LIST OF EXPERIMENTS
Course No.: EEC2910
II Year B.Tech. (Electrical), III Semester

S.No	Ex. No.	Experiment
1.	Ex3.1	Load test of single-phase transformer
2.	EX3.2	Open-circuit and short-circuit tests of single-phase transformer.
3.	Ex3.3	Sumpner's test of single-phase transformer.
4.	Ex3.4	Parallel operation of single-phase transformers.
5.	Ex3.5	Study of various three-phase transformer connections.
6.	Ex3.6	Phase-transformation.
7.	Ex4.1	Load test of three-phase induction motor.
8.	Ex4.2	No-load and blocked-rotor tests of three-phase induction motor.
9.	Ex4.5	No load and blocked rotor test of single-phase capacitor start induction motor.

1

General Instructions

In order to get good experimental results, some rules must be observed while working in an electric machine laboratory. This is also essential for the safety of the working personnel as well as the equipments. Some of these rules are discussed in this chapter. Report writing is also an important aspect of a laboratory course. Some guidelines for preparation of laboratory reports are also discussed.

1.1 SAFETY OF PERSONNEL

In electrical machines laboratory, most of the machines are rated for 230 V or more. A circuit at this level of voltage may give a fatal shock to the operating personnel. Some rules that may save the operating personnel from these accidents are listed below:

1. Always shut off power before handling the wiring.
2. Use only healthy power cords and leads.
3. Always wear dry shoes.
4. Avoid contact with metallic parts of the circuit while the circuit is energized.
5. Never wear loose clothes while working with rotating machines.
6. Do not take your eyes too close to an instrument or moving parts specially commutators.
7. Never work alone. Ensure that there are others to provide help in case of an accident.

1.2 SAFETY OF EQUIPMENTS

For methodical conduct of experiments, ensuring safety of the equipments, the following precautions must be observed:

1. The ratings of the instruments should be at least 20% more than the highest value of the quantity being measured. If instruments of required ratings are not available, instrument transformers (current transformer and potential transformer) may be used.
2. The ratings of the current-coil and pressure-coil of a wattmeter should be at least 20% more than the current and voltage of the circuit.
3. Do not use moving-coil instruments in ac circuits. The current or voltage could be increased beyond the rating of the instrument while the instrument will continue to indicate zero. This could damage the instrument.

4. Ensure that the polarity of the instrument is correct. In case any instrument indicates in the reverse direction, switch off the supply and interchange appropriate connections.
5. The wires used for making connections must be of sufficient cross-section to carry the current of the branch concerned. Thin flexible wires may be used as leads for voltmeters and pressure coils of wattmeters.
6. All new connections must be checked thoroughly before the circuit is energized. The help of technical staff of the laboratory may be sought.
7. In certain experiments, some pre-requisites must be satisfied before a machine is started or the circuit is energized. For example in operation of synchronous machine connected to bus bar, all the conditions for synchronization must be satisfied before the machine is connected to the bus bar. Make sure that all such pre-requisites are satisfied. In the event of a power failure, switch off the power mains and disconnect the machine. When the power restores, again satisfy all the pre-requisites before connecting the machine.

1.3 REPORT WRITING

The report on a laboratory experiment must be properly formatted. The format of the report and informations to be incorporated in the report are explained in this section.

1.3.1 INFORMATION FORMING TITLE-PAGE OF THE REPORT

The title page of the report must be in the Format given on the next page.

TITLE PAGE OF THE REPORT

1. Information about the Experiment

Title of the course (Name of the lab): Electrical Machine Lab 1

Course No.: EEC2910

Title of the experiment:……………………………………………………………

Date of performing the experiment:…………………………………………

Day of the Experiment:……………………….

Date of submission of the report:………………………………

2. Information about the student

Name: ………………………

Class S.No. : ………………………

Group No.: ………………………

College/Faculty No.: ………………………

Enrolment No.: ………………………

Name of group-partners:

1. ……………………

2.…………………

3. ……………………

INFORMATION FORMING BODY OF THE REPORT

The informations to be incorporated in the report may be formatted as follows:

Object

This should include the precise aim of the experiment as well as list of the main tests to be performed.

Description of apparatus

Under this head complete nameplate data of the equipment being tested must be given. The complete list of equipments, along with their type and range/rating, must be given. The list should also include the identification marks, e.g. equipment-number, manufacturer's name, and model, of all the equipments. This information may be needed to use the same set of equipments, in case verification of earlier observations is required or an incomplete experiment is to be completed. These informations may be tabulated as shown in table 1.1.

Table 1.1 Format for writing details of equipments used in the experiment

S.No.	Equipments/Devices	Range/Rating	Equipment No.	Manufacturer/ Make/Model

Theory

The report must include a brief theory related to the experiment. It may include theorems, laws, or characteristics to be verified by the experiment. Mathematical relations used in the experiment should also be given.

Circuit diagram

The circuit diagram is an essential part of the laboratory report. It must show complete connection diagram. The ratings of all the instruments should be indicated in the diagram. Alternatively, serial number of the equipments, as given in table 1.1, may be indicated in the diagram.

Procedure

Sequence of steps adopted during the experiment must be clearly written.

Observations

Observations recorded during the experiment should preferably be written in tabular form. The readings taken during the experiment should always be entered without any correction or modification. If required, some columns may be divided into two sub-columns, one column for recording the actual reading and the other for writing the true value of the quantity, after taking into account the corrections (e.g. zero error) or multiplying factor of the instrument.

Calculations

If required, calculations should be given along with the mathematical relations employed. If same process of calculation is used for different sets of observations, sample calculation for any one set of observations must be shown. Results of calculations may be suitably arranged in a tabular form.

Results

The results derived from the observations may be given in tabular, graphical or any other suitable form as per the requirement of the experiment.

In case of graphs, dependent variable should be plotted as the ordinate and independent variable as the abscissa. Thus, to plot speed-torque curve of a motor, the dependant variable, speed, should plotted on the Y-axis and the independent parameter, torque, should be plotted along X-axis.

If a number of curves are to be plotted on same sheet, points pertaining to different curves must be differentiated using different notations. For example, if the points of one curve are shown by ⊗, the points of the other curve may be represented by ⊕. The different curves may also be differentiated by plotting them in different colours.

Comments on the results

The conclusions drawn from the obtained results should be discussed. The experimental results must be compared with those expected theoretically. The probable reasons for any difference between experimental and theoretical results must be explained.

Precautions

Necessary precautions to be taken for performing the particular experiment must be briefly explained.

2

Indicating Instruments

2.1 INTRODUCTION

The more commonly used instruments in electrical machine laboratory are voltmeter, ammeter and wattmeter. These instruments can be classified according to their principle of operation as:

1. Permanent magnet moving-coil type,
2. Moving-iron type,
3. Electro-dynamometer or simply dynamometer type.

In all types of indicating instruments, a deflecting torque, which is proportional to the quantity being measured, is produced on a movable member. A pointer attached to this member moves over a graduated scale to indicate the quantity being measured.

For steady deflection, the net torque on the moving member must be zero. Therefore, a controlling torque, which balances the deflecting torque, must be produced. The controlling torque tends to bring back the moving system to its initial position. The controlling torque is usually produced by means of a spring.

When moving-member moves under the effect of deflecting torque, the controlling torque increases. The moving system comes to rest when the controlling torque becomes equal to the deflecting torque. The moving system must come to rest quickly without too many oscillations. To achieve this, a damping torque is required. The damping torque acts only when the moving member is in motion and it always opposes the movement of the moving member. This can be provided using air friction damping, liquid friction damping or eddy current damping.

2.2 AMMETERS AND VOLTMETERS

Both in ammeter and voltmeter, current through the instrument produces the deflecting torque. Ammeter is connected in series with the circuit in which current is to be measured, as shown in Fig. 2.1(a). Thus current through the ammeter is the current that is to be measured. A voltmeter is connected between the points across which the potential is to be measured, as shown in Fig. 2.1(b). To limit the current through the voltmeter, a high resistance is connected in series with the instrument inside the case of the instrument. However, the current through the instrument is still proportional to the voltage being measured and the scale is directly marked in volts.

Fig. 2.1 Connections of (a) ammeter and (b) voltmeter

The commonly used ammeters and voltmeters in the laboratory are either permanent magnet moving-coil type or moving-iron type. These are discussed in the following sections.

2.2.1 PERMANENT MAGNET MOVING-COIL INSTRUMENTS

In permanent magnet moving coil (PMMC) instruments, current is passed through a movable coil placed in the magnetic field of a permanent magnet. The resulting deflecting torque causes the coil to move. A pointer, attached to the frame of the coil, moves over a calibrated scale. The deflecting torque T_d is proportional to the current i through the coil. It is given by

$$T_d = k_1 i \tag{2.1}$$

where k_1 is a proportionality constant.

The controlling torque is provided by a spring and is proportional to the angle θ turned through by the coil. It is given by

$$T_c = k_s \theta \tag{2.2}$$

where k_s is the spring constant.

Under steady state condition, the controlling torque is equal to the deflecting torque. Therefore, from equations (2.1) and (2.2)

$$k_s \theta = k_1 i$$

or

$$\theta = \frac{k_1}{k_s} i$$

or

$$\theta = k i \tag{2.3}$$

where k is a constant equal to k_1/k_s . Eq. (2.3) shows that the deflection is directly proportional to the current. Therefore, scale of a PMMC instrument is uniformly divided.

The damping torque is produced by the eddy currents induced in the aluminium frame on which the moving coil is wound.

The principal advantages of a PMMC instruments are

1. Low power consumption
2. Very accurate and reliable
3. Uniform scale
4. Unaffected by stray magnetic field

The main drawbacks of a PMMC instrument are

1. It can be used for the measurement of dc voltage or current only
2. It is costlier as compared to a moving-iron instrument
3. The ageing of permanent magnet and the control spring may introduce some error

2.2.2 MOVING IRON INSTRUMENTS

In moving-iron instruments, the current to be measured is passed through a fixed coil. The coil produces a magnetic field of strength proportional to the value of the current. A set of movable iron vanes is so mounted in the field that it experiences a deflecting torque proportional to square of the current. A pointer, attached to the moving system, moves over a calibrated scale to indicate the r.m.s. value of the current or voltage being measured. The controlling torque is generally provided by a spring.

The deflecting torque is proportional to the square of the current. The deflection, which depends upon the average deflecting torque, is proportional to the mean value of the square of the current. With proper calibration, these instruments can be used to indicate r.m.s. value of the ac or dc current/voltage. Because of nonlinear relation between deflection and the quantity being measured, these instruments have crowded scales at the two ends as shown in Fig. 2.2.

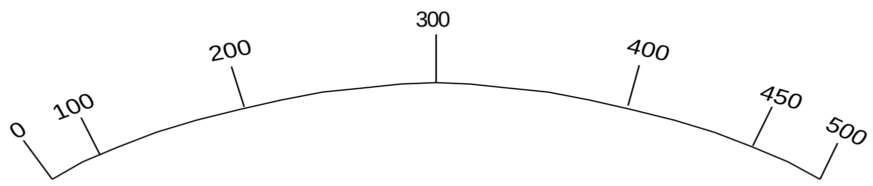


Fig. 2.2 Scale of a moving-iron instrument

A moving-iron instrument has the following advantages

1. Low cost.
2. Robust construction.
3. Can be used for both ac and dc.

The main drawbacks of a moving-iron instrument are

1. Useful range of scale is limited because of non-uniform scale.
2. Affected by external magnetic field.
3. When used for dc, hysteresis affects the reading.

Moving-iron instruments are generally calibrated for measurement of sinusoidal quantities and may give erroneous results when used to measure non-sinusoidal quantities. Also, the instrument may give errors when used for frequencies other than that for which the instrument is calibrated.

2.3 WATTMETERS

Wattmeters are used to measure power in a circuit. These are of three types

1. Dynamometer type
2. Induction type
3. Electro-static type

Most of the wattmeters used in laboratories are dynamometer type. This will be described in the following section.

2.3.1 DYNAMOMETER TYPE WATTMETER

A dynamometer type wattmeter has two fixed coils and a light moving-coil that can move inside the fixed coils. The two fixed coils, also called the pressure coil (PC), are of cylindrical shape and are wound over non-metallic formers. These coils are connected in series with the load circuit and therefore a field proportional to the load current and directed along the axis of the cylindrical fixed coils is set up. The moving-coil together with a large series resistance is connected across the load voltage as shown in Fig. 2.3. Therefore, the moving-coil carries a current proportional to the circuit voltage. The moving-coil is also called the current coil (CC). The average deflecting torque on the moving system is proportional to the average power flow.

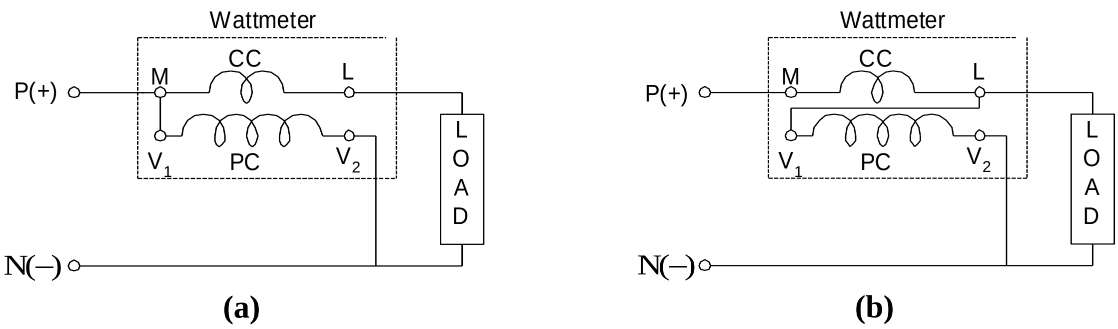


Fig.2.3 Connection of a wattmeter

The current coil terminals of a wattmeter are marked as M and L. M stands for mains while L stands for load. The terminal M must be connected to the phase terminal P (for ac power measurement) or positive terminal + (for dc power measurement) of the input mains. The other current coil terminal L must be connected to the load, as shown in Fig. 2.3. One of the pressure coil terminals is marked as V_1 or Common. This terminal may be connected to the terminal M or L of the CC, as shown in Fig. 2.3 (a) and Fig. 2.3 (b) respectively. With connection (a), the wattmeter reading will include the power loss in the current coil while with connection (b) the wattmeter reading will include the power loss in the pressure coil. Therefore, for high voltage and low current circuits, connection (a) is preferred and for low voltage and high current circuits, connection (b) is preferred. Generally, the losses in the two coils of a wattmeter are negligible and either of the two connections will cause insignificant error. The other terminal of the wattmeter marked as V_2, must be connected to the neutral terminal N (for ac power measurement) or negative terminal – (for dc power measurement) of the input mains.

2.3.2 MULTI-RANGE WATTMETERS

A multi-range wattmeter is designed to be operated at different voltages and currents. Several voltage ranges are provided by connecting taps in the series resistor of the pressure coil. These taps are taken out to terminals marked in terms of voltage ranges as shown in Fig. 2.4. Two current ranges are often provided (usually in the ratio of $2:1$) by constructing the fixed coils in two parts, which may be connected in series or parallel through the use of movable links or a drum switch.

