageous.

Harmonics in 3-phase Transformer banks:

From an economic point of view, a transformer is designed to operate in the saturating region of the magnetic core. This makes the exciting current non-sinusoidal [1]. The exciting current contains the fundamental and all odd harmonics, third one being the predominant one. Thus for all practical purposes harmonics greater than third (fifth, seventh, ninth, etc.) in the exciting current can be neglected. This section describes how these harmonics are generated in various connections of the three-phase transformer and ways to limit their effect [2].

Consider the system shown in Fig. 3.3. The primary windings are connected in star and the neutral point of the supply is available. The secondary windings can be connected in delta. Consider now the following cases:

Case 1: SW 1 CLOSED, SW2 OPEN

Because SW2 is open, no current flows in secondary windings. The currents flowing in the primary are the exciting currents. It is assumed that the exciting currents contain only fundamental and third harmonic currents.

$$i_A = I_{m1} \sin wt + I_{m3} \sin 3wt$$

$$i_B = I_{m1} \sin(wt - 120^\circ) + I_{m3} \sin(3wt - 120^\circ)$$

$$i_C = I_{m1} \sin(wt - 240^\circ) + I_{m3} \sin(3wt - 240^\circ)$$

The current in the neutral line is

$$I_{NN} = i_A + i_B + i_C = 3I_{m3} \sin 3wt$$

Note that fundamental currents in the winding are phase shifted by 120° from each other while third harmonic currents are all in phase (*co-phasal*). The neutral line carries only the third harmonic current.

Because the exciting current is non-sinusoidal, the flux in the core and hence the

induced voltages in the windings will be sinusoidal. The secondary windings are open and therefore the voltage across a secondary winding will represent the induced voltage.

Case 2: SW1 OPEN, SW2 OPEN

In this case the third harmonic currents cannot flow in the primary windings. Therefore the primary currents are essentially sinusoidal. If the exciting current is sinusoidal, the flux is non-sinusoidal because of nonlinear B-H characteristics of the magnetic core, and it contains third harmonic components. This will induce third harmonic voltage in the windings. The phase voltages are therefore non-sinusoidal, containing the fundamental and third harmonic voltages.

$$\begin{aligned} v_A &= v_{A1} + v_{A3} \\ v_B &= v_{B1} + v_{B3} \\ v_C &= v_{C1} + v_{C3} \end{aligned}$$

fundamental third harmonics
voltages voltages

The line-to-line voltage is

$$\begin{aligned} v_{AB} &= v_A - v_B \\ &= v_{A1} - v_{B1} + v_{A3} - v_{B3} \end{aligned}$$

Because v_{A3} and v_{B3} are in phase and have same magnitude,

$$v_{A3} - v_{B3} = 0$$

Therefore,

$$v_{AB} = v_{A1} - v_{B1}$$

Note that although phase voltages have third harmonic components, the line-to-line voltages do not. The open delta voltage of the secondary is

$$\begin{aligned} v_{\Delta 0} &= v_a + v_b + v_c \\ &= (v_{a1} + v_{b1} + v_{c1}) + (v_{a3} + v_{b3} + v_{c3}) \\ &= 3v_{a3} \end{aligned}$$

The voltage across the open delta is the sum of the three third harmonic voltages induced in the secondary windings.

Case 3: SW 1 OPEN, SW2 CLOSED

If SW2 is closed the voltage $v_{\Delta 0}$ will drive a third harmonic current around the secondary delta. This will provide the missing third harmonic component of the primary exciting current and consequently the flux and induced voltage will be essentially sinusoidal.

Laboratory Work

I.) Determination of polarity: Arbitrarily assign a dot to one of the HV terminals of a transformer unit and connect as shown in Fig. 3.1. Switch on the supply. The voltmeter would read either V_1+V_2 (additive polarity) or V_1-V_2 (subtractive polarity), where V_1 and V_2 are primary and secondary rated voltages respectively. In case the voltmeter reads V_1-V_2 , the

secondary terminal connected to the primary dotted terminal is marked dotted. Otherwise the other terminal is marked dotted. Similarly obtain the dots for the other two transformer units.

II.) Star-Star connection:

Step 1: Make the connections as per Fig 3.2 and apply an ac voltage of 400 Volts line to line by Variac with S open and measure line-to-line and line-to-neutral voltages on both primary and secondary sides. Connect the current probe to channel 1 of DSO to record the no-load current waveform in phase winding ‘A’ and connect the voltage differential probe on channel 2 across phase winding ‘A’ to record the no load phase voltage. Record both the waveforms on a same graph. Now connect channel 2 across any line-to-line terminals and just observe & record the waveform. Is it sinusoidal or non-sinusoidal? Comment on your observation.

Step2: Re-connect voltage differential probe across phase-winding ‘A’ and Close switch “S”, record the phase voltage and phase current waveforms on the same graph. Disconnect current probe from step 1 and measure the current through ground point E and observe & record the waveform and determine its frequency. Switch off the supply.

III.) Star-Delta Connection:

Step 1: Make the Star-Delta connections as in Fig. 3.3A keeping S closed but **do not** close the delta in the secondary. Connect a high range voltmeter across the open delta terminals as shown in fig.3.3B. Note the voltmeter reading. If the connection is made as per the polarity markings, voltmeter should be reading zero. If the reading on the voltmeter is not zero, can you explain why it is so? Reverse one of the secondary coils and again measure the voltage across open delta terminals. Also record the wave shape of the no load primary current. Is it different from the no load current of a single phase transformer?

Step 2: Make the circuit on the delta side such that the voltmeter reads zero. Open S and note down the new voltmeter reading. Does it still remain zero? Why? Connect the DSO across voltmeter terminals and record the waveform. Determine its frequency. What do you infer? Switch off the supply.

Step 3: Close the delta and again record the no load current waveform on primary side. Is it similar to one observed in step 1 or step 2? Why? Switch off the supply and set the variac to zero volts.

IV.) Delta-Delta Connection:

Now connect the primary windings with correct polarity as per Fig. 3.4. Apply **reduced voltage, i.e. 230 V line to line by variac**. Secondary is also to be connected in delta as in previous part. Introduce an ammeter in series with any one phase winding and another in the line and record the no load winding current i.e., phase current and no load line current. Record the wave shape of current in secondary of a closed delta as given in Fig. 3.4.

Report

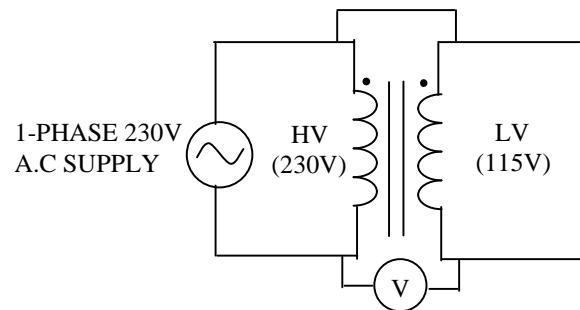
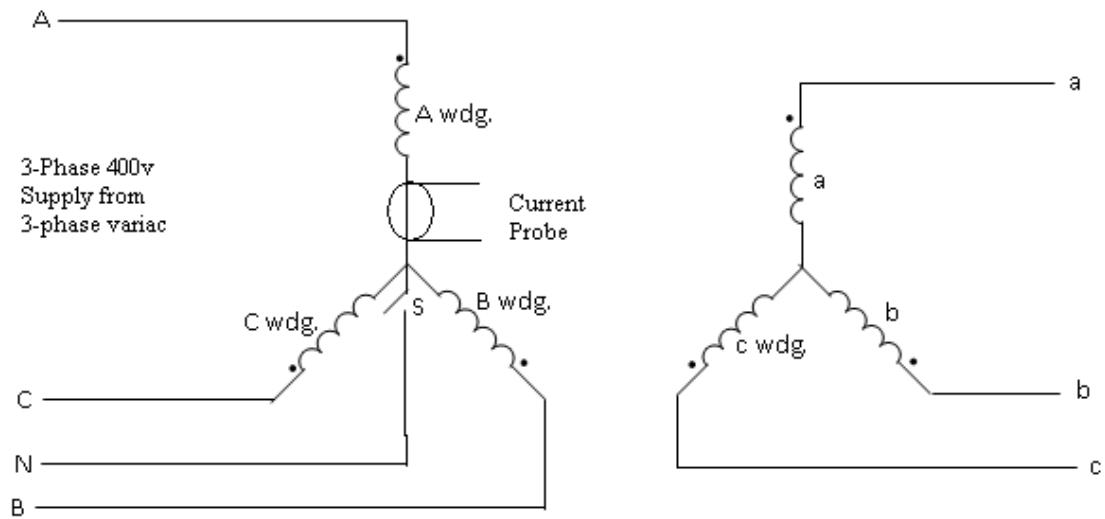
1. Draw the pharos diagram for the three connections. Follow general principles to construct the phasor diagrams:
 - a) The voltages of primary and secondary windings on the same link are in phase i.e. the phase voltages are always in phase despite any connection.
 - b) The e.m.f.s induced in the three windings are equal, balanced, displaced mutually one third period in time and have definite sequence.
2. Record the phase and line values of currents and voltages for each of the connections and comment on your observations.
3. Comment on the nature of wave shapes recorded as above for the three connections.