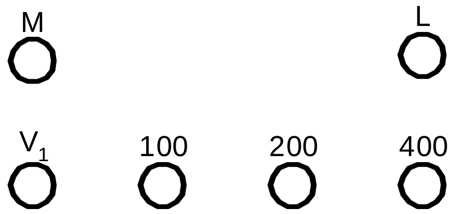


Fig. 2.4 Terminals of a multi-range wattmeter

The multiplying factor corresponding to any available combination of voltage and current ranges is the constant by which the reading on the dial of the instrument is multiplied in order to obtain the power recorded by the instrument. The multiplying factors for the various combinations of voltage and current ranges are usually marked on the cover of the instrument.

The wattmeter usually gives full-scale deflection if the voltage and current in the circuit are equal to the selected ranges. For example, a wattmeter with 1000 divisions on its dial used for a current range of 2.5 A and a voltage range of 200 V will indicate 1000 on the dial when the load voltage is 200 V and the load current is 2.5 A. The actual power that flows in the circuit (at unity power factor) is $200 \times 2.5 = 500\,\text{W}$. The wattmeter reading should therefore be multiplied with 0.5 to get the true power. If the wattmeter indicates 600, then the true power is $600 \times 0.5 = 300\,\text{W}$. Thus the true power can be obtained as

$$True\ power = wattmeter\ reading \times multiplying\ factor \tag{2.4}$$

where multiplying factor can be obtained as

$$Multiplying\ factor = \frac{voltage\ range \times current\ range}{number\ of\ divisions\ on\ the\ dial} \tag{2.5}$$

Eq. (2.5) holds only for wattmeters designed for unity power factor.

2.4 MEASUREMENT OF POWER IN THREE-PHASE CIRCUITS

Power in three-phase circuits can be measured by two-wattmeter method or one-wattmeter method.

2.4.1 TWO-WATTMETER METHOD

In this method two similar wattmeters are connected in the three-phase circuit as shown in Fig. 2.5. If W_1 and W_2 are the readings of the two wattmeters then the total power in the three-phase circuit is given by

$$P = W_1 + W_2 \tag{2.6}$$

where W_1 and W_2 may be positive or negative.

The power factor of the load is given by

$$p.f. = \cos\left[\tan^{-1}\sqrt{3}\frac{W_1 - W_2}{W_1 + W_2}\right] \tag{2.7}$$

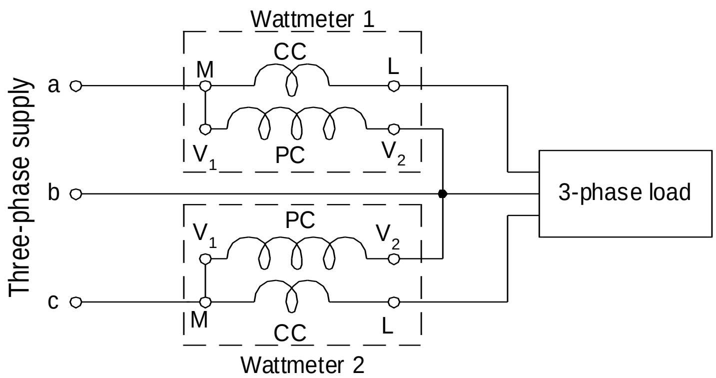


Fig. 2.5 Wattmeter connections for two-wattmeter method

Equations (2.6) and (2.7) are valid even for an unbalanced load.

For certain values of power factors, reading of one of the wattmeters may be negative. To record the negative reading, connections of the pressure coil must be reversed. This can be achieved with the help of a double-pole double-throw (DPDT) switch as shown in Fig. 2.6. To record positive reading, the DPDT switch must be connected to the position 11′ and to record negative reading the switch must be connected to the position 22′. In some wattmeters built in reversing switches are provided.

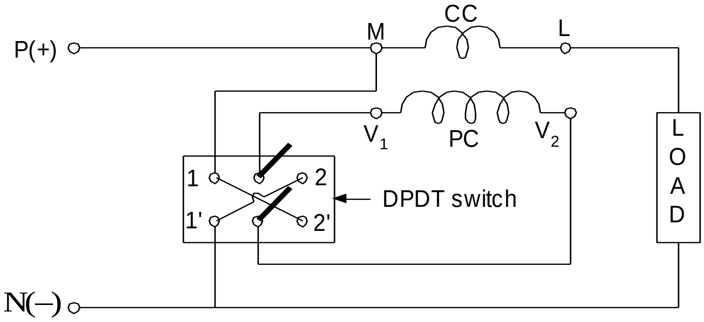


Fig. 2.6 Connections to reverse the pressure-coil current

2.4.2 ONE-WATTMETER METHOD

One-wattmeter method can be used to measure power in a balanced three-phase circuit. This method uses only one wattmeter whose current coil is connected in any one phase, say 'a', as shown in Fig. 2.7. The pressure coil is alternately connected between $a\,\&\,b$ and $a\,\&\,c$ to record the wattmeter readings W_1 and W_2. Negative wattmeter readings can be recorded as described in the previous section. The three-phase power and the power factor can be determined using equations (2.6) and (2.7).

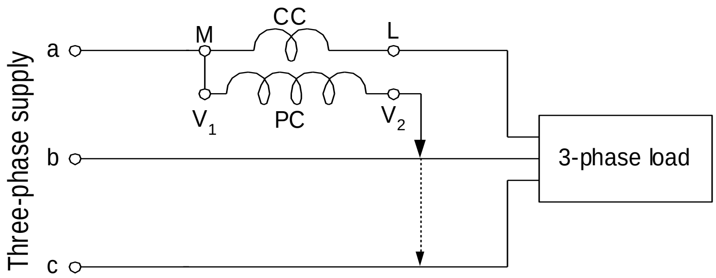


Fig. 2.7 Wattmeter connections for one-wattmeter method

2.5 CURRENT TRANSFORMER

When current through a circuit is more than the rating of an ammeter or the current coil of a wattmeter, current transformer (CT) is used to step down the current. The CTs are usually designed for a secondary current of 5 A. The primary winding has only a few turns and is designed to carry the current in the circuit where it is to be used. The ratio by which the current is stepped down is called the current transformation ratio or CT_{ratio}. It is defined as

$$CT_{ratio} = \frac{primary\ winding\ current}{secondary\ winding\ current} \tag{2.8}$$

The primary of a CT is always connected in series with the circuit. For measurement of current, ammeter is connected across the secondary as shown in Fig. 2.8(a). The current *I* through the circuit can be evaluated as

$$I = Ammeter\,reading \times CT_{ratio} \tag{2.9}$$

Connection of a CT for extension of range of a wattmeter is shown in Fig. 2.8(b). The power *P* in the circuit can be obtained as

$$P = Watmeter\,reading \times m.f \times CT_{ratio} \tag{2.10}$$

where $m.f$ is multiplying factor of the wattmeter.

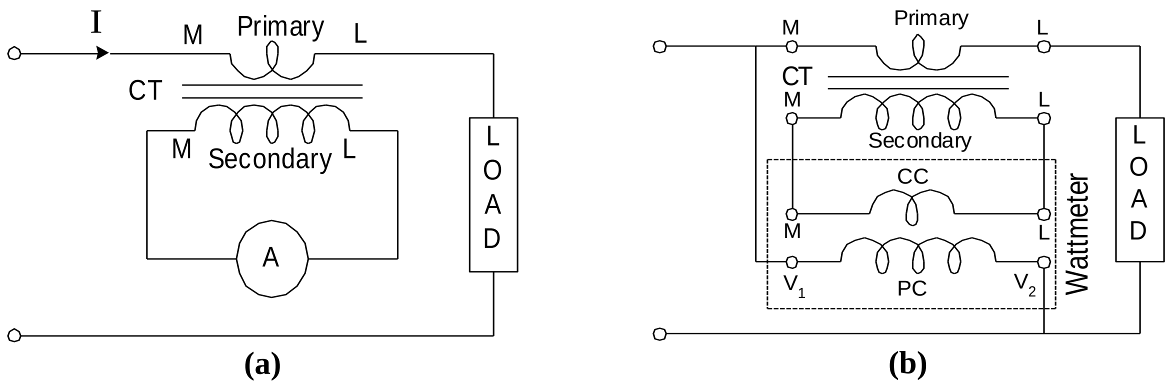


Fig. 2.8 Connection of CT for extension of range of (a) ammeter (b) wattmeter

Under normal operating conditions, both primary and secondary windings carry currents. These currents produce mmfs that balance each other. The small difference between the primary and secondary mmfs maintains the required flux in the core. If the secondary winding is opened while the primary winding still carrying the load-current, the secondary mmf falls to zero and the net mmf, which is now equal to the primary mmf, becomes very large. This large mmf produces a very large flux in the core till it saturates. This large flux induces a very high voltage in the secondary winding that could be dangerous to the CT insulation as well as to the person who has opened the circuit. Therefore, a very important precaution to be observed while operating a CT is that **"Never open the secondary winding circuit while the primary winding circuit is energized".**

3

Experiments on Transformer

EXPERIMENT 3.1

LOAD TEST OF SINGLE-PHASE TRANSFORMER

OBJECT

To perform load test on a single-phase transformer and determine

(a) voltage regulation of the transformer
(b) efficiency of the transformer and to plot efficiency versus load curve.

THEORY

The voltage regulation of a transformer is defined as the change in the magnitude of the secondary terminal voltage, as a percentage of the rated secondary voltage, when the full-load at a specified power factor is disconnected, while the primary voltage and frequency are kept constant. Mathematically, it may be defined as

$$\%VR = \frac{V_{2o} - V_{2fl}}{V_{2rated}} \times 100 \qquad (3.1.1)$$

Where,

V_{2o} is the no-load secondary voltage,

V_{2fl} is the full-load secondary voltage, and

V_{2rated} is the rated secondary voltage.

The percentage efficiency of the transformer is defined as

$$\eta = \frac{P_o}{P_{in}} \times 100 \tag{3.1.2}$$

where P_o is the output power and P_{in} is the input power.

Eq. (3.1.2) can be written as

$$\eta = \frac{V_2 I_2 \cos\varphi}{P_{in}} \times 100 \tag{3.1.3}$$

where V_2 and I_2 are the secondary voltage and secondary current of the transformer respectively and $\cos\varphi$ is the power factor of the load. For a unity power factor (resistive) load Eq. (3.1.3) may be written as

$$\eta = \frac{V_2 I_2}{P_{in}} \times 100 \tag{3.1.4}$$

The input power may be measured using a wattmeter. It can be written as

$$P_{in} = P_o + P_{loss} \tag{3.1.5}$$

where P_{loss} is the power loss in the transformer. It consists of iron-loss (or core-loss), copper-loss (or I^2R-loss), stray-loss and dielectric-loss. Stray-loss and dielectric-loss are generally negligible as compared to iron-loss and copper-loss.

Iron-loss takes place in the iron core of the transformer. It results due to the alternating flux of the core. The two components of iron-loss are hysteresis-loss and eddy-current-loss. These losses depend on the magnitude and frequency of the alternating flux. For a supply of constant voltage and frequency, the magnitude and frequency of the alternating flux remains constant. Therefore, at constant voltage and frequency, iron-loss remains constant, irrespective of the load on the transformer. Iron-loss is therefore also called constant-loss.

Copper-loss is the I^2R-loss that takes place in the windings (usually made of copper) of the transformer and varies as the load on the transformer varies. This loss is therefore also called the variable-loss of the transformer. At no-load, the transformer draws a very small current (Less than 5% for large and medium rating transformer and less than 10% for small rating transformer). The copper-loss due to such a small current is negligible and the power drawn from the transformer is nearly same as the iron loss of the transformer.

Load test is performed for the measurement of voltage regulation, efficiency and temperature rise of the transformer. In this test, a variable load is connected to the secondary winding and rated supply is given to the primary winding. Output voltage, output power and input power are recorded for different loads.

EXPERIMENTAL SETUP

In load test, the rated voltage is to be applied to the primary. The rated voltage may be applied to the primary with the help of a singe-phase variable auto transformer. The kVA rating of the autotransformer should be equal to or more than the transformer under test. To load the transformer, a lamp load consisting of a number of incandescent lamps may be used. The combined rating of the lamp load should be somewhat more than that of the kVA rating of the transformer.

The wattmeter required to measure the input power of the transformer must have a pressure coil rated for at least the rated primary voltage of the transformer. The current is to be varied from very low value to the rated value. Therefore the current coil of the wattmeter should be rated at least for the rated primary current of the transformer. For accurate measurement of power at low values of current, lower rating current coil may be used. For this a wattmeter with multi range current coil should be preferred.

The voltmeters required for the primary and the secondary sides should be rated for the rated voltages of the corresponding sides of the transformer. An ammeter rated for a minimum of rated secondary current of the transformer is required to measure the secondary current.

PROCEDURE

(i) Make the connections of the transformer as shown in Fig. 3.1.1 using instruments of appropriate ratings. Adjust the autotransformer to the rated voltage of the primary side of the transformer.

(ii) Record the secondary voltmeter reading and the wattmeter reading under no-load condition.

(iii) Keeping the primary voltage constant at its rated value, increase the load on the transformer in small steps up to rated load and record the readings of the voltmeter and ammeter connected to the secondary side and the wattmeter reading in each step.

OBSERVATIONS

The meter readings for different loads can be tabulated as:

S.No.	Secondary Current I_2 (Amperes)	Secondary Voltage V_2 (volts)	Input Power P_1 (Watts)
1.	0	V_{2o} = ……	……..
2.	…….	……..	…….
3.	…….	…….	…….
: :			
n	I_{2fl} = ……	V_{2fl} = …….	……

REPORT

(i) With the secondary voltmeter reading corresponding to no-load condition V_{2o}, and the secondary voltmeter reading corresponding to full-load condition V_{2fl}, use equation (3.1.1) to determine the voltage regulation of the transformer.

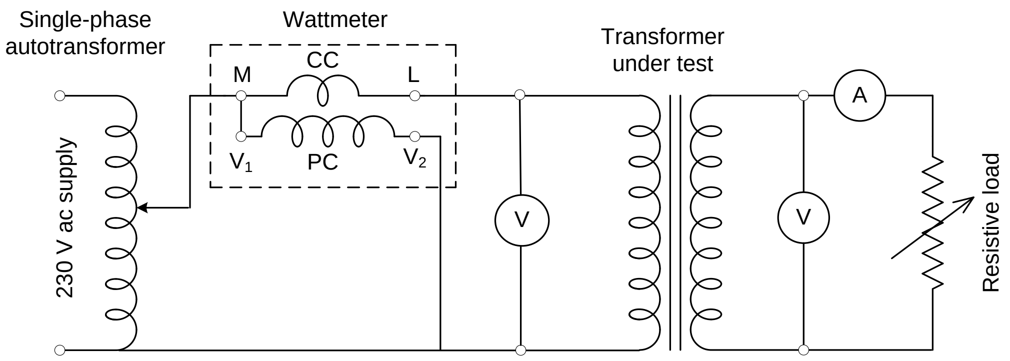


Fig. 3.1.1 Circuit diagram for load-test of a transformer

(ii) Calculate the efficiency of the transformer for different readings using Eq. (3.1.3) and plot efficiency versus load VA (V_2I_2) curve. From the curve, find out the load for maximum efficiency.

SAMPLE QUESTIONS

1. Explain why the load-test gives more accurate values of the performance parameters of a transformer as compared to open-circuit and short-circuit tests.
2. What are the limitations of load-test?
3. What will be the ratings of the instruments required to perform load test on a 2 kVA, 230/115V, single-phase transformer?

EXPERIMENT 3.2

OPEN-CIRCUIT AND SHORT-CIRCUIT TESTS OF SINGLE-PHASE TRANSFORMER

OBJECT

To perform open-circuit and short-circuit tests on a single-phase transformer and determine

(a) The equivalent circuit parameters referred to either sides of the transformer.
(b) The voltage regulation of the transformer for (i) unity power-factor load, (ii) 0.8 power-factor lagging load and (iii) 0.8 power-factor leading load.
(c) The efficiency of the transformer for different values of load at unity power factor and to plot efficiency versus load curve.

THEORY

The performance parameters of a transformer, namely, voltage regulation and efficiency, may be obtained by load-test as explained in Experiment 3.1. However, it may not be always possible to perform load-test in a laboratory, especially for large rating transformers. The laboratory might not have the sanctioned load more than the kVA rating of the transformer. Also, it may be difficult to arrange the load for direct loading of the transformer. Even if the laboratory has the enough sanctioned load and the load is made available, direct loading result in large wastage of energy. Therefore, for large rating transformers, the performance parameters are determined with the help of the equivalent circuit of the transformer.

Equivalent Circuit

The equivalent circuit of a single-phase transformer is shown in Fig. 3.2.1. Here

r_1 is the resistance of the primary winding,

x_1 is the leakage reactance of the primary winding,

r_2' is the resistance of secondary winding (r_2) referred to the primary side. It is given by

$$r_2' = a^2 r_2 \tag{3.2.1}$$

where a is turn ratio of the transformer. It is very close to the transformation ratio of the transformation of the transformer. It is given by

$$a = \frac{N_1}{N_2} = \frac{V_1}{V_2} \tag{3.2.2}$$

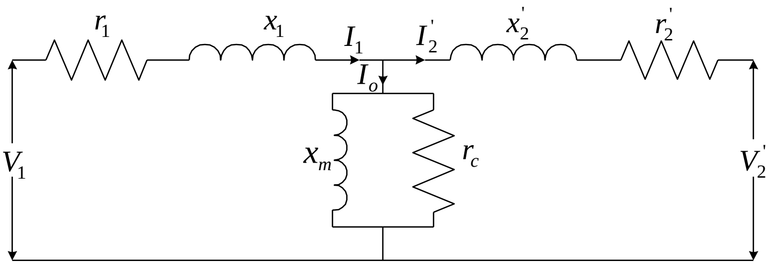


Fig. 3.2.1 Equivalent circuit of transformer referred to primary.

where N_1 and N_2 are the number of turns in the primary and secondary windings, respectively. V_1 and V_2 are respectively the primary and secondary voltages of the transformer.

$x_2^{'}$ is the leakage reactance of the secondary winding (x_2) referred to the primary side. It is given by

$$x_2^{'} = a^2 x_2 \tag{3.2.3}$$

r_c is the core-loss resistance,

x_m is the magnetizing reactance,

I_1 are the primary current,

$V_2^{'}$ is the secondary voltage referred to the primary side. It is given by

$$V_2^{'} = aV_2 \tag{3.2.4}$$

$I_2^{'}$ is the secondary current (I_2) referred to the primary side. It is given by

$$V_2^{'} = I_2/a \tag{3.2.5}$$

I_o is the no-load current.

In practice, it is difficult to determine the parameters of the equivalent circuit shown in Fig. 3.2.1. The circuit may be simplified by shifting the shunt branch to the input terminals, as shown in Fig. 3.2.2. Here R_1, X_1, Z_1 are respectively the equivalent resistance, equivalent leakage-reactance and equivalent leakage-impedance of the transformer referred to primary. These are given by

$$R_1 = r_1 + r_2' \tag{3.2.6}$$

$$X_1 = x_1 + x_2' \tag{3.2.7}$$

$$Z_1 = R_1 + jX_1 \tag{3.2.8}$$

In the approximate circuit of Fig. 3.2.2, the voltage across the shunt branch becomes V_1 instead of $V_1 - I_1(r_1 + jx_1)$. For the range of values of r_1 and x_1 for a transformer, the voltage drop $I_1(r_1 + jx_1)$ is negligible as compared to V_1. Thus, the change in the magnitude of the no-load

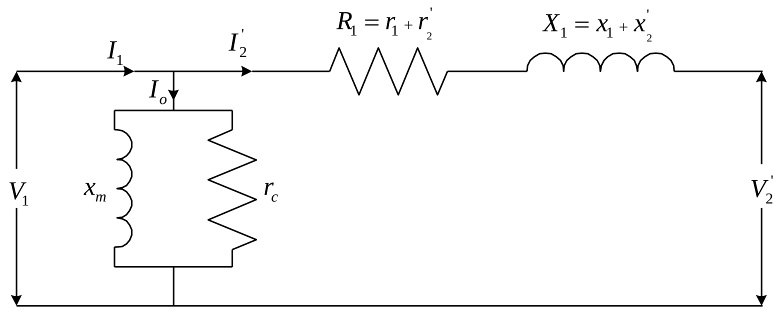


Fig. 3.2.2 Approximate equivalent circuit of transformer referred to primary.

current is insignificant. In approximate equivalent circuit, the current through the primary impedance $r_1 + jx_1$ is $I_2{'}$ instead of $I_o + I_2{'}$ as it was in the exact equivalent circuit. This results in insignificant error as the magnitude of no-load current is very small as compared to the full-load current of the transformer (no-load current is 2 to 5% of full-load current). Thus the equivalent circuit of Fig. 3.2.2 is a good approximation of the equivalent circuit of Fig. 3.2.1 and it may be used to obtain performance parameters of the transformer without any significant error.

The equivalent circuit of a transformer referred to the secondary side is shown in Fig. 3.2.3.

Here

$r_1^{'}$ is the resistance of primary winding referred to the secondary side. It is given by

$$r_1^{'} = r_1 / a^2 \tag{3.2.9}$$

$x_1^{'}$ is the leakage reactance of the primary winding referred to the secondary side. It is given by

$$x_1^{'} = x_1 / a^2 \tag{3.2.10}$$

$x_m^{'}$ is the magnetizing reactance referred to secondary side. It is given by

$$x_m^{'} = x_m / a^2 \tag{3.2.11}$$

r_c is the core-loss resistance referred to secondary side. It is given by

$$r_c^{'} = r_c / a^2 \tag{3.2.12}$$

$V_1^{'}$ is the primary voltage referred to the secondary side. It is given by

$$V_1^{'} = V_1 / a \tag{3.2.13}$$

$I_1^{'}$ is the primary current referred to the secondary side. It is given by

$$I_1^{'} = aI_1 \tag{3.2.14}$$

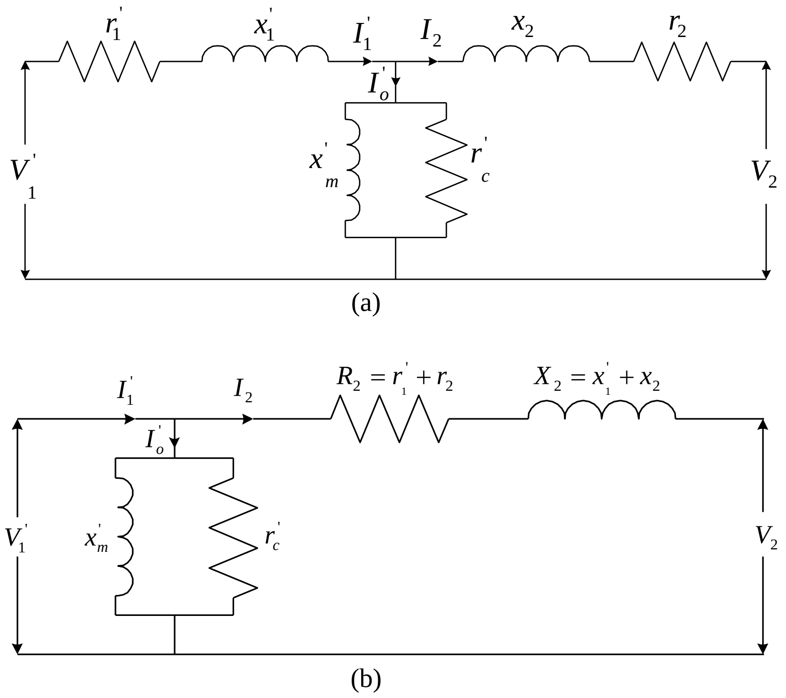


Fig. 3.2.3 Equivalent circuit of transformer referred to secondary (a) exact circuit (b) approximate circuit.

I_o' is the no-load current referred to the secondary side. It is given by

$$I_o' = aI_o \tag{3.2.15}$$

R2, *X2*, *Z2* are respectively the equivalent resistance, equivalent leakage reactance and equivalent leakage impedance of the transformer referred to secondary. These are given by

$$R_2 = r_1' + r_2 \tag{3.2.16}$$

$$X_2 = x_1' + x_2 \tag{3.2.17}$$

$$Z_2 = R_2 + jX_2 \tag{3.2.18}$$

Using Eqs. (3.2.1) and (3.2.9), Eq. (3.2.16) can be written as

$$R_2 = \frac{r_1}{a^2} + \frac{r_2'}{a^2} = \frac{r + r_2'}{a^2} = \frac{R_1}{a^2} \tag{3.2.19}$$

Similarly equivalent reactance and equivalent impedance referred to secondary can be related to the corresponding quantities referred to primary as

$$X_2 = \frac{X_1}{a^2} \tag{3.2.20}$$

and

$$Z_2 = \frac{Z_1}{a^2} \tag{3.2.21}$$

The parameters of the approximate equivalent circuit of a transformer are determined by conducting open-circuit and short-circuit tests. In these tests, power consumption is simply that required to supply losses in the transformer. These tests are therefore called non-loading tests.

Open-circuit (OC) test

Open-circuit test is performed to determine the shunt branch parameters of the equivalent circuit of a transformer. In this test, one of the windings (usually high voltage winding) is kept open and rated voltage, rated frequency supply is given to the other winding. The input power (P_o), current, (I_o), and voltage (V_o) are recorded.

Under no-load condition, the secondary current is zero and the voltage drop in the primary leakage impedance due to no-load current I_o, is negligible. The equivalent circuit of the transformer, shown in Fig. 3.2.1, may be simplified for the no-load condition as shown in Fig. 3.2.4. From the circuit, the shunt branch parameters may be evaluated. The shunt branch impedance is given by

$$Z_o = \frac{V_o}{I_o} \tag{3.2.22}$$

The core loss resistance is given by

$$r_c = \frac{V_o^2}{P_o} \tag{3.2.23}$$

The magnetizing reactance is given by

$$x_m = \frac{1}{\sqrt{\frac{1}{Z_o^2} - \frac{1}{r_c^2}}} \tag{3.2.24}$$

As the copper loss due to small no-load current is negligible, the power input in the no-load test gives the iron loss (P_i) of the transformer.

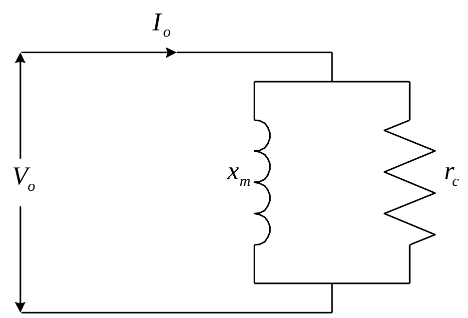


Fig. 3.2.4 Equivalent circuit under no-load condition

Short-circuit (SC) test

Short-circuit test is performed to evaluate the series parameters of the equivalent circuit of a transformer. In this test, one of the windings (usually low voltage winding) is short circuited and a reduced voltage at rated frequency is applied to the other winding so that the transformer draws a current which is equal to or less than the rated current. The input voltage (V_{sc}), current (I_{sc}), and power (P_{sc}) are recorded under this condition.

The voltage required to circulate the rated current under short-circuit condition is much less than the rated voltage (less than 10%). With this small voltage, the shunt branch current is very small and therefore, it may be neglected. Under this condition, the equivalent circuit of the transformer, shown in Fig. 3.2.1, reduces to a simple circuit as shown in Fig. 3.2.5. From the circuit, the series parameters may be evaluated. The leakage impedance of the transformer is given by

$$Z = \frac{V_{sc}}{I_{sc}} \tag{3.2.25}$$

The equivalent resistance is given by

$$R = \frac{P_{sc}}{I_{sc}^2} \tag{3.2.26}$$

The equivalent leakage reactance is given by

$$X = \sqrt{Z^2 - R^2} \tag{3.2.27}$$

The power input in the short circuit test gives the copper loss for the current I_{sc}. The full-load copper loss may be obtained as

$$P_c = \left(\frac{I_{fl}}{I_{sc}}\right)^2 P_{sc} \tag{3.2.28}$$

where I_{fl} is the full-load current of the transformer.

The equivalent circuit parameters obtained using OC and SC tests are referred to the side on which the tests are performed. The parameters referred to the other side may be obtained using following general relation:

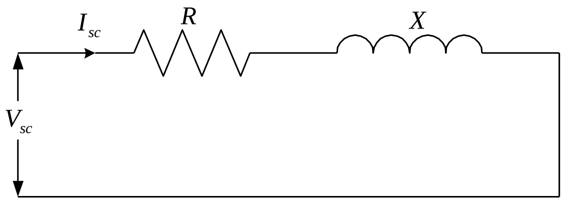


Fig. 3.2.5 Equivalent circuit under short-circuit condition

$$\frac{\text{Parameter referred to primary}}{\text{Parameter referred to secondary}} = \left(\frac{V_1}{V_2}\right)^2 \tag{3.2.29}$$

Efficiency

The efficiency of the transformer may be defined as

$$\eta = \frac{P_o}{P_{in}} = \frac{P_o}{P_o + P_{loss}} \tag{3.2.30}$$

Where the output power, P_o, is given by

$$P_o = V_2 I_2 \cos\varphi = V_2 I_{2fl} \frac{I_2}{I_{2fl}} \cos\varphi$$

Or

$$P_o = S\,x \cos\varphi \tag{3.2.31}$$

Here S = $V_2 I_{2fl}$ is the VA rating of the transformer and
$x = I_2 / I_{2fl}$ is the per unit load of the transformer.

The power loss in the transformer, P_{loss}, mainly consists of iron loss, P_i and copper loss, P_{cu}.

$$P_{loss} = P_i + P_{cu} \tag{3.2.32}$$

The iron loss remains constant for constant voltage and constant frequency supply and is independent of load on the transformer. The copper loss is given by

$$P_{cu} = I_2{}^2 R_2 = \frac{I_2{}^2}{I_{2fl}{}^2} I_{2fl}{}^2 R_2$$

Or

$$P_{cu} = x^2 P_c \tag{3.2.33}$$

Where $P_c = I_{2fl}{}^2 R_2$ is the full-load copper loss of the transformer.

Using Equations. (3.2.31)-(3.2.33), Equation. (3.2.30) can be written as

$$\eta = \frac{S\,x \cos\phi}{S\,x \cos\phi + P_i + x^2 P_c} \tag{3.2.34}$$

Voltage Regulation

The voltage regulation of a transformer is defined as the change in secondary terminal voltage, expressed in percentage of rated secondary voltage, when the rated load of a specified power-factor is thrown off.

$$VR = \frac{V_{2o} - V_{2fl}}{V_{2rated}} \tag{3.2.35}$$

Where,

V_{2o} is the no-load secondary voltage,

V_{2fl} is the full-load secondary voltage, and

V_{2rated} is the rated secondary voltage.