Precautions

1. Before switching on the 3-phase power supply, you must ensure that the variac kept in the 0 (zero voltage) position.
2. While giving the supply to the Delta-Delta connection do not exceed the line-to-line voltage above 230V.
3. Do not press unnecessary buttons/knobs of DSO.
4. Choose the correct setting of voltage differential/ current Probes.

References:

- [1] I J Nagrath, D P Kothari, Electric Machines. New Delhi, India: Tata McGraw-Hill Publishing Company Limited, 1981.
- [2] P C Sen, Principles of Electric Machines and Power Electronics, New York, USA., John Wiley & Sons Inc., 1997.

**FIG 3.1 Connections for Polarity testing****FIG. 3.2 Star Star Connection**

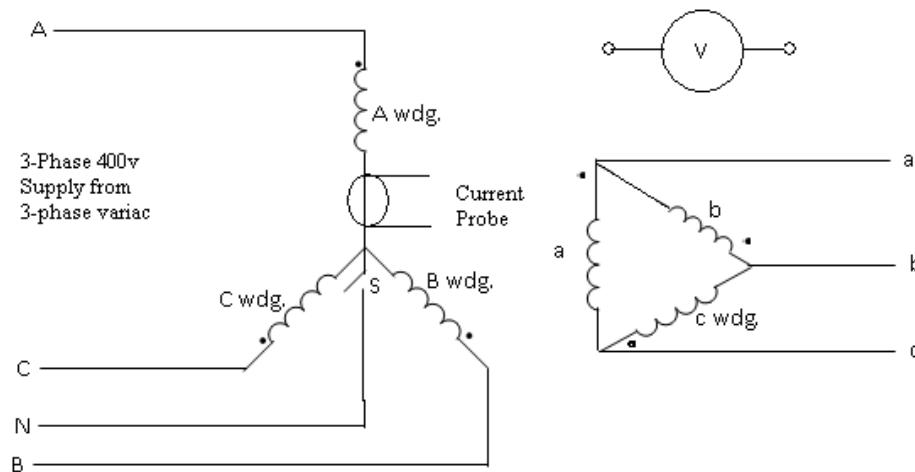
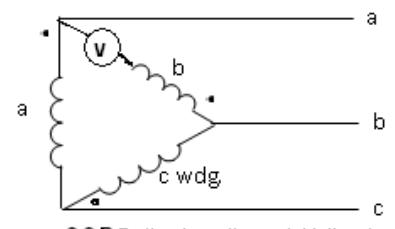


FIG.3.3 A Star Delta Connection



3.3 B Delta close through Voltmeter

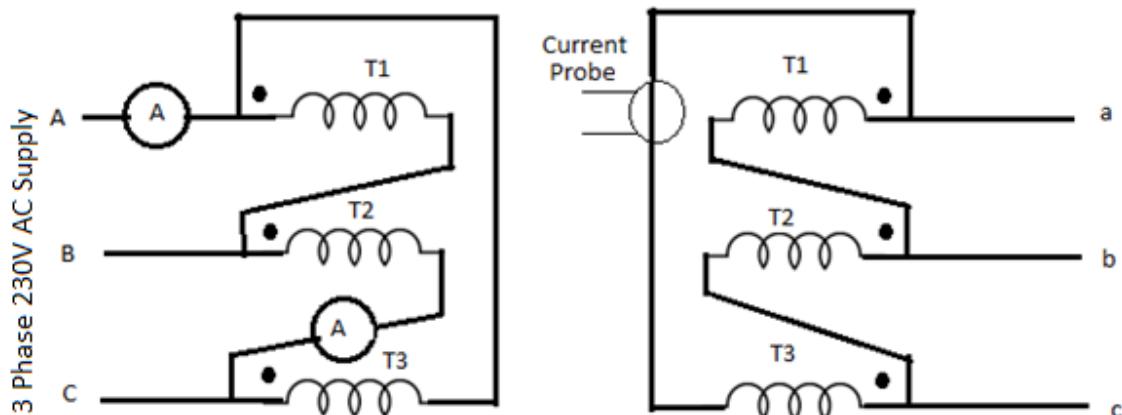


Fig. 3.4

Delta - Delta Connection

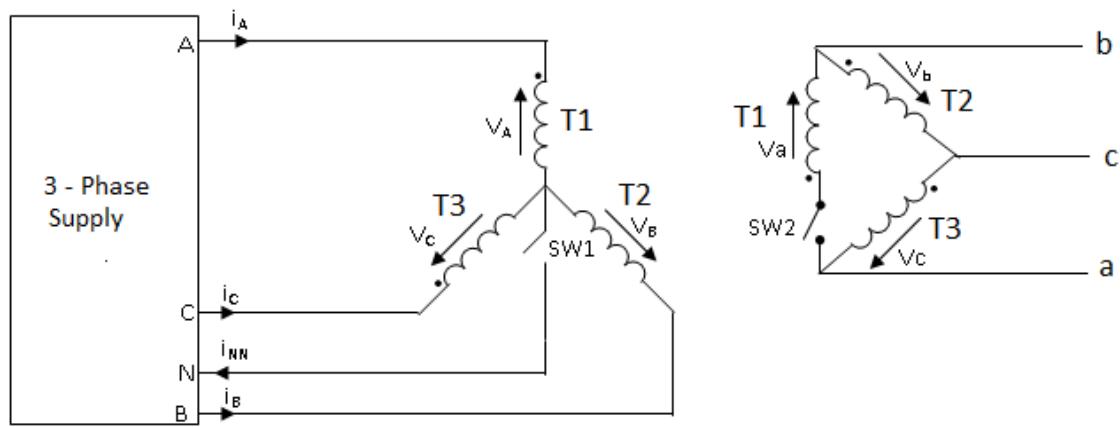


Fig. 3.5 Star - Delta connection for studying Harmonics

EXPERIMENT NO. 4

Objective

To perform no-load, blocked rotor and load tests on 1-phase capacitor start- capacitor run induction motor and determine:

- (a) The parameters for the equivalent circuit.
- (b) Compute the performance of motor from the parameters and compare with experimental results.

Theory

1-phase induction motors are constructed much the same way as poly-phase induction motors except that their stators have single-phase-winding-and the rotor is normally a squirrel cage rotor. The poly-phase motors are self starting, while 1-phase motors are not, since its torque, when at rest is zero. In order to start 1-phase induction motor some means are required. The various types of 1-phase induction motors are:

- | | |
|-----------------|---|
| (a) Split phase | (b) Capacitor motor (capacitor start and capacitor run) |
| (c) Shaded pole | (d) Repulsion start |

There are two theories for the analysis of 1-phase induction motor, i.e.

- (1) Cross field theory, and
- (2) Revolving field theory.

Based upon revolving field theory, the equivalent circuit of a 1-phase induction motor with only main winding effective is shown in Figs. 4.1 and 4.2, where,

R_1 = Main winding effective resistance

X_1 = Main winding leakage reactance

Z_f = Rotor impedance with respect to the forward rotating field referred to stator
 $= R_{2f} + jX_{2f}$

Z_b = Rotor impedance with response of the backward rotating field referred to stator
 $= R_{2b} + jX_{2b}$

(It is assumed that $R_{2f} = R_{2b} = 0.5 R_2$, $X_{2f} = X_{2b} = 0.5 X_2$)

Y_f = Admittance representing excitation characteristics for the forward field
 $= G_f + jB_f$

Y_b = Admittance representing the excitation characteristics for the backward field
 $= G_b + jB_b$

s = Fractional slip with respect to forward field.

In no-load test the motor is run at rated voltage and frequency without applying any mechanical load. The auxiliary winding is disconnected through centrifugal switch as soon as the motor picks up approximately 60% of its rated speed. The input current I_o , voltage E_o , and

input power P_o are recorded.

Under no-load condition, s is very small, R_{2f}/s becomes very large and the equivalent circuit reduces to that shown in Fig.4.3.

In blocked rotor test, a reduced voltage is applied to main winding only, disconnecting the auxiliary winding through autotransformer such that a full rated current is flowing in the main winding. The reduced voltage applied E_s , the rated input current I_s and the input power P_s are recorded.

At rotor standstill, s is unity and the equivalent circuit takes the form shown in Fig.4.4. Just after the blocked rotor test, D.C. resistance of main winding $R_{1,dc}$ is measured to get the value at operating temperature.

Computation of parameters from the test data

As pointed out earlier, under no-load conditions, impedance of the load branch in the equivalent circuit for forward field is very high (slip small), and may be considered infinite. Further, the voltage across backward field load branch under no-load conditions is so low that the exciting branch for the backward field may be neglected, i.e. admittance of the exciting branch for backward field is assumed to be zero. The equivalent circuit of Fig.4.1 and 4.2 then reduces to the form shown in Fig.4.3.

The total no-load power input is used up as stator copper loss, $I_o^2 R_1$, backward field resistance copper loss $I_o^2 R_{2b}/2$, forward field excitation (iron) loss and backward field excitation loss (see discussion of this experiment). Under no-load conditions, the magnitude of the backward rotating field is very small, and therefore the backward iron loss may be neglected.

$$\text{Forward field iron loss} = P_{if} = P_o - I_o^2 R_1 - I_o^2 R_{2b}/2$$

$$\begin{aligned}\text{Voltage across the forward exciting circuit} &= V_f \\ &= E_o - I_o \{R_1 + jX_1 + jX_{2b} + (R_{2b}/2)\}\end{aligned}$$

$$\text{Therefore, Exciting circuit admittance, } Y_f = I_o/V_f$$

$$\text{Exciting circuit conductance } G_f = P_{if}/V_f^2$$

$$\text{Exciting circuit susceptance } B_f = \sqrt{Y_f^2 - G_f^2}$$

$$\text{Also, } B_b = B_f, G_b = G_f$$

Thus, all the parameters of the equivalent circuit pertaining to running condition (no-load) are known.

If Z_{sc} is equivalent impedance of the machine during blocked rotor test, $Z_{sc} = E_s/I_s$.

Also if,

$$Z_{sc} = R_{sc} + jX_{sc}$$

$$\text{Then, } R_{sc} = P_s/I_s^2$$

From these relationships, R_{sc} and X_{sc} may be obtained.

As the blocked rotor test is performed at a reduced voltage, the exciting current and core loss during this test are very small and may be neglected. In terms of equivalent circuit, this assumption means that excitation branch admittance is zero. Further, at $s=1$, frequency of the currents on account of both the forward field and backward field are same.

Under this condition, therefore, $R_{2f}=R_{2b}=R_{2e}$ (say), the equivalent circuit of Figs. 4.1 and 4.2 then takes the form shown in Fig.4.4.

If X_2 is the total rotor reactance ($=X_{2f}+X_{2b}$) then $X_1+X_2 = X_{se}$. It is not possible to separate X_1 , X_2 , but it is customary to consider $X_1=X_2=X_{se}/2$. Under blocked rotor condition, it is easy to visualize that $X_{2f}=X_{2b}$

$$X_{2f}=X_{2b}=X_2/2$$

The effective value of main winding resistance at line frequency is usually 1.1 to 1.3 times the d.c. value, the actual ratio depending upon conductor configuration etc..

Thus

$$R_I \approx (1.1 \text{ to } 1.3) R_{1dc}$$

It is seen from Fig.4.4 that

$$R_{sc}=R_I+2R_{2e}$$

where,

$$R_{2e}=(R_{sc}-R_I)/2$$

R_{2e} being the effective rotor resistance at line frequency.

Calculation of Parameters

Under normal running conditions, the forward field-slip is small, and therefore the rotor resistance for this field will be nearly the dc resistance, i.e. R_{2e} divided by a suitable factor to reduce it to its dc value. The factor has a value in the range 1.2 to 1.4 (say 1.3).

Therefore,

$$R_{2f}=R_{2dc}=R_{2e}/k$$

where,

$$1.2 < k < 1.4.$$

With respect to the backward field, the frequency of the rotor currents under running conditions is approximately twice the line frequency. Effective rotor resistance with respect to the backward field at this high frequency is generally 1.6 to 1.8 times R_{2dc} . Therefore, $R_{2b}=1.6$ to $1.8R_{2dc}$, say $1.7R_{2dc}$.

Thus, from known values of R_I , blocked-rotor-data and suitable choice of factors for converting effective resistance into d.c. resistance and vice versa, R_{2f} , R_{2b} , X_{2f} , X_{2b} and X_I are obtained.

Laboratory Work

1. Note down the specification of the machine under test.
2. Draw the circuit diagram as shown in Fig.4.5A, 4.5B and 4.7 for no-load, blocked-rotor and load test respectively and get it approved by lab instructor.
3. Make the connections as shown by the dotted lines and get it checked by the lab instructor for both no-load (use LPF wattmeter) and blocked rotor test (use UPF wattmeter) separately.

No load test:

4. Connect the auxiliary winding of the motor by switching on the MCB provided on the motor base.
5. Apply the rated voltage to the induction motor having both main and auxiliary windings connected together through 1-phase autotransformer. The auxiliary winding will be disconnected automatically by the centrifugal switch as soon as the motor attains about 60% of rated speed.
6. Record the applied rated voltage E_o , no-load current I_o and input power P_o .
7. Increase the applied voltage by 10% and record no-load current and power input.
8. Reduce the applied voltage in suitable equal steps and record the current and power input for several values of the applied voltage but not less than 180V.
9. Stop the motor.

Blocked rotor test:

10. Disconnect the auxiliary winding by switching off the MCB provided at the motor base.
11. Slowly increase the voltage to the main winding starting from 0V, with the autotransformer such that the rated full load current flows in the stator main winding. Do not hold this condition for long time otherwise; it will burn down the main winding of motor.
12. Record the applied voltage E_s , the rated input full load current I_s and power P_s .
13. After performing the blocked rotor test, measure the D.C. resistance of the stator, R_{ldc} .

Load test:

14. Now work on the motor which is coupled to the D.C shunt generator. Make the connections as shown in Fig. 4.7.

15. Switch on the cooling fan of the DC generator.
16. Apply rated voltage to the induction motor and run the generator under no-load condition.
17. Note down the readings of input power, input current, output voltage, output current and speed of the motor.
18. Switch on the dc supply of field circuit of dc generator and set output voltage 180V of dc generator by varying the rheostat and keep it constant throughout the experiment.
19. Now switch on the load box switches step by step up to when the rated current flows in the induction motor. Note down all the meter readings.
20. Repeat the steps for reduced input voltage (**90% of rated value**). Tabulate your readings as follows.

Applied voltage	Input power	Input current	DC-Generator current	DC-Generator voltage	Speed

Report

1. (a) Plot no load current power input as a function of applied voltage in case of no-load test and obtain from there the no load current, I_a , and power input P_o corresponding to the rated voltage.
 (b) Extrapolate the curve of P_o up to zero voltage to obtain the friction and windage loss as shown in Fig.4.6.
2. Compute the parameters of the equivalent circuit.
3. From the equivalent circuit, compute input current, input power, efficiency and torque when the motor is running at the rated voltage with slip of 5%.
4. From load test data, plot Torque vs. Slip characteristics for different voltage levels

Discussion

The equivalent circuit derived in this experiment is based on number of approximations. R_{2f} and R_{2b} are the effective values of resistances, which change with slip. However, for normal range of running speeds ($s=1-5\%$), these effective values may be assumed to remain constant. The leakage reactance is assumed to be equally divided between the stator and rotor, whereas actually it may not be so. The factor for converting effective values of resistance into d.c. values and vice-versa are arbitrary and cannot be easily determined.

By far, the most important assumption is that the friction and windage losses, which are mechanical, are combined with the other losses in calculating the loss conductances, G_f and

G_b . For a more accurate analysis, friction and windage loss should be subtracted from the mechanical power developed, and should not be included along with excitation losses.