From the approximate equivalent circuit of transformer referred to secondary (Fig. 3.2.3b) it can be observed that at no-load the secondary voltage $V_{2o} = V_1^{'}$. Therefore, Eq (3.2.35) can be written as

$$VR = \frac{V_1^{'} - V_{2fl}}{V_{2rated}} \tag{3.2.36}$$

The phasor diagram of the transformer supplying full-load at a lagging power factor is shown in Fig. 3.2.6(a). The voltage drops $I_{2fl}R_2$ and $I_{2fl}X_2$ are shown on a magnified scale for clarity. For a well designed transformer these drops are very small as compared to full-load voltage V_{2fl}. Under this condition, $\delta \approx 0$ and $V_1^{'} = OD \approx OC = OA + AB + BC = V_{2fl} + I_{2fl}R_2\cos\varphi + I_{2fl}X_2\sin\varphi$. Thus

$$V_1^{'} - V_{2fl} = I_{2fl}R_2\cos\varphi + I_{2fl}X_2\sin\varphi \tag{3.2.37}$$

Using Eq. (3.2.37), Eq. (3.2.36) can be written as

$$VR = \frac{I_{2fl}R_2\cos\varphi + I_{2fl}X_2\sin\varphi}{V_{2rated}} \tag{3.2.38}$$

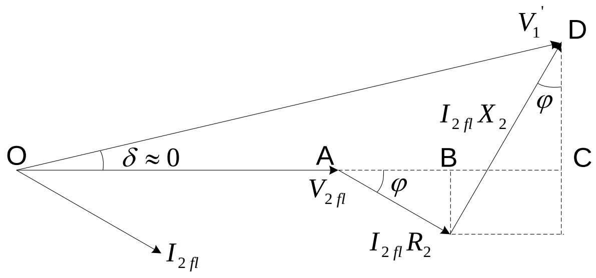
From the phasor diagram for a leading power factor load, shown in Fig. 3.2.6(b), it can be shown that

$$VR = \frac{I_{2fl}R_2\cos\varphi - I_{2fl}X_2\sin\varphi}{V_{2rated}} \tag{3.2.39}$$

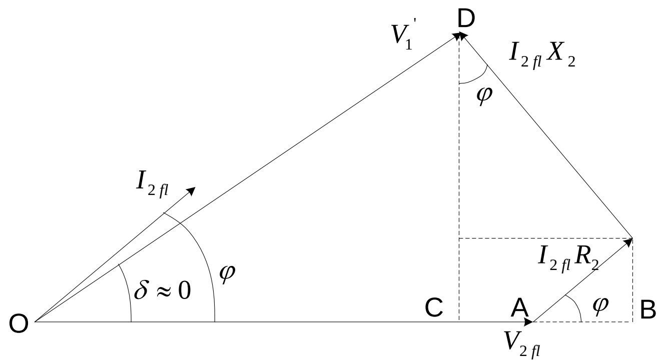
Recognizing that $\frac{I_{2fl}R_2}{V_{2rated}} = R_{pu}$(per-unit resistance) and $\frac{I_{2fl}X_2}{V_{2rated}} = X_{pu}$(per-unit leakage-reactance), Eq. (3.2.38) and (3.2.39) can be written as

$$VR = R_{pu}\cos\varphi \pm X_{pu}\sin\varphi \tag{2.3.40}$$

Where + sign is for lagging power factor and – sign is for leading power factor.



(a)



(b)

Fig. 3.2.6 Phasor-diagram of the transformer for (a) lagging power factor (b) leading power factor load

EXPERIMENTAL SETUP

In open-circuit test, rated voltage is to be applied to one of the windings. The rated voltage may not be directly available from the supply. The rated voltage may be applied through a variable auto transformer. The voltmeter and the pressure coil of the wattmeter should be rated for a voltage more than the rated voltage of the transformer winding. For transformers with large voltage ratings (e.g. a 2000/200V transformer), it is always convenient to perform the open-circuit test on low voltage side. However, for transformers with low voltage ratings (e.g. 230/115 V transformer), the test may be conveniently performed on either side of the transformer.

The current drawn by the transformer during open-circuit test has a very low power factor and is much less than the full-load current of the transformer. It is of the order of 5% for large and medium size transformer and of the order of 10% for small transformer. The ammeter and current coil of the wattmeter should be of suitable range, say, 15% of the full-load current of the transformer. The wattmeter should be of low power factor (e.g. 0.2 power factor) to give enough deflection.

In the short-circuit test, less than 10% of the rated voltage required to circulate the full-load current in the transformer. The voltmeter should be suitably rated to accurately read this small voltage. A digital voltmeter may be used to measure this small voltage. The ammeter and current coil of the wattmeter should be rated for somewhat more than the rated current of the transformer. To reduce the required rating of the ammeter and current coil of the wattmeter, the test is usually conducted on the low voltage side. The pressure coil of the wattmeter should also be rated for low voltage (about 15% of the rated voltage).

PROCEDURE

Open-circuit test

(i) Make the connections as shown in Fig. 3.2.7 using instruments of appropriate ratings.
(ii) Leave the secondary terminals of the transformer open.
(iii) Adjust the autotransformer to supply the rated voltage to the primary side.
(iv) Take readings of voltmeter, ammeter and wattmeter.

Short-circuit test

(i) Make the connections as shown in Fig. 3.2.8 using instruments of appropriate ratings. In the short-circuit test, a low voltage is required to circulate the rated current. At this low voltage and high current, the voltage drop across current-coil of the wattmeter and ammeter are not negligible as compared to the applied voltage. Therefore, the connections are made to ensure that the voltages across the pressure coil of the wattmeter and the voltmeter are same as the voltage across the primary of the transformer.
(ii) Short-circuit the secondary terminals.
(iii) Gradually increase the primary input voltage from zero. Record the readings of voltmeter, ammeter and wattmeter for 25%, 50%, 75%, and 100% of the full-load current of the transformer.

OBSERVATIONS

Open-circuit test

Voltmeter reading V_o =………………..
Ammeter reading I_o =…………………
Wattmeter reading P_o =………………..

Short-circuit test

S.No.	Ammeter reading I_{sc}	Voltmeter reading V_{sc}	Wattmeter reading P_{sc}

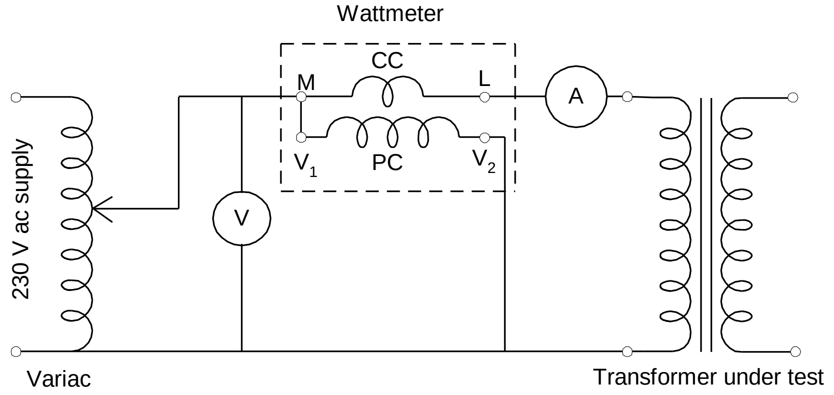


Fig. 3.2.7 Circuit diagram for open-circuit tests

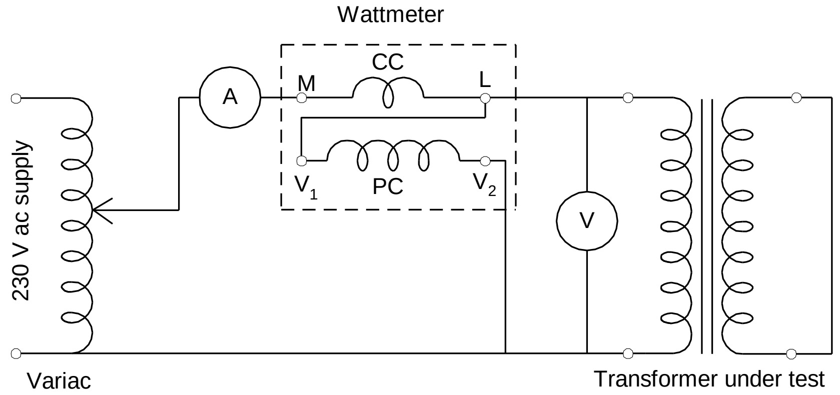


Fig. 3.2.8 Circuit diagram for short-circuit tests.

REPORT

(i) Use equations (3.2.22) to (3.2.24) to calculate the shunt branch parameters.

(ii) Determine the series parameters and full-load copper loss of the transformer for different readings and obtain their mean value. Tabulate the result as:

S.No.	$Z = \dfrac{V_{sc}}{I_{sc}}$	$R = \dfrac{P_{sc}}{I_{sc}^2}$	$X = \sqrt{Z^2 - R^2}$	$P_c = \left(\dfrac{I_{fl}}{I_{sc}}\right)^2 P_{sc}$

Mean R =... Mean X =... Mean P_c =....

(iii) Use equation (3.2.29) to obtain the parameters referred to the other side of the transformer.

(iv) With iron loss P_i (obtained from open-circuit), and mean value of P_c , as obtained in (ii), use equation (3.2.34) to obtain efficiency of the transformer for different values of x (from 0 to 1 in steps of 0.1) at the given power factor. Use the result to plot efficiency-load curve.

(v) With mean values of *R* and *X*, use equation (3.2.38) or (3.2.39) to obtain voltage regulation of the transformer at the specified power factors.

SAMPLE QUESTIONS

1. Give range and ratings of the instruments needed to perform open-circuit test on 11kV/230V, 250kVA, single-phase transformer if the instruments are to be connected on (i) HV side (ii) LV side
2. Give range and ratings of the instruments needed to perform short-circuit test on 11kV/230V, 250kVA, single-phase transformer if the instruments are to be connected on (i) HV side (ii) LV side
3. Explain why the open-circuit test is usually performed on LV side while the short-circuit test is usually performed on HV side.
4. The open-circuit test gives approximate value of the iron-loss while the short-circuit test gives approximate value of copper-loss. Explain.
5. What is the condition for maximum efficiency of a transformer?
6. What is the condition for zero voltage regulation of a transformer?
7. Under what condition, the voltage regulation of a transformer may become negative?

EXPERIMENT 3.3

SUMPNER'S TEST OF SINGLE-PHASE TRANSFORMER

OBJECT

To perform Sumpner's test on two single-phase transformers and determine

(a) efficiency of the transformers for different values of load at unity power factor and to plot efficiency versus load curve.

(b) voltage regulation of the transformer for (i) unity power-factor load, (ii) 0.8 power-factor lagging load and (iii) 0.8 power-factor leading load.

THEORY

Temperature rise in a transformer under load conditions, cannot be determined by open-circuit and short-circuit tests because in these tests, the power loss in the transformer is either iron loss or copper loss but not the both. To determine the temperature rise, load test can be performed. However, load test is too expensive and sometimes not practicable, especially for large transformers. The steady state temperature rise can be determined, without actually loading the transformer, by Sumpner's test.

The Sumpner's test needs two identical transformers. The primaries of the two transformers are connected in parallel to a circuit having a voltage equal to the rated primary voltage. The two secondary-windings are connected in series in such a way that emf's induced in the two secondary-windings are in phase-opposition and the voltage across the open terminals is zero. A variable voltage source (autotransformer) is connected to the series-connected secondary-windings.

When the variable voltage applied to the secondary-circuit is zero (short-circuited), the secondary emf's of the two transformers balance each other and they behave as an open-circuit with respect to primary. The currents in the two primary-windings will be equal to their no-load currents and the supply circuit will furnish the core losses of the two transformers.

With respect to the supply on the secondary side the primaries are short-circuited. Therefore, if the secondary voltage is gradually increased any desired amount of current may be made to flow in both the windings of the two transformers. The wattmeter connected in the secondary circuit will read the copper losses of the two transformers corresponding to the current circulated. It may be noted that this current does not affect the current drawn from the source on the primary side. The primary-side wattmeter will continue to read the iron losses of the two transformers. Thus in the Sumpner's test, the transformers are subjected to both iron and copper losses even though the transformers are not actually loaded.

Let V_P, I_P and W_P be the readings of voltmeter, ammeter and wattmeter of the primary side respectively and V_s, I_s and W_s be the readings of voltmeter, ammeter and wattmeter of the secondary side, respectively. The performance parameters of the transformer may be obtained as follows:
The iron-loss of each transformer is given by

$$P_i = \frac{W_p}{2} \tag{3.3.1}$$

The full-load copper loss of each transformer is given by

$$P_c = \left(\frac{I_{rs}}{I_s}\right)^2 \frac{W_s}{2} \tag{3.3.2}$$

Where I_{rs} is the rated current of the secondary winding.
The efficiency of transformer at a per unit load x (ratio of actual current to full-load current) is given by

$$\eta = \frac{S\,x\cos\phi}{S\,x\cos\phi + P_i + x^2 P_c} \tag{3.3.3}$$

Where S is VA rating of each transformer and $\cos\phi$ is the power factor of the load.
The equivalent leakage-impedance of each transformer referred to secondary side is given by

$$Z_2 = \frac{V_s/2}{I_s} \tag{3.3.4}$$

The equivalent-resistance of each transformer referred to secondary side is given by

$$R_2 = \frac{W_s/2}{I_s^2} \tag{3.3.5}$$

The equivalent leakage-reactance of each transformer referred to secondary side is given by

$$X_2 = \sqrt{Z_2^2 - R_2^2} \tag{3.3.6}$$

The percentage voltage-regulation of the transformer for power factor $\cos\phi$ is given by

$$VR = \frac{I_{rs}}{V_{rs}}\left(R_2\cos\phi \pm X_2\sin\phi\right)\times 100 \tag{3.3.7}$$

where V_{rs} is the rated secondary voltage of each transformer. Moreover, positive (+) and negative (−) signs refer to lagging and leading power-factors, respectively.

EXPERIMENTAL SETUP

In the primary-side circuit, rated voltage is to be applied. The rated voltage may be applied through a variable auto transformer. The voltmeter and the pressure coil of the wattmeter should be rated for a voltage more than the rated voltage of the transformer winding. The current drawn by the primary-side circuit is twice the no-load current of each transformer. As the no-load current of a transformer is of the order of 5% for large and medium size transformer and of the order of 10% for small transformer, the ammeter and current coil of the wattmeter should be of suitable range, say, 25% of the full-load current of the transformer. The wattmeter should be of low power factor (e.g. 0.2 power factor) to give enough deflection.

The voltage required by the secondary circuit to circulate full-load current in the transformer is usually in the range of 10-20% of the rated voltage of the secondary winding of the transformers. A variable auto transformer may be used to supply the reduced voltage. The voltmeter should be suitably rated to accurately read this small voltage. A digital voltmeter may be used to measure this small voltage. The pressure coil of the wattmeter should also be rated for low voltage (about 20% of the rated secondary voltage). The current drawn by the secondary circuit is the rated secondary current of the transformer. The ammeter and current coil of the wattmeter should be rated for somewhat more than the rated secondary current of the transformer.