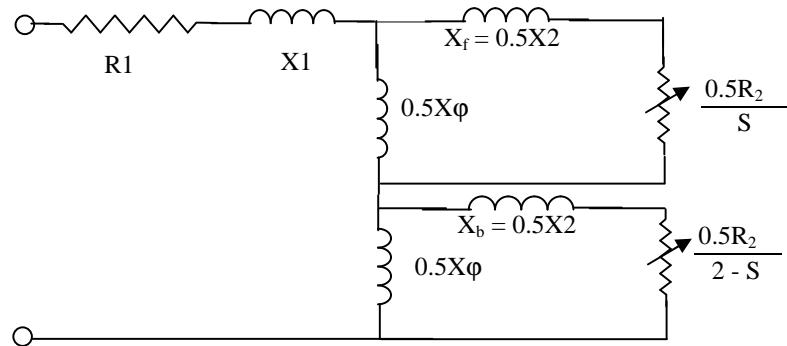


FIG. 4.1 Equivalent circuit of a 1-phase Induction motor

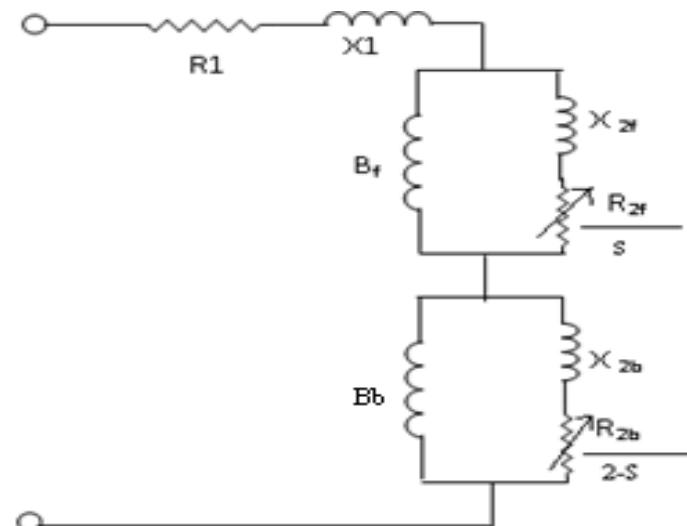


FIG. 4.2 Equivalent circuit of 1-phase Induction motor (alternate representation)

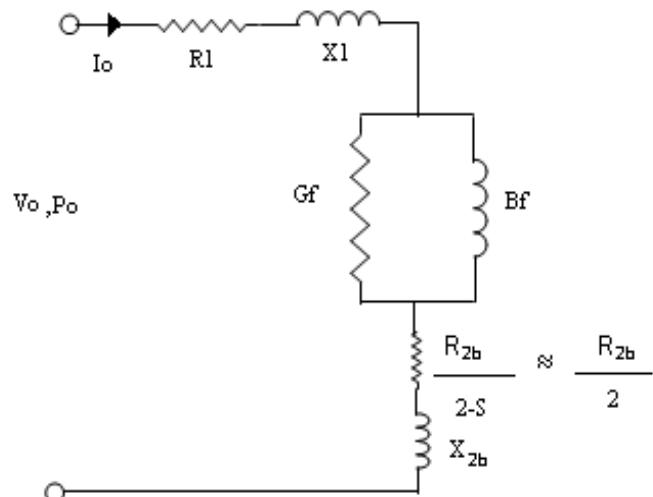


FIG. 4.3 Simplified equivalent circuit under no-load

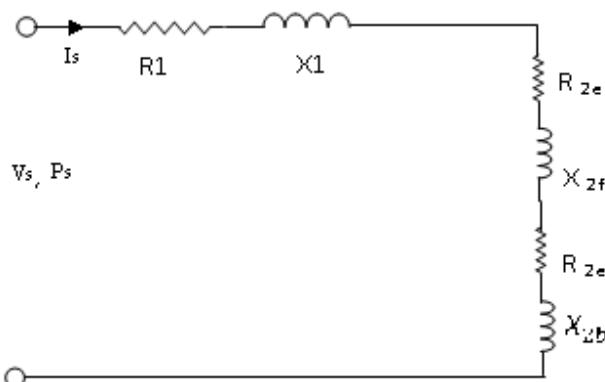
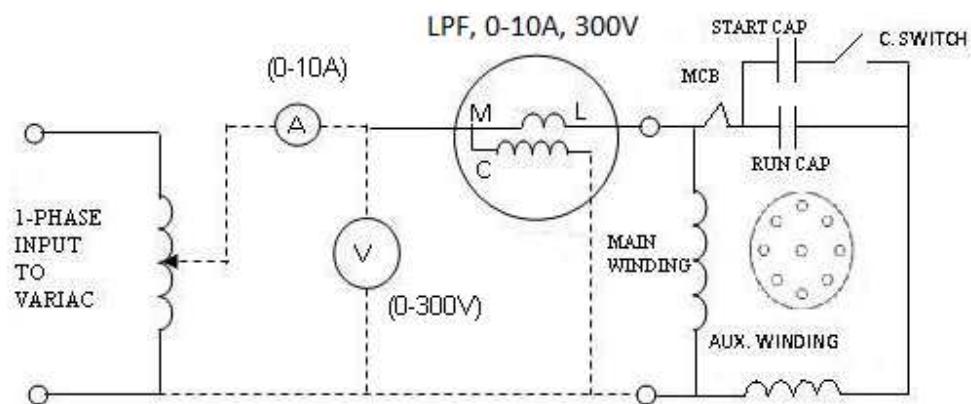
FIG. 4.4 Simplified equivalent circuit during blocked rotor test $S \approx 1$ 

FIG.4.5A Connection diagram for No-Load Test

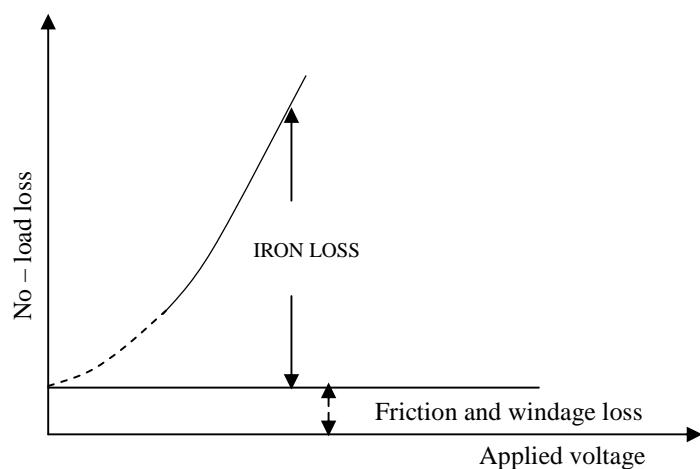
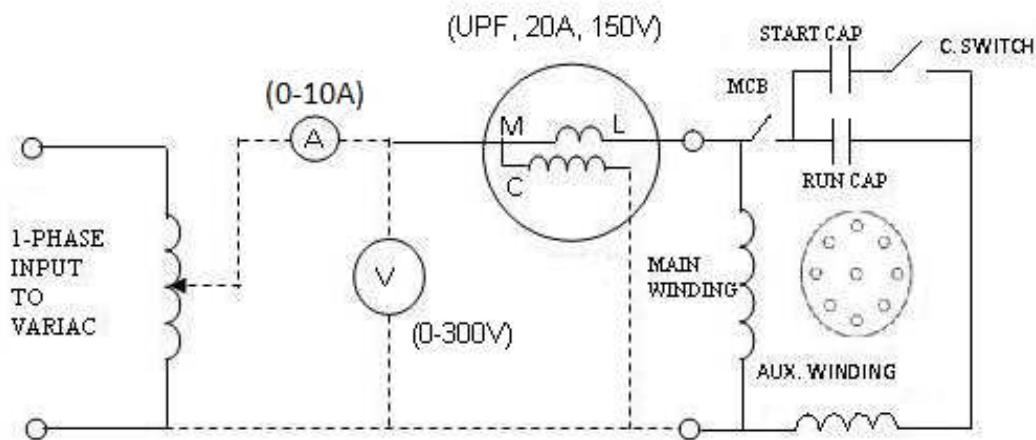


FIG. 4.6 Determination of friction and windage loss

Note: The low power factor wattmeter required the additional single phase ac supply for working. The connection cord is provided for the purpose

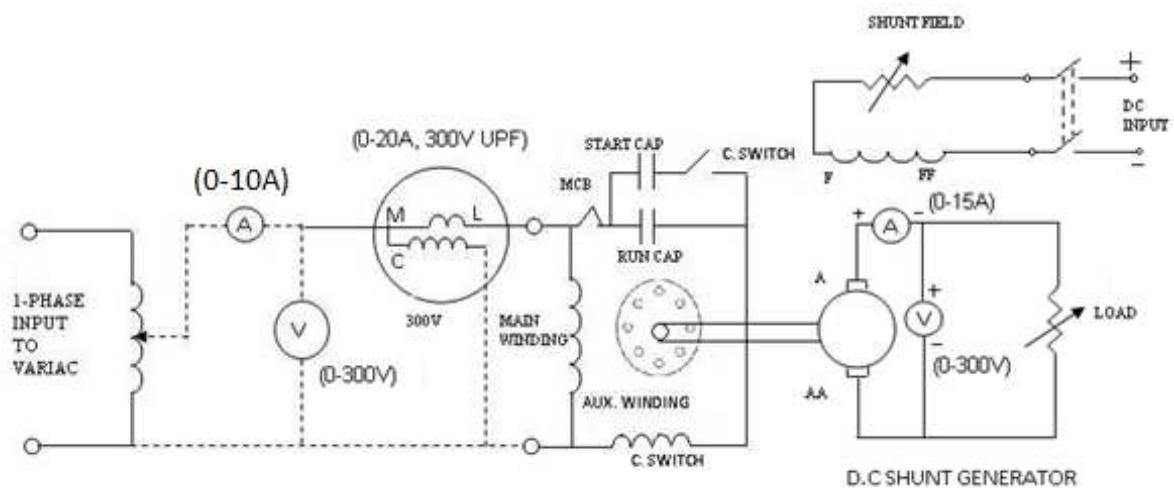


FIG. 4.7 Connection diagram for Load Test

EXPERIMENT NO. 5

Objective

To perform no load, blocked rotor and load tests on a 3-phase squirrel cage induction motor and draw its equivalent circuit referred to the stator and calculate the efficiency of the motor. Also obtain the performance characteristics of the motor theoretically from the equivalent circuit parameters and compare it with the experimentally obtained results.

Laboratory Work

No load and blocked rotor tests:

1. Write down the specifications motor and dc generator.
2. Draw the circuit diagram as shown in Fig.5.1A for no-load test and 5.1B for blocked-Rotor test showing the proper ranges of the meters according to specification of the machine for both no-load and blocked rotor test and get it approved by lab instructor.
3. Make the connections as shown by the dotted lines and get it checked by the lab instructor for both no-load and blocked rotor test separately.
4. Conduct a no-load test at the rated voltage and note down the line current and input power of the motor [See Fig. 5.1]. Use the appropriate ranges of meters. Start with variac in zero position.
5. Conduct a blocked rotor test by blocking the rotor from rotating. Use the same circuit as in Fig. 5.1, with meters changed to appropriate ones. Before switching on, make sure that the variac is in zero position and increase voltage slowly up to a value when the rated current of induction motor will flow. Note down the reading of all the meters.
6. Switch off the three phase main supply and bring back the variac to zero position.
7. Measure the d.c. resistance of the stator.

Load test:

1. This test is to be conducted with the motor coupled to the D.C shunt generator. Make the connections as shown in Fig. 5.2. (Note: Switch On the supply of cooling fan of DC generator before starting the load test.)
2. Apply the rated voltage to the induction motor and run the generator under no-load condition with its field resistance at maximum position. Adjust the field resistance so that generator output voltage attains 180V and keep it constant.
3. Note down the readings of input power, input current, output voltage, output current and speed of the induction motor.

4. Now increase the load i.e. current of dc generator by switching on the switches of load box step by step, (while maintaining the terminal voltage of DC shunt generator at 180V by varying the field rheostat). **Take the readings of all the meters at 50%, 60%, 70%, 80% and 100% of rated current** the 3-phase induction motor. (Note: At 100% rated current of induction motor, the terminal voltage of DC Shunt Generator may be required to set less than 180V because constant step loading.)

5. Repeat the same experiment for reduced input voltage of induction motor (**90% and 70% of rated value**). Tabulate your readings as follows.

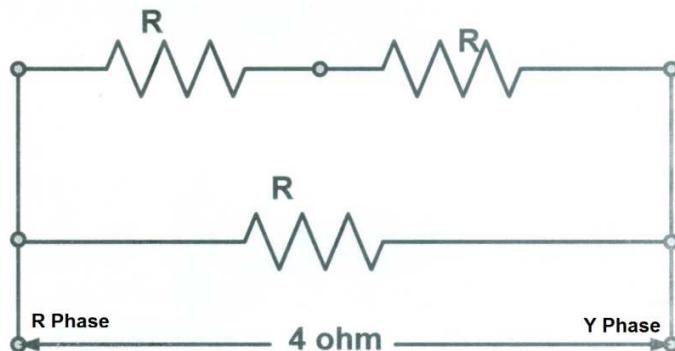
Load test (readings)

Sl. No	Motor Voltage (Stator, V)	Motor Current (Stator, Amp)	P ₁ (W)	P ₂ (W)	N (rpm)	DC Generator Voltage (V)	DC Generator Current (Amp)

Calculation of Equivalent Circuit Parameters:

The one-phase equivalent circuit of a three phase induction motor is shown in Figure 5.3. $(R_1 + jX_1)$ is the stator winding impedance per phase, $(R_2 + jX_2)$ is the rotor winding impedance per phase referred to the stator side, $(G_c + jB_m)$ is the magnetizing circuit admittance per phase, and 's' is the rotor slip of the motor, which, generally varies between 1-5% under normal running condition. The parameters of the equivalent circuit can be determined from the results of the blocked rotor and the no-load tests, similar to the case of single phase motor in the experiment-4, and briefly given as following.

Calculation of the DC Resistance of Stator winding of a delta connected three-phase Induction Motor:



In the above figure the resistance between the R phase and Y phase is measured using the multimeter, the measured value of resistance between the R phase and Y phase is **4 ohm**, let

us consider the winding of the 3 phase induction motor are identical and having resistance of each winding is $R \Omega$.

So per phase resistance of stator winding is:

$$\begin{aligned} R_{RY} &= (R+R) \parallel R \\ 4 &= 2R \times \frac{R}{3R} \\ R_{dc} &= 6\Omega = R_{1dc} \end{aligned}$$

1. From the measured value of DC resistance of the stator winding per phase (R_{1dc}), compute $R_1 = k \cdot (R_{1dc})$, where k accounts for skin effect and varies between 1.1 to 1.3.
2. Under block rotor test, the applied voltage is quite small and slip $s=1$. The approximate equivalent circuit, neglecting the magnetizing branch is shown in Figure 5.5. Using the ammeter, voltmeter and wattmeter reading per phase, the value of R_2 and $(X_1 + X_2)$ can be computed from Fig. 5.5. It is assumed that $X_1 = X_2$.
3. Under no load condition, the full rated voltage is applied and slip is very small, close to zero. The approximate equivalent circuit under no load can be drawn, by shifting magnetizing branch across the supply, as shown in Figure 5.4. From this figure and using the ammeter, voltmeter and wattmeter readings, the magnetizing branch parameters G_c and B_m can be computed.

Report

1. The report should include the equivalent circuit of the motor with all parameter values indicated and the performance characteristics mentioned in the section "Objective", derived from the equivalent circuit. While calculating the efficiency of the induction motor, assume the efficiency of the DC generator as 90%.
2. Plot the torque-speed characteristics of the motor on a graph paper for the different input voltages, determined through theoretical calculations.
3. On the same graph plot the torque-speed characteristics, obtained experimentally

Circuit for No-Load Test:

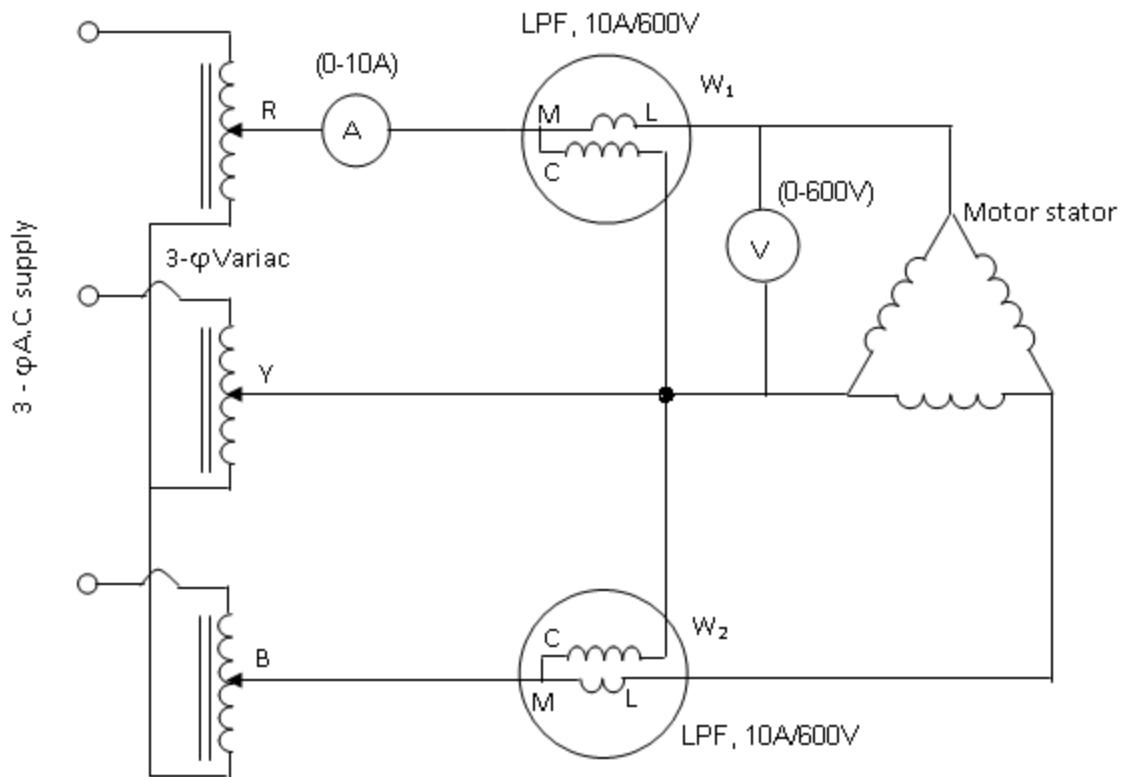


FIG.5.1A. Connections for No-Load Test

Note: The Low Power Factor Wattmeter required the additional single phase ac supply for working. The connection cord is provided for the purpose.