PROCEDURE

(i) Make the connections on the primary side, as shown in Fig. 3.3.1, using instruments of appropriate ratings.

(ii) Join together one secondary-terminal of each transformer. Between remaining two terminals of secondary windings connect a voltmeter of a range double the secondary rated voltage.

(iii) Apply the rated voltage on primary side. If the voltmeter connected on the secondary side reads zero (or almost zero) the secondary windings are in series-opposition.

(iv) If the voltmeter reading is not zero, switch off the supply, interchange one of the secondary terminals and again connect the same voltmeter between the open terminals. It should now read zero when rated voltage is applied on the primary side.

(v) Switch-off the supply and complete the connections on the secondary side as shown in the Fig. 3.3.1 using instruments of appropriate ratings. If the rating of the current coil of the available wattmeter is less than the rated current of the secondary side, a current transformer of suitable current transformation ratio may be used as shown in Fig. 3.3.2.

(vi) Apply rated voltage on the primary side and note down the readings of different meters on the primary side.

(vii) Gradually increase the input voltage of the secondary-circuit from zero. Record the readings of voltmeter, ammeter and wattmeter of the secondary side for 25%, 50%, 75%, and 100% of the full-load current of the secondary windings of the transformers.

OBSERVATIONS

Primary side

Voltmeter reading V_p =………………..

Ammeter reading I_p =…………………

Wattmeter reading W_p =………………..

Secondary side

S.No.	Voltmeter reading V_s	Ammeter reading I_s	Wattmeter reading W_s

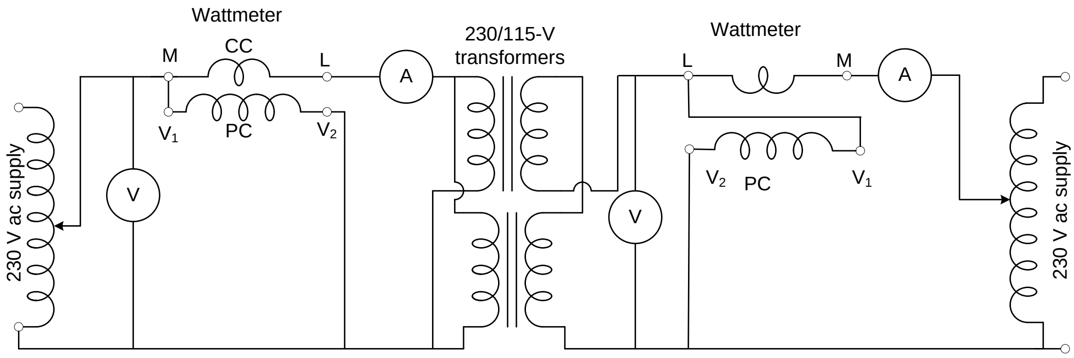


Fig. 3.3.1 Circuit diagram for the Sumpner's test

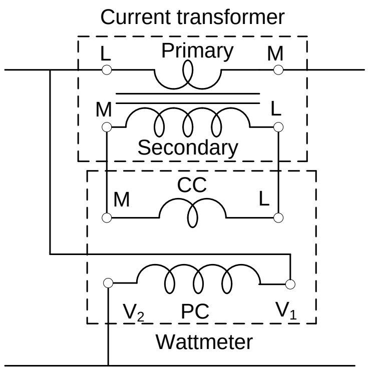


Fig. 3.3.2 Connection of wattmeter with a current transformer.

REPORT

(i) Use Eq. (3.3.1) to calculate iron loss of each transformer.

(ii) Series parameters and full-load copper loss of the transformers may be determined and tabulated as follows:

S.No.	$Z_2 = \frac{V_s/2}{I_s}$	$R_2 = \frac{P_s/2}{I_s^2}$	$X_2 = \sqrt{Z_2^2 - R_2^2}$	$P_c = \left(\frac{I_{rs}}{I_s}\right)^2 \frac{W_s}{2}$
		Mean R_2 =...	Mean X_2 =...	Mean P_c =....

(iii) With iron loss P_i and mean value of P_c (as obtained in ii), use Eq. (3.3.3) to obtain efficiency of the transformer for different values of x at the given power factor.

(iv) With mean values of R_2 and X_2, use Eq. (3.3.7) to obtain voltage regulation of the transformer at the specified power factors.

SAMPLE QUESTIONS

1. Why is it necessary to have two identical transformers to perform the Sumpner's test?
2. Give range and ratings of the instruments needed to perform Sumpner's test on 11kV/230V, 250kVA, single-phase transformer if
   (i) HV windings are connected in parallel and LV windings in series opposition.
   (ii) LV windings are connected in parallel and HV windings in series opposition.
3. What is the advantage of Sumpner's test over open-circuit and short-circuit tests?
4. How full-load steady state temperature rise is determined using Sumpner's test? Is there any other method to determine the temperature rise? If yes, then what are the advantages of Sumpner's test?

EXPERIMENT 3.4

PARALLEL OPERATION OF SINGLE-PHASE TRANSFORMERS

OBJECT

To connect and operate two single-phase transformers in parallel and to plot
(a) currents shared by the two transformers against the load-current
(b) powers shared by the two transformers against the output power.

THEORY

Two transformers may be connected in parallel by connecting their primary windings in parallel to the supply and their secondary windings in parallel to a common load as shown in Fig. 3.4.1. The dots shown on the windings of the two transformers indicate the in-phase points. The two secondary windings form a closed path. For the polarities of the induced voltages, shown in Fig. 3.4.1, the net voltage in the closed path is $E_{2A} - E_{2B}$.

In order to avoid any circulating current in the local circuit of the secondary windings, the voltages induced in the secondary windings must cancel each other. To fulfill this condition, the two transformers should have exactly the same turn ratios. Moreover, the two secondary windings must be connected such that induced voltages in these windings are in phase opposition. In other words, the secondary terminals with same instantaneous polarity must be connected together to a terminal of the load.

For full utilization of the transformers, the load shared by the two transformers must be proportional to their ratings. For this, their percentage (or per unit) equivalent impedances should be same.

EXPERIMENTAL SETUP

The experimental setup consists of two 230/115-V transformers A and B, as shown in Fig. 3.4.2. The transformer A is rated for 2-kVA and the transformer B is rated for 3-kVA. An autotransformer is used to apply rated voltage to the primaries of the two transformers. The autotransformer should have a kVA rating at least equal to the combined kVA ratings of the two transformers under test (5-kVA in the present case). The voltmeters on the primary and secondary sides should be rated for the voltage ratings of the respective windings. The voltmeter Vs, used for polarity check, should have a voltage rating double the rated voltage of the secondary windings. The two wattmeters should be rated for equal to or more than secondary rated voltage

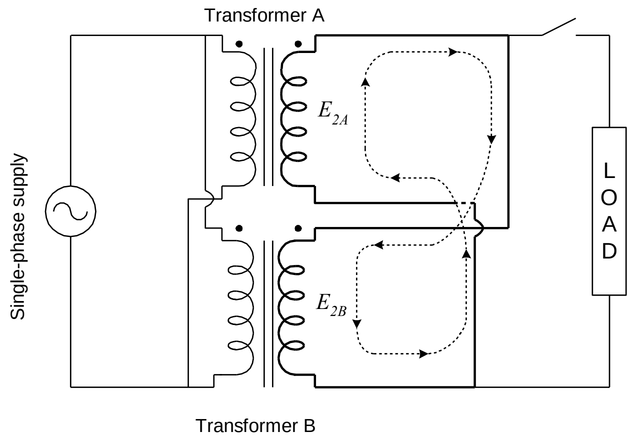


Fig. 3.4.1 Flow of circulating current in a transformer

and currents of the two transformers. A parallel combination of a rheostat-load and a lamp-load is used to load the transformers.

PROCEDURE

(i) Make the connections on the primary side as shown in Fig. 3.4.2. This will connect the two primary windings in parallel.
(ii) Connect one secondary-terminal of transformer A with one secondary-terminal of transformer B. Connect a voltmeter V_s, rated for at least twice the rated secondary voltage of the transformers, across the other two terminals of the secondary side.
(iii) Switch-on the supply and apply rated voltage on the primary side. Observe the voltmeter reading. For proper parallel operation, the voltmeter should read zero or near zero.
(iv) If the voltmeter does not read zero, switch-off the supply and interchange the connections on the secondary side. Again switch-on the supply and observe the voltmeter reading. The voltmeter will now read zero or near zero.
(v) Switch-off the supply, remove the voltmeter V_s and complete the secondary side connections as shown in Fig. 3.4.2, using instruments of appropriate ratings.
(vi) Keep the load-switch off and apply the rated voltage to the primary side. Record the readings of the ammeters. This will give the value of no-load circulating current.
(vii) Load the transformers gradually. Keep the primary side voltage constant at its rated value with the help of the autotransformer and record the readings of the different meters.

OBSERVATIONS

Primary side voltage =…..
No-load circulating current =…..

S.No.	Transformer A		Transformer B		Load		
	Ammeter reading I_A	Wattmeter reading W_A	Ammeter reading I_B	Wattmeter reading W_B	Voltmeter reading V_L	Ammeter reading I_L	Output power $P_o = V_L I_L$

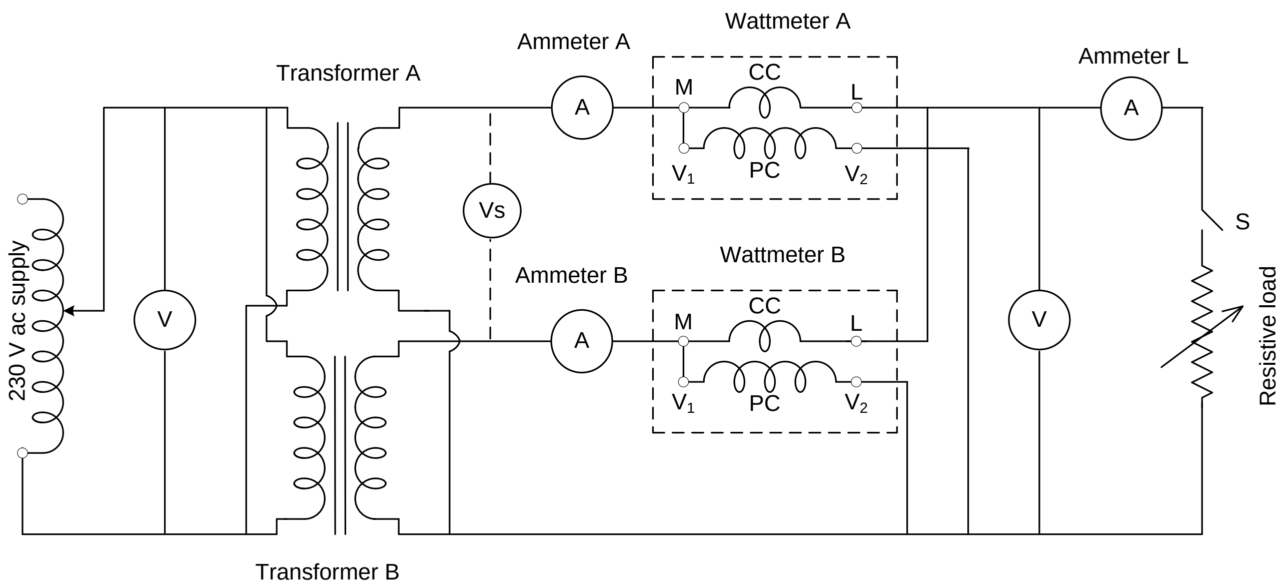


Fig. 3.4.2 Circuit diagram for the parallel operation of transformers

REPORT

Plot the following curves:

(i) I_A and I_B versus I_L

(ii) W_A and W_B versus P_o

SAMPLE QUESTIONS

1. Do the two transformers carry the load in proportion to their kVA ratings? If not, give the reason.
2. If the load is increased gradually, which transformer will first reach its rated kVA?
3. What are the conditions for parallel operation of two three-phase transformers? What are the consequences of violating these conditions?

EXPERIMENT 3.5

STUDY OF VARIOUS THREE-PHASE TRANSFORMER CONNECTIONS

OBJECT

To phase out six secondary windings of a 3-phase transformer and to connect these windings in (a) star (b) delta and (c) zig-zag star.

THEORY

In a 3-phase transformer there are three primary windings and three secondary windings. These winding are connected in star, delta or zig-zag star.

In star connection, one terminal of each winding is connected together to form a neutral terminal 'n' in such a way that the voltage across any pair of the open terminals is $\sqrt{3}$ times the voltage across any of the three windings. A star-connected winding and its phasor diagram are shown in Fig. 3.5.1. Here, V_a, V_b, and V_c are the three phase voltages, each of magnitude V_p and V_{ab}, V_{bc}, and V_{ca} are the three line voltages, each of magnitude V_L. It may be observed that in star connection the line voltage is $\sqrt{3}$ times the phase voltage whereas the line and phase currents are equal. Moreover, there is a time phase difference of 120 degrees between the phase quantities and also between the line quantities.

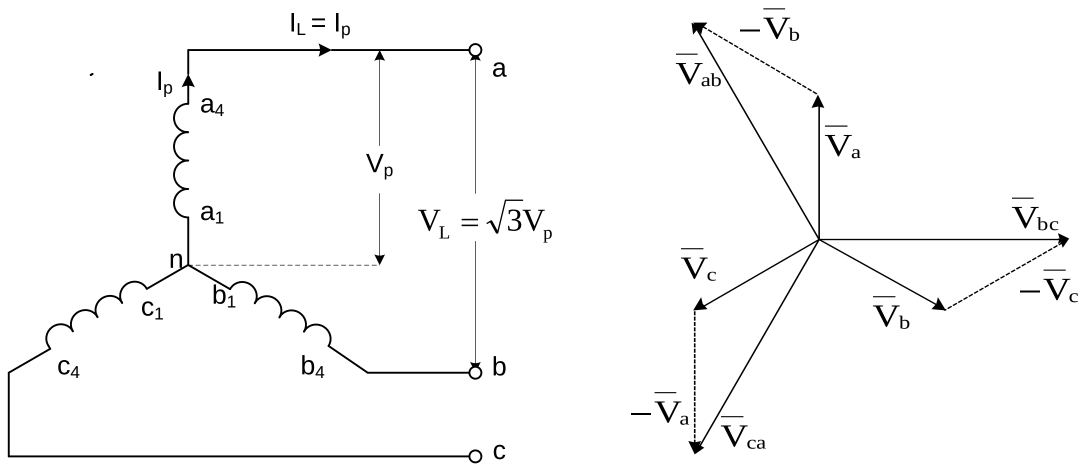
In delta connection, the three windings are connected to form a closed path such that the total voltage in the closed path is zero, as shown in Fig. 3.5.2. In a delta-connected winding, the line voltage is equal to the phase voltage whereas the line current is $\sqrt{3}$ times the phase current.