Circuit for Blocked-Rotor Test:

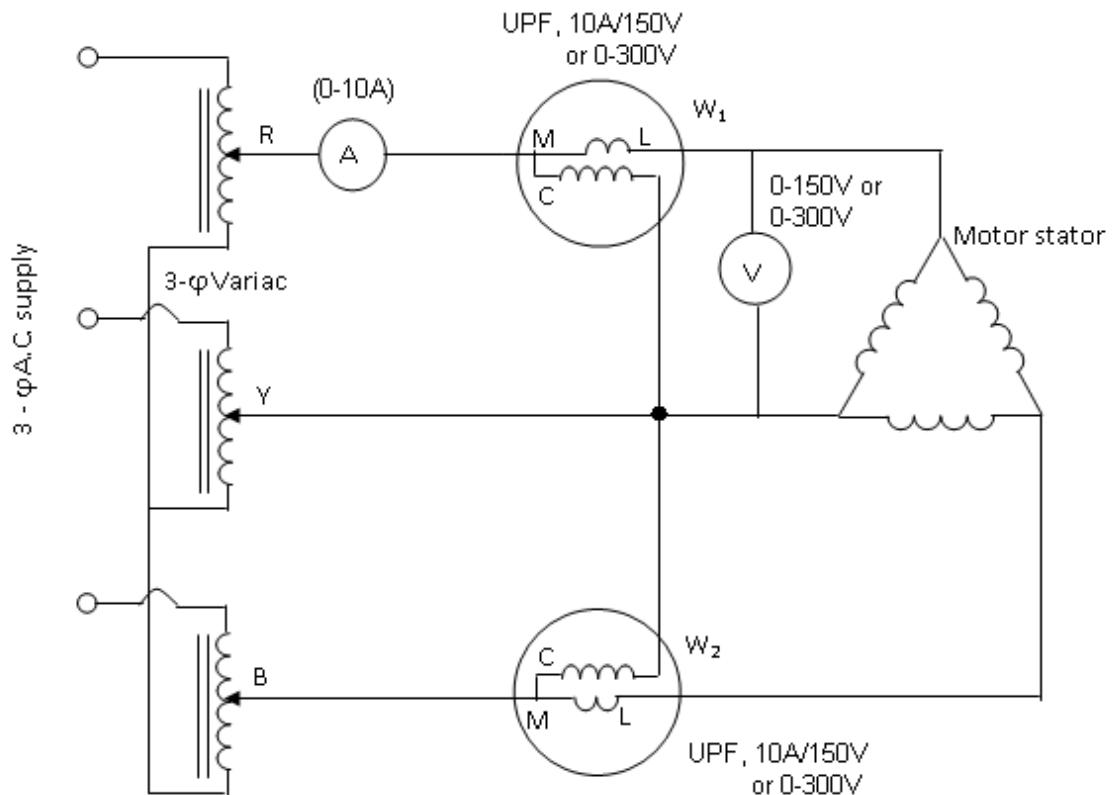


FIG. 5.1B Connections for Blocked-Rotor Test.

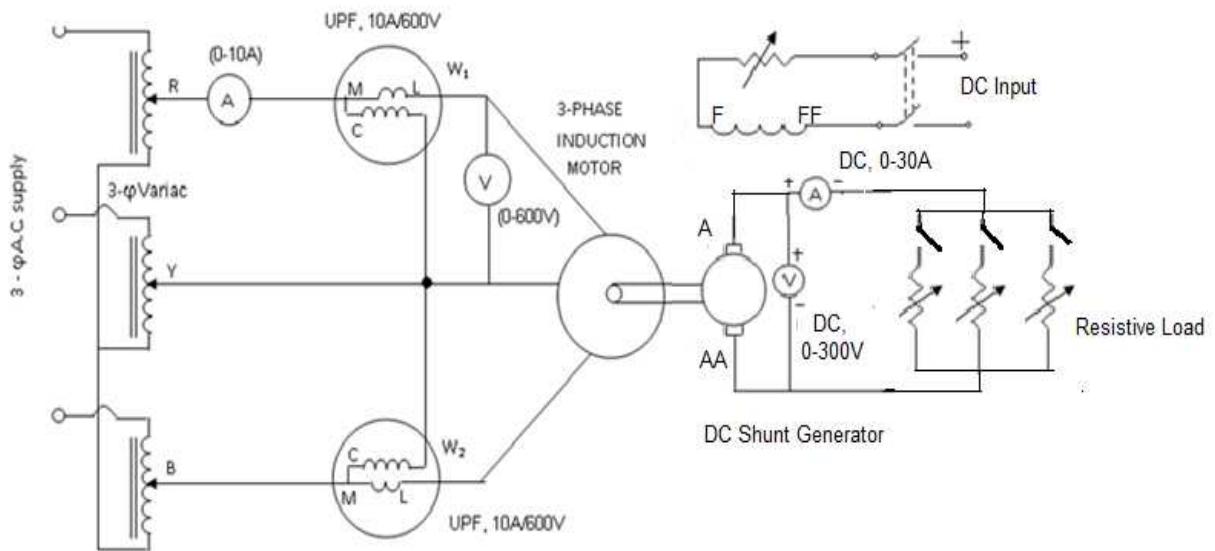
Circuit for Load Test:

FIG. 5.2: Connections for load test on a three -phase squirrel cage induction motor

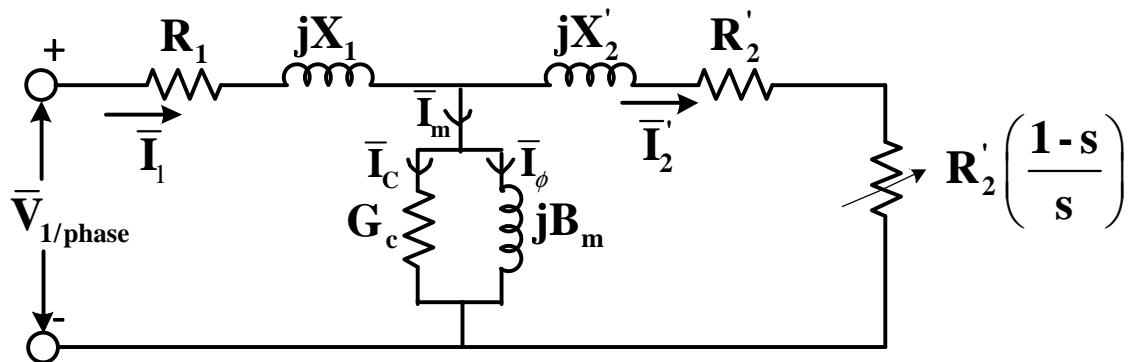


Fig.5.3 One phase Equivalent Circuit of 3-phase Induction Motor

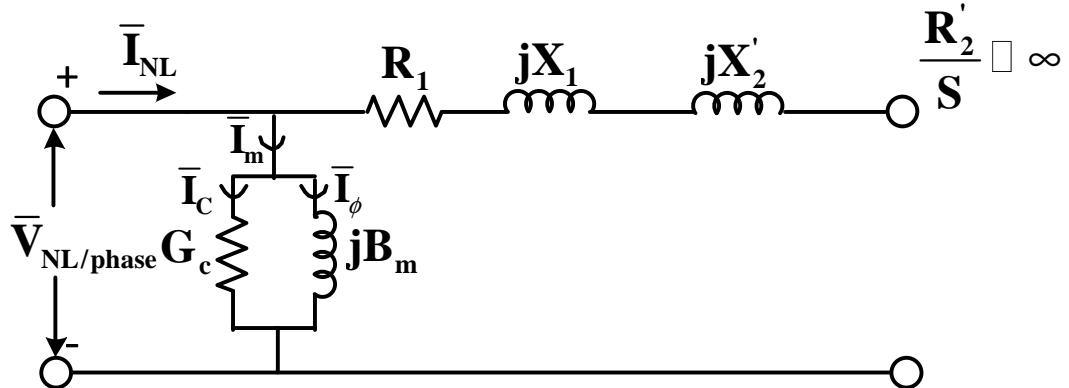


Fig.5.4 One phase Equivalent Circuit of 3-phase Induction Motor under No Load Test