In zig-zag star connection, the winding of each phase is divided into two equal halves (a_1a_2 and a_3a_4 for phase-a, b_1b_2 and b_3b_4 for phase-b, c_1c_2 and c_3c_4 for phase-c). Each leg of the star connection is formed by connecting two halves from two different phases so that the resultant line to neutral voltage ($V_{p\text{-}zz}$) is $\sqrt{3}$ times the voltage of each half $(V_p/2)$, as shown in Fig. 3.5.3. The line-to-line voltage may be obtained as

$$V_L = \sqrt{3} \times V_{p-zz} = \sqrt{3} \times \left(\sqrt{3} V_p / 2\right) = \frac{3}{2} V_p$$

EXPERIMENTAL SETUP

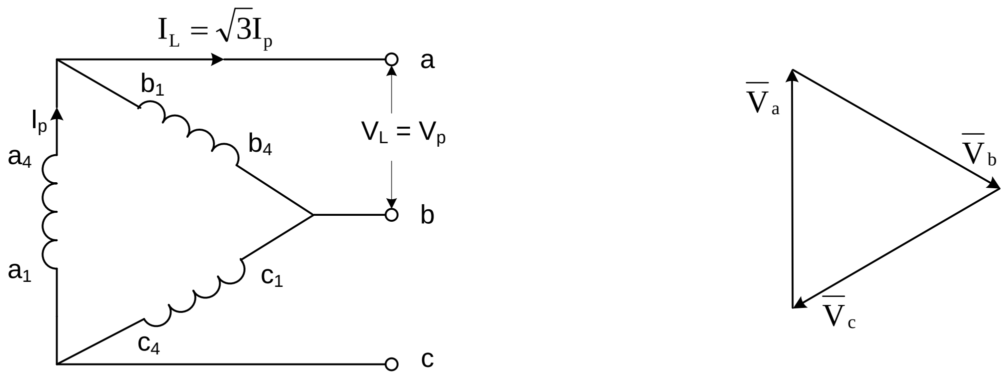
In the experimental setup, the primary windings of a 3-phase transformer are connected in delta. Each of the three secondary windings is divided into two equal halves. Hence there are six



(a) Connection

(b) Phasor diagram

Fig. 3.5.1 Star-connected winding



(a) connection

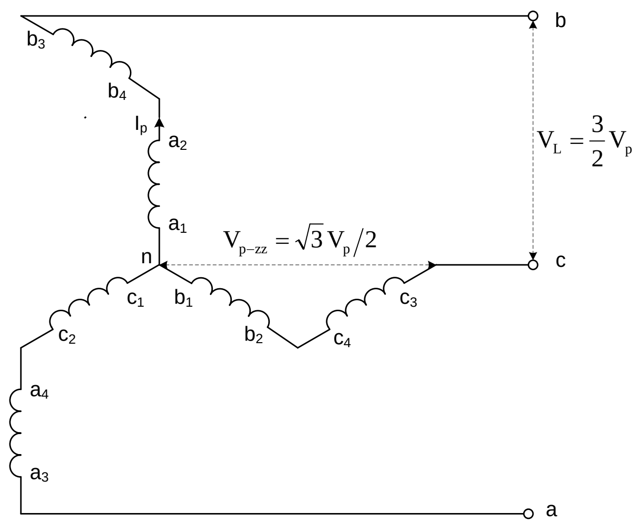
(b) phasor diagram

Fig. 3.5.2 Delta-connected winding

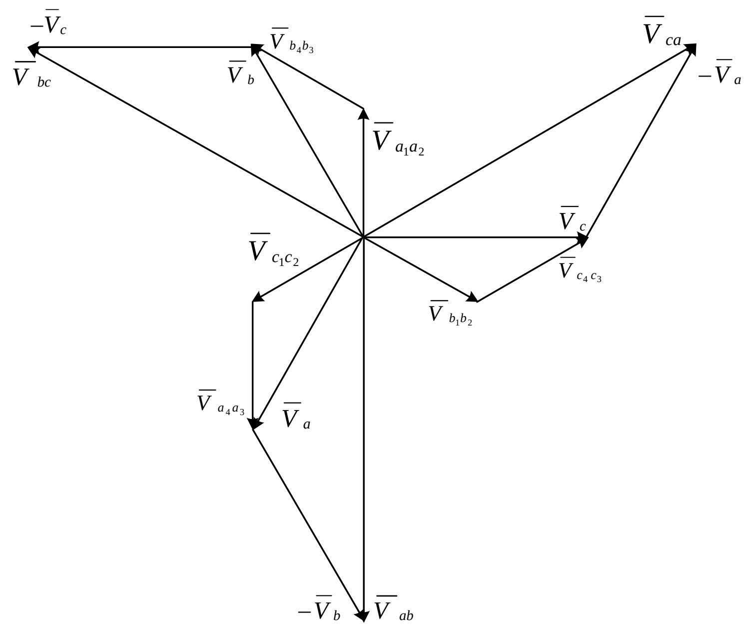
windings on the secondary side (two from each phase). From these six windings, twelve terminals are brought out.

PROCEDURE

(i) **To find the terminals of the same winding:**
Connect the primary to the three-phase supply. Connect a voltmeter across any two of the secondary terminals. If the voltmeter has some deflection, the two terminals belong to the same winding. If the voltmeter does not have any deflection, then these two terminals are not from the same winding. Discard this pair. Identify the six pairs of terminals of the six secondary windings. Record the voltages across these windings



(a) Connection



(b) phasor diagram

Fig. 3.5.3 Zig-zag star connected winding

(ii) **To find out the windings of the same phase:**

Connect any two windings in series and measure the voltage across them. If the voltmeter reads zero or double the voltage of each winding then the two windings belong to the same phase. Thus separate the two windings of each phase. Connect the two windings of each phase in series such that the total voltage is twice that of one winding. Repeat the procedure for the other windings and sort out the winding of the three phases (a_1a_4, b_1b_4 and c_1 c_4). Record the voltage across the winding of the each phase (phase-voltage).

(iii) **To connect the three secondary windings in star:**
Take any two windings, join two terminals together and connect the voltmeter across the other two terminals. If this voltage is $\sqrt{3}$ times the phase voltage, the two windings are correctly connected in star. If the voltage is not equal to $\sqrt{3}$ times the phase voltage, interchange the terminals of any of the two phase windings. The terminals joined together form the star-point. Join one terminal of the third winding to the star-point and connect the voltmeter between the other terminal and one of the other two phase terminals. If the voltage is $\sqrt{3}$ times the phase voltage the connection is correct, otherwise interchange the terminals of the third windings. Record the three line-voltages.

(iv) **To connect the secondary windings in delta:**
Disconnect the star connection of secondary windings. Take any two windings, join two terminals together and connect voltmeters across the other two. If the voltage is equal to the phase voltage then the connection is correct, otherwise interchange the terminals of any of the two windings. Now, join one terminal of the third winding in series with the above combination and connect a voltmeter across the two open terminals. If the voltmeter reads zero voltage, then the connection is correct, otherwise interchange the terminals of the third winding. Disconnect the voltmeter (which now reads zero) and join the open ends of the windings. It forms a delta connection.

(v) **To connect the secondary winding in zig-zag**:
After step (i), there are six windings, two for each phase. A voltage across each winding is half the secondary phase voltage (i.e. $V_p/2$). Connect one set of secondary windings in star as in step (iii) with phase voltages as ($V_p/2$) and line voltages as $\sqrt{3}V_p/2$. Now connect one of the remaining three windings in series with one of the phase terminals of the star. Measure the voltage between the neutral points and the other terminal of the above winding. If the voltage is $\sqrt{3}V_p/2$, the winding is correctly connected in zig-zag star. If the voltage is not equal to $\sqrt{3}V_p/2$, interchange the connection. Repeat the procedure to connect the remaining two windings in series with the other phase terminals of the star. Record the three phase voltages and the three line voltages.

OBSERVATIONS

To find the terminals of same winding

Mark the terminals between which the voltmeter has some deflection as 1-1′, 2-2′, 3-3′, 4-4′, 5-5′, and 6-6′. Record the following voltages:
$V_{11'}$ = ….., $V_{22'}$ = ….., $V_{33'}$ = ….., $V_{44'}$ = ….., $V_{55'}$ = ….., $V_{66'}$ = …..

To find the windings of same phase

S. No.	Terminals shorted	Terminals between which, voltmeter is connected	Voltmeter reading	Inference

To connect the windings in star

Connect the winding in star. Mark the star point winding-terminals as a_1, b_1, and c_1 and the open-end terminals (line terminals) as a_4, b_4, and c_4 and record :
Phase voltages: $V_{a_1-a_4} = ...$, $V_{b_1-b_4} = ...$, $V_{c_1-c_4} = ...$
Line voltages: $V_{a_4-b_4} = ...$, $V_{b_4-c_4} = ...$, $V_{c_4-a_4} = ...$

To connect the winding in delta

S. No.	Terminals shorted	Terminals between which, voltmeter is connected	Voltmeter reading	Inference

Phase voltages: $V_{a_1-a_4} = ...$, $V_{b_1-b_4} = ...$, $V_{c_1-c_4} = ...$
Line voltages: $V_{a_1-a_4} = ...$, $V_{b_1-b_4} = ...$, $V_{c_1-c_4} = ...$

To connect the winding in zig-zag star

S. No.	Terminals shorted	Terminals between which, voltmeter is connected	Voltmeter reading	Inference

Phase voltages:
Line voltages:

REPORT

For the observed values of the different phase voltages, draw the phasor diagrams for all the connections and determine the line voltages and compare with the observed values. Assume 120° phase difference between the three phases.

SAMPLE QUESTIONS

1. What are the relative advantages and disadvantages of different three-phase transformer connections?
2. If voltages across two each half of the secondary windings is known to be 50 volts, what are the possible voltages across the open terminals in case
   (i) two halves of two different phases are connected in series,
   (ii) two halves of the same phase are connected in series.

EXPERIMENT 3.6

PHASE-TRANSFORMATION

OBJECT

To convert a three-phase supply into (i) single-phase supply (ii) two-phase supply and (iii) six-phase supply.

THEORY

In a balanced poly-phase system all the voltages are equal in magnitude. In a 2-phase system, the two phase-voltages have a time-phase difference of 90 degrees. In a 3-phase system the phase difference between any two phase-voltages is 120 degrees. In a 6-phase system, any two adjacent phase-voltages have a time-phase difference of 60 degrees. In an *n*-phase system, any two adjacent, voltages have a time-phase difference of $\frac{360}{n}$ degrees.

Single-phase, two-phase and six-phase supplies may be obtained from a three-phase supply as follows:

Three-phase to single-phase transformation

Three-phase to single-phase transformation is required to distribute a large single-phase load in the three phases of a three-phase supply system. For this transformation a three-phase transformer may be connected as shown in Fig. 3.6.1. The single-phase voltage obtained at the output is twice the secondary phase voltage as shown in the phasor diagram of Fig. 3.6.2.

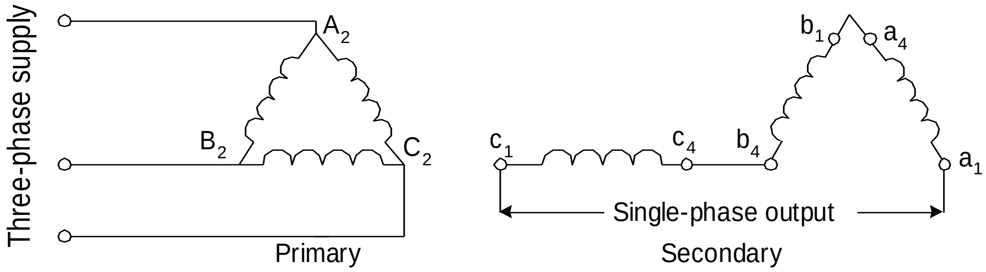


Fig. 3.6.1 Three-phase to single-phase transformation

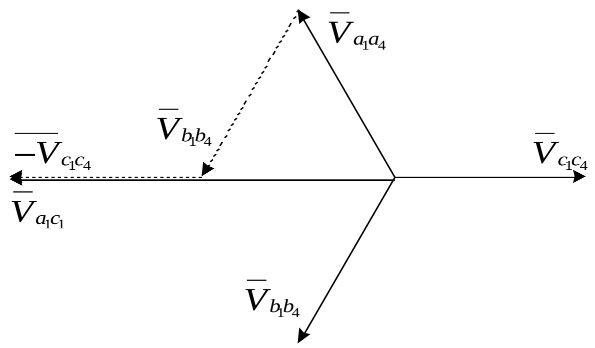


Fig. 3.6.2 Phasor diagram for three-phase to single-phase transformation

Three-phase to six-phase transformation

For three-phase to single-phase transformation, a three-phase transformer with its secondary windings divided in two equal halves should be available. The primary windings are delta-connected, as shown in Fig. 3.6.1. One set of three-phase secondary winding is connected in normal star, while the other set is connected in inverted star. Both star points are joined together to obtain six-phase balanced supply, as shown in Fig. 3.6.3. The resulting connection is called double star connection. This type of connection is employed in rectifier circuits, where a path for dc current is needed.

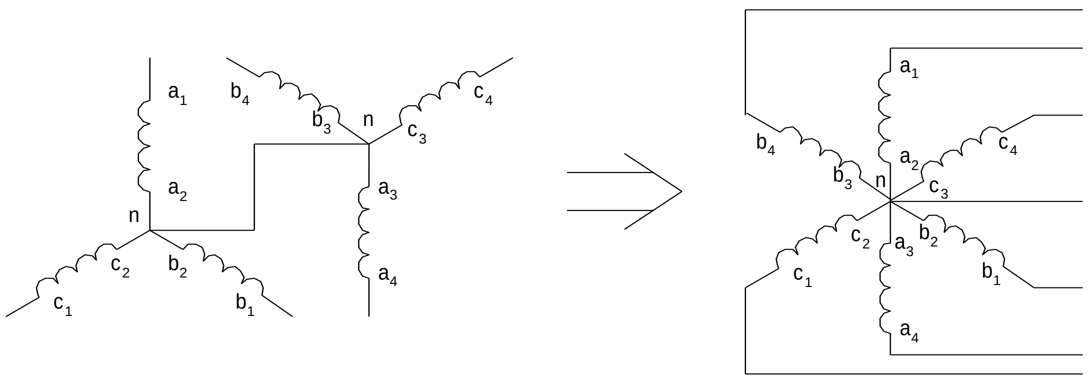


Fig. 3.6.3 Secondary winding connection for three-phase to six-phase transformation

Three-phase to two-phase transformation

Three-phase to two-phase transformation is needed in special cases, such as in supplying two-phase electric arc furnaces. For this transformation, two single-phase transformers are used. One of them is called the main transformer and the other is called the teaser transformer. Primary of the main transformer must be center-tapped. One of the terminals of the primary of the teaser transformer is connected to the center tapping of the primary of the main transformer. The three-phase supply is given to these transformers as shown in Fig. 3.6.4. The resulting connection is called Scott connection.

The voltage across the primary of the main transformer is the line-to-line voltage of the three-phase supply. The voltage across the primary of the teaser transformer may be written as

$$\bar{V}_{AM} = \bar{V}_{AC} - \frac{\bar{V}_{BC}}{2} = -\bar{V}_{CA} - \frac{\bar{V}_{BC}}{2} \tag{3.6.1}$$

The phasor-diagram of Fig. 3.6.5 shows that the voltages across the two primaries, $\bar{V}_{AM}$ and $\bar{V}_{BC}$ have a phase difference of 90 degrees. If V_L is the line value of the supply voltage, the magnitude of the voltage $\bar{V}_{AM}$ can be shown to be $\frac{\sqrt{3}}{2}V_L$. The voltages across the two secondary windings, $\bar{V}_{a_1a_2}$ and $\bar{V}_{b_1b_2}$, have a phase difference of 90 degrees from each other. The magnitude of $\bar{V}_{a_1a_2}$ may be obtained as

$$\bar{V}_{a_1a_2} = V_{AM} / a_T$$

or

$$\bar{V}_{a_1a_2} = \frac{\sqrt{3}}{2}V_L \Big/ a_T \tag{3.6.2}$$

where a_T is the turn ratio of the teaser transformer.