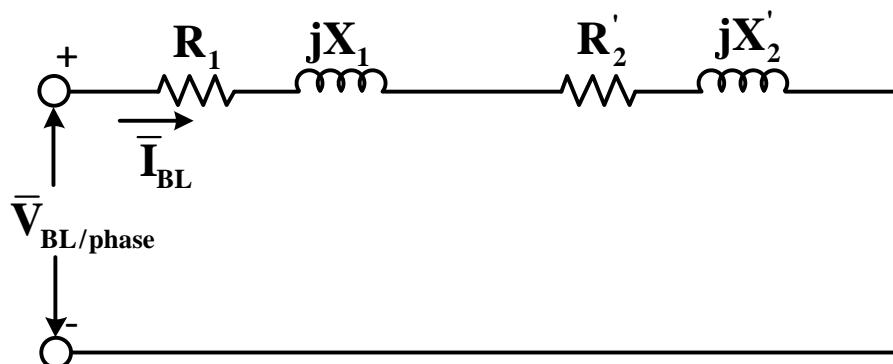


Fig.5.5 One phase Equivalent Circuit of 3-phase Induction Motor under Blocked Rotor Test

EXPERIMENT NO. 6

Objective

1.
 - (a) To perform open and short circuit tests on a synchronous generator and determine its synchronous impedance (i) neglecting saturation and (ii) considering saturation.
 - (b) To write an equivalent circuit of the generator using the synchronous impedance values determined in 1(a)(i) and (ii).
 - (c) To determine and draw the terminal voltage versus load current characteristics of the generator for unity power factor load using the equivalent circuit determined in (b). Also to determine voltage regulation of the generator for unity power factor load.
2. To perform a load test on the generator for unity power factor load. To draw the terminal voltage versus load current characteristic and to compare it with the results in 1 (c). Also to determine voltage regulation and compare it with results in 1 (c).

Theory

Synchronous impedance Z_s can be determined by open and short circuit tests on the generator. The generator is run at its rated speed. Open circuit characteristic (OCC) of generator is the plot of its terminal voltage against field current. This is also called the magnetization characteristic of the machine. Short circuit characteristic (SCC) is the plot of generator short circuit current versus field current. See Fig. 6.1. The synchronous impedance magnitude, Z_s neglecting saturation is

$$Z_s(\text{unsaturated}) = \frac{\text{Rated voltage on Air - gap line}}{\text{S.C.current on SCC}} \Big|_{I_f \text{ for rated voltage}}$$

$$Z_s(\text{unsaturated}) = \frac{\text{O.C.Voltage corresponding to AD}}{\text{S.C.corresponding to AB}} \Big|_{\text{for the same field current OA}} \quad (1)$$

where AB is the short circuit current corresponding to the field current OA. The generator impedance adjusted for saturation is

$$Z_s(\text{adjusted for saturation}) = \frac{\text{Rated voltage on OCC}}{\text{S.C.current on SCC}} \Big|_{I_f \text{ saturated}}$$

$$Z_s(\text{adjusted for saturation}) = \frac{\text{O.C.Voltage corresponding to AC}}{\text{S.C.Current corresponding to AB}} \Big|_{\text{for the same field current OA}} \quad (2)$$

where, AB is the short circuit current corresponding to the field current OA.

Note that the values as determined above are approximate because to consider exactly the effect of armature reaction mmf, it is necessary to determine the orientation of armature

reaction mmf in the machine (the reactance of the magnetic path depends on the orientation of the resultant mmf due to main field and armature reaction in machines with salient poles), and magnitude of the mmf (since this decides the level of saturation in the magnetic circuit).

These are not accurately taken into account in the two ways mentioned for finding synchronous impedance. Synchronous reactance is given by

$$X_s = \sqrt{(Z_s^2 - R_a^2)} \quad (3)$$

where R_a is the effective resistance of the armature. R_a can be measured for d.c. conditions (using voltmeter-ammeter method, say) and the result multiplied by a factor of 1.6 to get a good estimate of the effective value of the ac resistance. (See the discussion about this point in Chapter 14 ‘Alternating-Current Machine’ by Puchtein, Lloyd and Conrad).

We can now write an equivalent circuit for the generator in terms of a constant voltage behind the synchronous impedance. Per unit voltage regulation is defined as

$$\text{p.u. voltage regulation} = \frac{|\bar{E}_{ph}| - |\bar{V}_{ph}|}{|\bar{V}_{ph}|} \quad (4)$$

where, \bar{E}_{ph} and \bar{V}_{ph} denote, respectively, the phase values of no-load and full-load terminal voltages, for constant field excitation, rated speed and with $|\bar{V}_{ph}|$ = rated voltage of the machine.

Laboratory Work

1. Note the nameplate details of the machines (alternator and prime mover) for the experiment. Use only half of the panel board (dc motor and alternator terminals) for this experiment.

Open Circuit Test

2. Make suitable connections as shown in Fig. 6.1 and get them checked.
3. Keep the armature rheostat of dc motor to maximum position.
4. Switch on the dc supply of prime mover and start the prime mover. Bring the speed to the rated value (1500 rpm) of alternator by reducing the resistance of armature rheostat. If the rated speed is not attained by armature rheostat then reduce the field current of prime mover and maintain the speed constant at this value during the experiment.
5. Keep the resistance of field rheostat of alternator at maximum and switch on the dc supply of field of alternator.
6. Switch on the output of alternator and set the rated voltage by changing the field current of

alternator by filed rheostat.

7. Take the reading of all the meters.
8. Switch off output supply of alternator and bring back the field rheostat at maximum position. Do not stop the prime mover.

Short Circuit Test

9. Draw a circuit diagram of the test setup, including the prime mover circuit and show all the meters and their ranges.

10. Make suitable connections and get them checked.
11. Switch on the output supply of alternator.
12. Now switch on the dc supply of field circuit of alternator but before switching on the field supply make sure that the field rheostat should be at maximum position. Maintain the rated speed of alternator throughout the experiment.
13. Increase the field current of alternator so that the rated current of alternator will flow through the stator. Note down the reading of all the meters. Do not go beyond the full load current of alternator.
14. Switch off output supply of alternator and bring back the field rheostat at maximum position. Do not stop the prime mover.

Load Test at unity Power Factor (See Fig. 6.1A)

15. Draw the circuit diagram for the load test. Show all the meters and their ranges.
16. Make suitable connections as per Fig. 6.1A and get them checked.
17. Switch on the output supply of alternator and loading of alternator is done by a 3-phase resistive load.
18. Adjust the load and alternator field current to give full load current and rated voltage at the terminals of the alternator.
19. Keeping the field excitation of the alternator constant, gradually reduce the load current and note down the current and terminal voltage of the alternator.
20. Make sure that throughout the experiment the speed of the alternator remains constant at 1500 rpm by adjustment of dc motor field excitation or armature rheostat.
21. After taking all the required readings stop the prime mover.

Measurement of d.c. Resistance of Alternator Armature

Measurement of resistance is to be done by LCR Bridge.

Report

Draw a circuit diagram of the test setup and show all the meters and their ranges. This should include circuit for prime mover (which is d.c. shunt motor).

The report should contain all the things required to done as stipulated in the section 'Objective'.

1. Plot OCC and SCC on the same axes (as shown in Fig. 6.2).
2. Determine Z_s , R_a , and X_s as explained in 'Notes'.
3. Write equivalent circuit of alternator with values of circuit parameters shown.
4. Determine the voltage regulation of alternator at unity power factor using the equivalent circuit of item 3.
5. Determine and draw the load characteristics, i.e. plot of terminal voltage against load current of alternator at unity power factor using the equivalent circuit of item 3.
6. On the same axes as for item 5 above, draw the load characteristics as determined experimentally.
7. Discuss the results obtained in items 5 and 6.
8. Compare the regulation as calculated in item 4 and as determined from the characteristic in item 6.

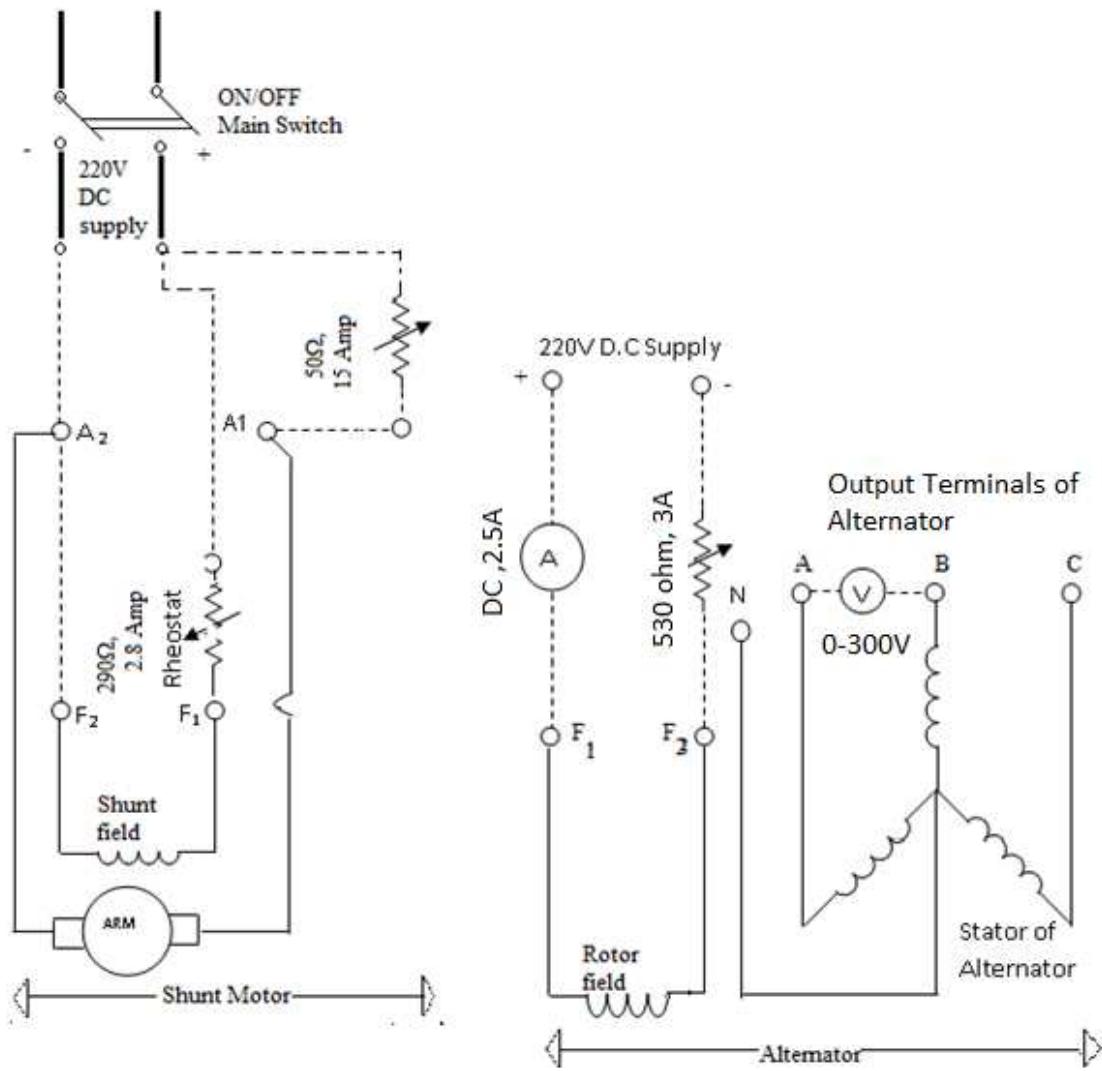


FIG 6.1 Circuit diagram of an alternator coupled with DC Shunt motor
(Panel board diagram)

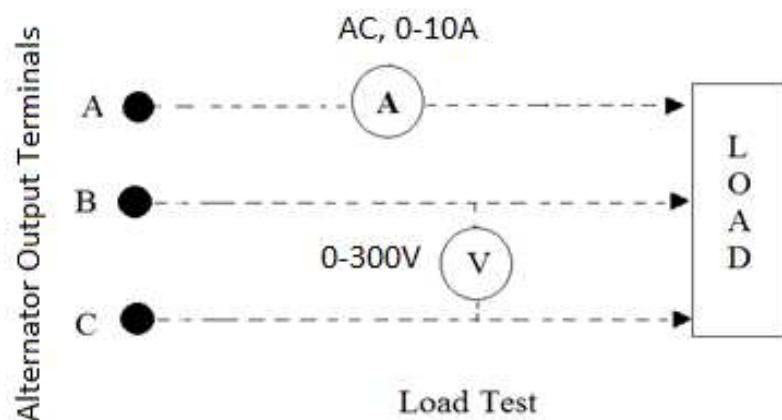
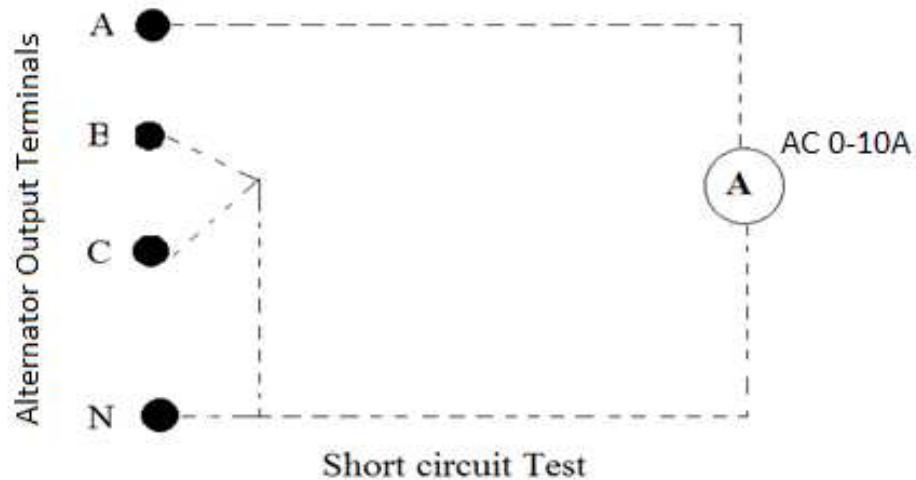


Fig. 6.1A

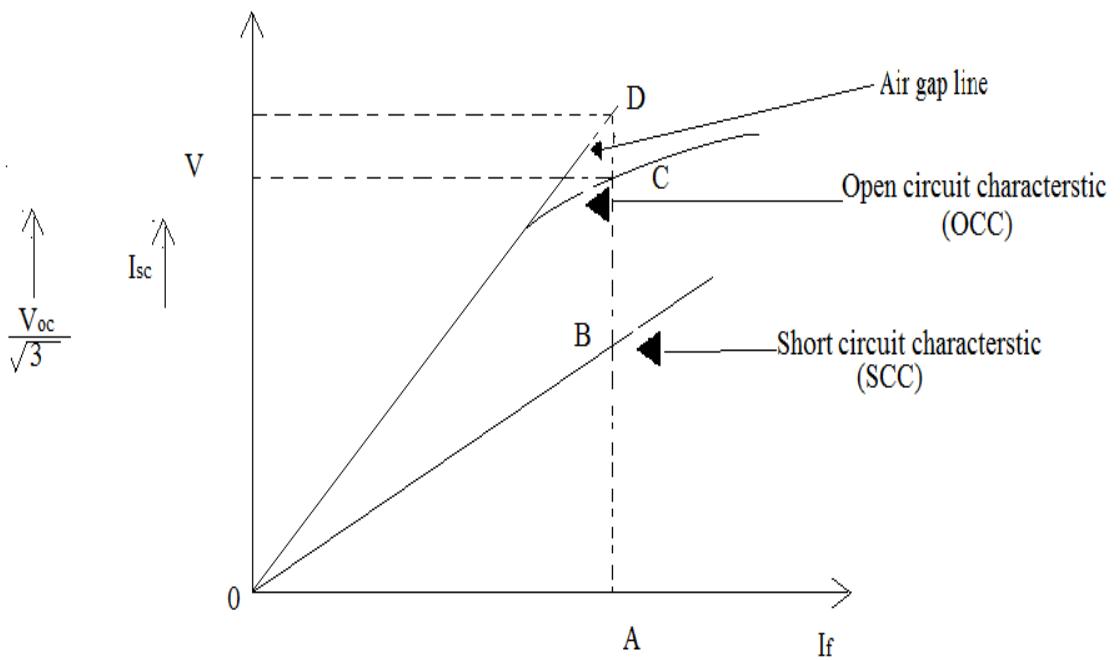


FIG 6.2 : Open and short circuit characteristics