The magnitude of the of $\bar{V}_{b_1b_2}$ may be obtained as

$$\bar{V}_{b_1b_2} = \frac{V_L}{a_M} \tag{3.6.3}$$

where a_M is the turn ratio of the main transformer.

For a balanced two-phase supply, the two voltages must have same magnitude. Therefore, from equations (3.6.2) and (3.6.3)

$$\frac{\frac{\sqrt{3}}{2}V_L}{a_T} = \frac{V_L}{a_M}$$

Or

$$a_T = \frac{\sqrt{3}}{2}a_M \tag{3.6.4}$$

Therefore, for balanced three-phase to two-phase transformation, the turn ratio of the teaser transformer should be $\sqrt{3}/2$ times the turn ratio of the main transformer.

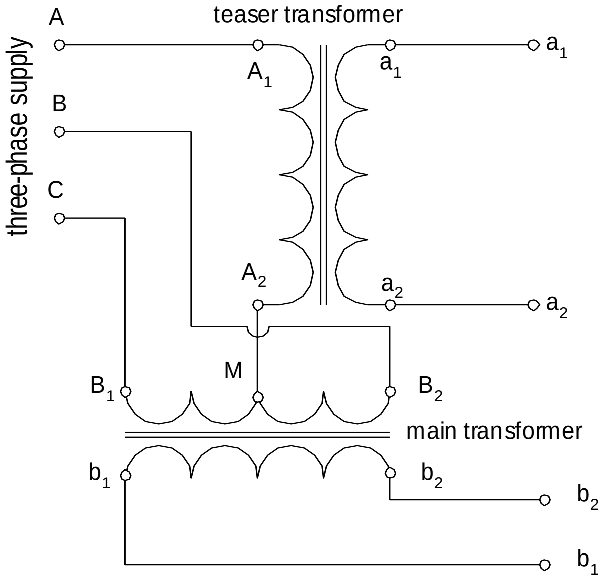


Fig. 3.6.4 Scott-connected transformers

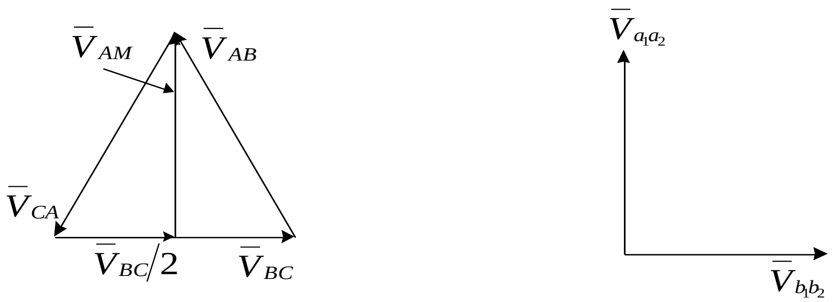


Fig. 3.6.5 Phasor diagram for three-phase to two-phase transformation

Therefore, for balanced three-phase to two-phase transformation, the turn ratio of the teaser transformer should be $\sqrt{3}/2$ times the turn ratio of the main transformer.

PRCEDURE AND OBSERVATIONS

Three-phase to single-phase transformation

Connect the secondary windings of the three-phase transformer as shown in Fig. 3.6.1. Connect the delta-connected primary to the three-phase supply. Record the voltages across the three secondary windings and the singe-phase output voltage.
The three secondary-windings voltages are

$$V_{a_1 a_4} = \ldots\ldots,\ V_{b_1 b_4} = \ldots\ldots,\ V_{c_1 c_4} = \ldots\ldots$$

And the single-phase output voltage is

$V_{a_1 c_1} =$

Three-phase to six-phase transformation

Make the connections as shown in Fig. 3.6.3 and record the phase and line voltages of the six-phase output voltage.
The phase voltages are
$V_{a_2 a_1}$ = ….., $V_{b_3 b_4}$ = ….., $V_{c_2 c_1}$ = ….., $V_{a_3 a_4}$ = …….., $V_{b_2 b_1}$ = …….., $V_{c_3 c_4}$ = ……..

The line voltages are
$V_{a_1 b_4}$ = ….., $V_{b_4 c_1}$ = ….., $V_{c_1 a_4}$ = ….., $V_{a_4 b_1}$ = …….., $V_{b_1 c_4}$ = …….., $V_{c_4 a_1}$ = ……..

Three-phase to two-phase transformation

Make the connections as shown in Fig. 3.6.4. Record the following voltages.
Line voltages on the primary side:
V_{AB} =……, V_{BC} =……, V_{CA} =……,
Voltage across primary of the main transformer: $V_{B_1, B_2} = V_{BC}$ = …..

Voltage across primary of the teaser transformer = $V_{A_1, A_2} = V_{AM}$ = …..

Secondary phase voltage: $V_{a_1 a_2}$ =….., $V_{b_1 b_2}$ =…….

Connect terminals a_2 and b_2 and measure the voltage $V_{a_1 b_1}$. If the output voltage is balanced, the voltage $V_{a_1 b_1}$ will be equal to $\sqrt{2}$ times the secondary phase voltage.

REPORT

For the observed values of the different phase voltages, draw the phasor diagrams for all the cases and determine the line voltages and compare with the observed values. Assume 120^{o} phase difference between the three phases.

SAMPLE QUESTIONS

1. Mention a few applications of different types of conversions.
2. In Scott connected transformers, are the iron losses for the main and teaser transformers equal? If so, why?
3. A 400 V, 3-phase supply is to be transformed into a 100 V, 2-phase supply using Scott connected transformers. What should be the turn ratios of the two transformers?

4

Experiments on Induction Machines

EXPERIMENT 4.1

LOAD TEST OF THREE-PHASE INDUCTION MOTOR

OBJECT

To perform load test on a three-phase induction motor and determine full-load slip and full-load torque of the motor and plot the following curves:

(a) Speed versus torque.
(b) Efficiency versus output power.
(c) Torque versus slip.
(d) Power-factor versus output power.

THEORY

When a balanced three-phase supply is given to the stator winding of a three-phase induction motor, a rotating magnetic field is produced in the air-gap. The speed of rotation of this magnetic field is called synchronous speed of the machine. It is given by

$$n_S = \frac{120\,f}{P} \text{ rpm} \tag{4.1.1}$$

Where f is the supply frequency in Hz. and P is the number of poles in the machine.

The rotating magnetic field links with the rotor conductors to induce an emf in it. As the rotor conductors form close circuits, induced currents start flowing in these conductors. These induced currents act in conjunction with the rotating magnetic field and a torque is developed. The rotor starts rotating in the direction of torque at a speed slightly less than the synchronous speed. The difference between the speed of the rotating field and that of the rotor, as a ratio of the synchronous speed, is called slip. It is given by

$$s = \frac{n_s\text{-}n}{n_s} \tag{4.1.2}$$

Where n is the speed of the rotor for a given load.

The full-load slip may be obtained as

$$s_{fl} = \frac{n_s\text{-}n_{fl}}{n_s} \tag{4.1.3}$$

Where n_{fl} is the full-load speed of the motor.

The motor may be loaded by applying mechanical or friction brakes using a pulley-belt arrangement. In this arrangement, a pulley is coupled to the motor shaft. The load applied is through friction of a belt. Tightening the belt may increase the load. The tensions on the two sides of the belt can be recorded using two spring balances. The output torque T (in Newton-meter), may be calculated as

$$T = (T_1 - T_2) \times R \times g \tag{4.1.4}$$

Where T_1 and T_2 are the tensions on the two sides of the belt in kgf, R is the radius of the pulley in meters and g is acceleration due to gravity. It may be taken as 9.81 m/sec^2.

The output power of the motor, for load torque T and speed n, can be obtained as

$$P_{out} = \frac{2 \times \pi \times n \times T}{60} \text{ Watts} \tag{4.1.5}$$

Efficiency of the machine is defined as the percentage of output power and input power. It may be written as

$$\eta = \frac{P_{out}}{P_{in}} \times 100 \tag{4.1.6}$$

The input power P_{in}, can be measured using either one-wattmeter method or two-wattmeter method. If W_1 and W_2 are the two readings of the wattmeter, then the algebraic addition of W_1 and W_2 will give total input power. The input power-factor may be obtained using the following relation:

$$p.f. = \cos\left(\tan^{-1}\sqrt{3}\,\frac{W_1 - W_2}{W_1 + W_2}\right) \tag{4.1.7}$$

EXPERIMENTAL SETUP

In load test the rated voltage is to be applied to the motor. The rated voltage may be applied to the primary with the help of a three-phase variable auto transformer. The kVA rating of the autotransformer should be equal to or more than the motor under test. The motor may be loaded by applying mechanical or friction brakes using a pulley-belt arrangement.

The power input to the motor may be measured using one-wattmeter method as described in section 2.4.2. The wattmeter must have a pressure coil rated for at least the rated line voltage of the motor. The current is to be varied from very low value to the rated value. Therefore the current coil of the wattmeter should be rated at least for the rated current of the motor. For accurate measurement of power at low values of current, lower rating current coil may be used. For this a wattmeter with multi range current coil should be preferred. The voltmeter and ammeter should be rated for equal to or more than the rated voltage and rated current of the motor, respectively.

PROCEDURE

(i) Make the connections as shown in Fig. 4.1.1 using instruments of appropriate ratings. Keep the motor on no-load by keeping loose the belt of the pulley-belt arrangement.

(ii) Apply rated voltage to the motor with the help of the autotransformer.

(iii) Load the motor gradually by tightening the belt, till the motor draws its rated current from the supply. Record the input voltage, the input current, the motor speed, the tensions in the springs and the supply frequency. To measure the input power, connect the terminal V_2 of the pressure coil of the wattmeter to the terminals B and C of the motor alternately and record the corresponding wattmeter readings W_1 and W_2. W_1 and W_2 may be positive or negative. Record these readings with signs. Algebraic addition of W_1 and W_2 will give the total input power.

(iv) Reduce the load on the motor gradually by loosening the belt. Record the various quantities as above, for different loads (up to no-load).

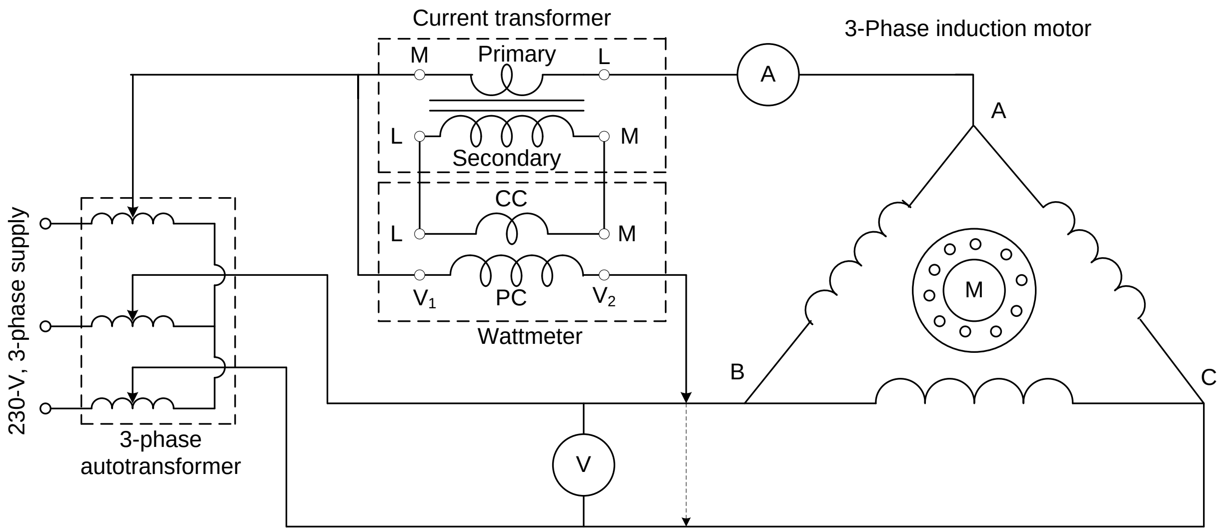


Fig. 4.1.1: Circuit for the load test of induction motor

OBSERVATIONS

Radius of the pulley R =

The readings for the different loads, from full-load to no-load, may be recorded and tabulated as follows:

S. No.	Voltmeter Reading V	Ammeter Reading I	Wattmeter readings		Tension		Speed n	Frequency f
			W_1	W_2	T_1	T_2		

REPORT

(i) Calculate the synchronous speed using equation (4.1.1)
(ii) Calculate the slip using equation (4.1.2)
(iii) Calculate the input power by algebraically adding the wattmeter readings W_1 and W_2 and multiplying by the multiplying-factor of the wattmeter (mf_W) and the CT ratio of the current-transformer (CT_{ratio}).

$$P_{in} = (W_1 + W_2) \times mf_W \times CT_{ratio}$$

(iv) Calculate the output torque using equation (4.1.4).
(v) Calculate the output power using equation (4.1.5).
(vi) Calculate the motor efficiency using equation (4.1.6).
(vii) Calculate the input power-factor using equation (4.1.7).

The calculated results, along with the relevant observations may be tabulated as follows:

S. No.	Motor speed n	Slip s	Input power P_{in}	Torque T	Output power P_{out}	Power factor $p.f.$	Efficiency η

From the tabulated results plot:
(i) Speed versus torque curve
(ii) Speed versus output power curve.
(iii) Torque versus slip curve.
(iv) Power factor versus output power curve.

The slip and torque corresponding to the first reading (for full-load current) give the full-load slip and full-load torque of the motor.

SAMPLE QUESTIONS

1. The power factor of induction motor increases as the motor is loaded from no-load to full-load. Explain with the help of suitable phasor diagram.
2. What are the different methods of loading a motor in a laboratory?

EXPERIMENT 4.2

NO-LOAD AND BLOCKED-ROTOR TESTS OF THREE-PHASE INDUCTION MOTOR

OBJECT

To perform no-load and blocked-rotor tests on a three-phase induction motor and determine its equivalent circuit parameters.

THEORY

The per-phase equivalent circuit of a three-phase induction motor is shown in Fig. 4.2.1. Here

r_1 is the per-phase resistance of the stator winding,

x_1 is the per-phase leakage reactance of the stator winding,

r_2' is the per-phase resistance of the rotor winding referred to the stator side,

x_2' is the per-phase leakage reactance of the rotor winding referred to the stator side,

r_c is the per-phase core-loss resistance,

x_m is the per-phase magnetizing reactance,

V_1 and I_1 are the per-phase stator voltage and current respectively,

I_2' is the per-phase rotor current, referred to the stator side,

I_o is the per-phase no-load stator current.

The parameters of the equivalent circuit may be obtained from the following tests;

(i) No-load test.
(ii) Blocked-rotor test.
(iii) DC test.

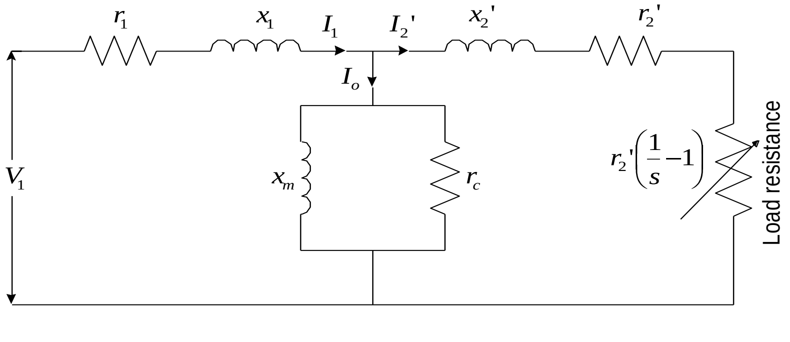


Fig. 4.2.1: Per phase equivalent circuit of three-phase induction motor

No-load test

In no-load test, the motor is run on no-load at rated voltage and frequency. The applied voltage V_{oL} (line to line), the current drawn I_{oL} (line current), and the three-phase power input to the motor (P_o) are recorded under this condition. As the motor is on no-load, it runs at a speed close to its synchronous speed and the motor slip is nearly equal to zero. The load resistance of the equivalent circuit of the motor (Fig. 4.2.1) tends to infinity and the equivalent circuit is simplified under this condition, as shown in Fig. 4.2.2. From the circuit, the shunt branch parameters may be evaluated.

The shunt branch impedance is given by

$$Z_o = \frac{V_{sh}}{I_o} \tag{4.2.1}$$

where V_{sh} is the voltage across the shunt branch and I_o is the per phase input current under no-load condition. If the small voltage drop in the stator winding impedance is neglected, V_{sh} is equal to the per phase input voltage V_o. With this approximation, Eq. (4.2.1) may be written as

$$Z_o = \frac{V_o}{I_o} \tag{4.2.2}$$

For the delta-connected motor, $V_o = V_{oL}$ and $I_o = I_{oL} \big/ \sqrt{3}$. Eq. (4.2.2) may be written as

$$Z_o = \frac{V_{oL}}{I_{oL} \big/ \sqrt{3}} \tag{4.2.3}$$

The core loss resistance is given by

$$r_c = \frac{V_{oL}^2}{P_{sh}} \tag{4.2.4}$$

Where P_{sh} is the power across the shunt branch. This may be evaluated by subtracting per phase stator copper loss from the per phase no-load input power $P_o/3$ as follows:

$$P_{sh} = \frac{P_o}{3} - \left(\frac{I_{oL}}{\sqrt{3}}\right)^2 \times r_1 = \frac{P_o - I_{oL}^2 \times r_1}{3} \tag{4.2.5}$$

Where r_1 is the stator winding resistance that may be determined by conducting DC test as explained later.

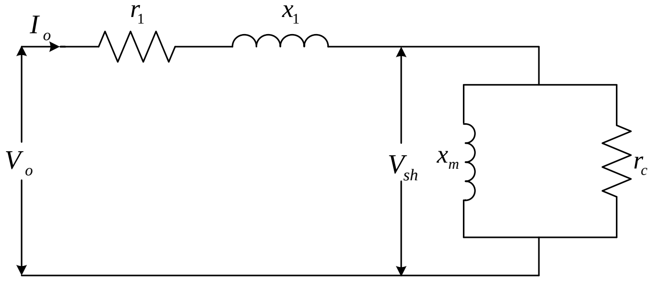


Fig. 4.2.2: Equivalent circuit under no-load condition

Using Eq. (4.2.5), Eq. (4.2.4) can be written as

$$r_c = \frac{3 \times V_{oL}^2}{P_o - I_{oL}^2 \times r_1} \tag{4.2.6}$$

The magnetizing reactance is given by

$$x_m = \frac{1}{\sqrt{\dfrac{1}{Z_o^2} - \dfrac{1}{r_c^2}}} \tag{4.2.7}$$

Blocked-rotor test

In blocked-rotor test, the rotor is mechanically blocked and a three-phase reduced voltage is applied to the stator winding so that the motor draws a current equal to or less than its rated current. The applied voltage V_{BR} (line to line), the current drawn I_{BR} (line current), and the three-phase power input to the motor (P_{BR}) are recorded under this condition.

Under blocked-rotor condition, the motor slip s is equal to unity and the load resistance of the equivalent circuit is short-circuited. Therefore, the voltage required to circulate the rated current under this condition is much less than the rated voltage. With this small voltage, the shunt branch current is very small and therefore, it may be neglected. The equivalent circuit of the motor reduces to a simple circuit as shown in Fig. 4.2.3. From the circuit, the per-phase series parameters of the delta-connected motor may be evaluated.

The blocked-rotor impedance of the motor is given by

$$Z_{BR} = \frac{\sqrt{3} V_{BR}}{I_{BR}} \tag{4.2.8}$$

The equivalent resistance of the motor is given by

$$R = \frac{P_{BR}}{I_{BR}^2} \tag{4.2.9}$$

The equivalent leakage- reactance of the motor is given by

$$X = \sqrt{Z_{BR}^2 - R^2} \tag{4.2.10}$$

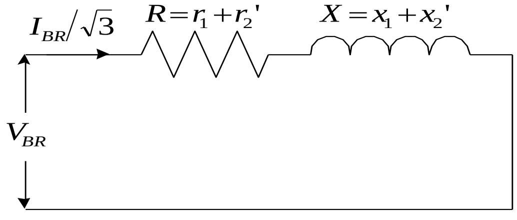


Fig. 4.2.3: Equivalent circuit under blocked-load condition

DC test

This test is performed to determine the stator winding resistance of the induction motor. In this test a small dc voltage is applied across any two terminals of the motor such that the motor draws a current, which is less than the rated current of the motor. The applied voltage V_{dc} and the current drawn I_{dc} are recorded. As the applied voltage is dc, the inductive reactance of the motor is zero. The equivalent circuit of the motor under this condition will be as shown in Fig. 4.2.4. From the circuit the dc stator winding resistance r_{1dc} may be obtained as

$$\frac{2}{3} r_{1dc} = \frac{V_{dc}}{I_{dc}} \Rightarrow r_{1dc} = \frac{3}{2}\frac{V_{dc}}{I_{dc}} \tag{4.2.11}$$

The stator winding resistance obtained using equation (4.2.11) is valid only for dc supply. For 50-Hz ac supply, r_{1dc} may be multiplied by 1.15 to take care of skin and proximity effects. Thus, the stator winding resistance for 50-Hz ac supply may be written as

$$r_1 = 1.15 \times \frac{3}{2}\frac{V_{dc}}{I_{dc}} \tag{4.2.12}$$

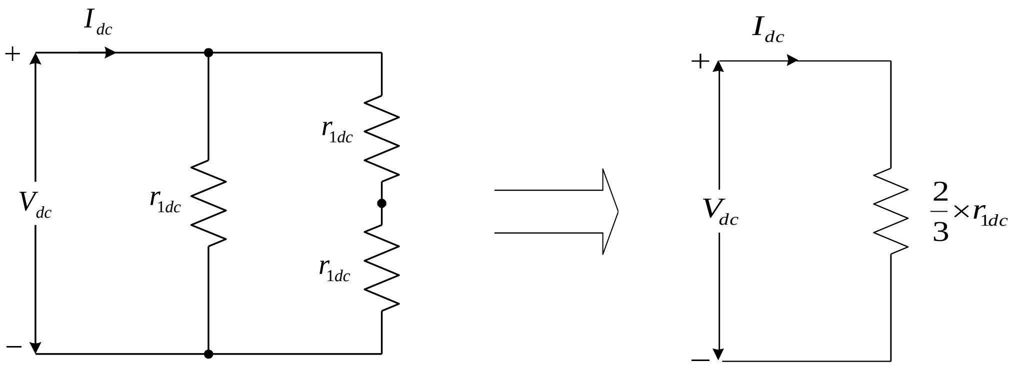


Fig. 4.2.4 Equivalent circuit of the motor for the DC test.

EXPERIMENTAL SETUP

In no-load test the rated voltage is to be applied to the motor. The rated voltage may be applied to the primary with the help of a three-phase variable auto transformer. The same autotransformer may be used to supply variable voltage in the blocked-rotor test. The autotransformer should have the secondary voltage and current more than the rated line voltage and current of the motor.

The power input to the motor may be measured using one-wattmeter method as described in section 2.4.2. For no-load test the voltmeter and the pressure coil of the wattmeter and must be rated for at least the rated line voltage of the motor. The ammeter and the current coil of the wattmeter should be rated for about 50% of the rated current of the motor. For blocked-rotor test the voltmeter and the pressure coil of the wattmeter and must be rated for about 50% of the rated line voltage of the motor. The ammeter and the current coil of the wattmeter should be rated for at least the rated current of the motor.

PROCEDURE

No-load test

(i) Make connections as shown in Fig 4.2.5.
(ii) Keep the motor on no-load and apply rated voltage to the stator with the help of the autotransformer.
(iii) Note down the readings of the ammeter and voltmeter. Connect the pressure coil terminal V_2 of the wattmeter to terminals B and C of the motor alternately and note down the corresponding readings W_1 and W_2.

Blocked-rotor test

(i) Block the rotor mechanically.
(ii) Increase the input voltage gradually by the autotransformer till the motor draws its rated current.
(iii) Note down the readings of the voltmeter and ammeter. Connect the pressure coil terminal V_2 of the wattmeter to terminals B and C of the motor alternately and note down the corresponding readings W_1' and W_2'.

DC test

Make the connections as shown in Fig. 4.2.6. Keeping the potential divider setting at zero, switch on the 230-V dc supply. Increase the dc input voltage to the motor gradually till the motor draws a current equal to or less than the rated current of the motor. Record the voltmeter reading V_{dc} and the ammeter reading I_{dc}.

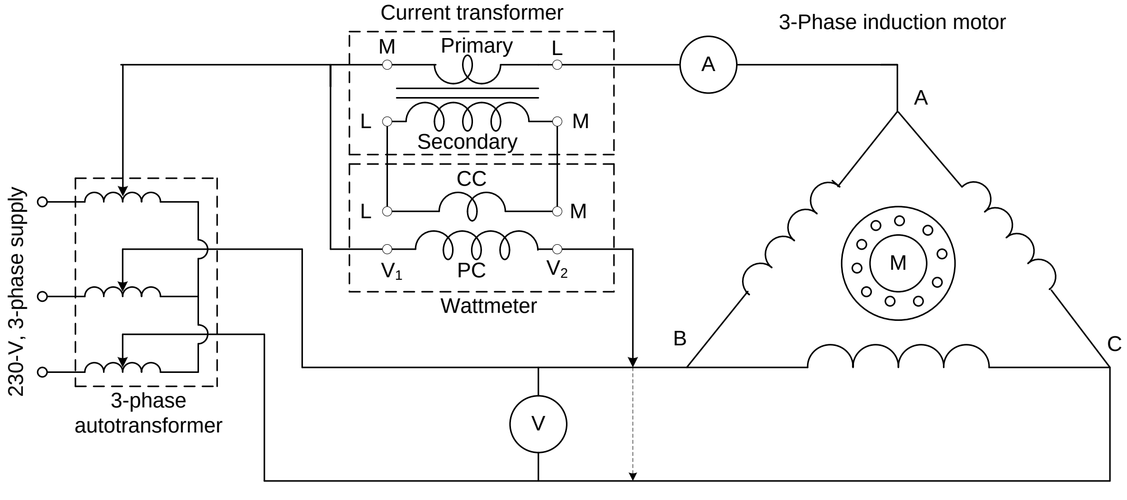


Fig. 4.2.5 Circuit diagram for the no-load and blocked rotor tests

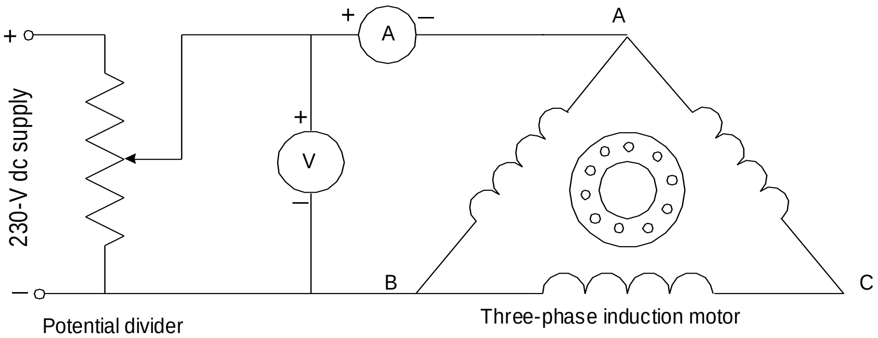


Fig. 4.2.6 Circuit diagram for the DC test

OBSERVATIONS

No-load test

Voltmeter reading V_{oL} =

Ammeter reading I_{oL} =

Wattmeter readings:

W_1 =…..(with sign)

W_2 =…..(with sign)

No-load input power

$$P_o = (W_1 + W_2) \times mf_W \times CT_{ratio} = \text{.........}$$

Where, mf_W is the multiplying factor of the wattmeter and CT_{ratio} is the current transformation ratio of the current-transformer.

Blocked-rotor test

Voltmeter reading V_{BR} =

Ammeter reading I_{BR} =

Wattmeter readings:

W_1' =…..(with sign)

W_2' =…..(with sign)

Blocked-rotor input power $P_{BR} = (W_1' + W_2') \times mf_W \times CT_{ratio}$ =……

DC test

Voltmeter reading V_{dc} =

Ammeter reading I_{dc} =

REPORT

(i) Calculate the stator winding resistance r_1 using equation (4.2.12).
(ii) Calculate the shunt branch impedance Z_o using equation (4.2.3).
(iii) Calculate the core loss resistance r_c using equation (4.2.6).
(iv) Calculate the magnetizing reactance x_m using equation (4.2.7).
(v) Calculate the blocked-rotor impedance Z_{BR} using equation (4.2.8).
(vi) Calculate the equivalent resistance R using equation (4.2.9).
(vii) Calculate the equivalent leakage-reactance X using equation (4.2.10).

SAMPLE QUESTIONS

1. The no-load current drawn by an induction motor, as a percentage of its full-load current, is higher as compared to that of a transformer. Explain.
3. What are the assumptions involved in the determination of equivalent circuit parameters of a three-phase induction motor by conducting no-load and blocked-rotor tests? Can these assumptions be justified?

EXPERIMENT 4.5

NO-LOAD AND BLOCKED-ROTOR TEST OF SINGLE-PHASE CAPACITOR-START INDUCTION MOTOR

OBJECT

To perform no-load and blocked-rotor test on a single-phase, capacitor-start induction motor and determine its equivalent circuit parameters there from.

THEORY

When a single-phase sinusoidal supply is given to a single-winding, single-phase induction motor, a pulsating magnetic field is produced. The pulsating magnetic field may be resolved into two oppositely rotating magnetic fields. The field rotating in the direction of the rotation of the rotor is called the forward rotating field and that rotating in the opposite direction is called the backward rotating field. If the motor slip with respect to the forward field is *s*, then the motor slip with respect to the backward field may be shown to be 2-*s*. At starting, both forward and backward slips are unity and the two fields produce equal and opposite torques. As a result, the net starting torque of the motor is zero. To provide the starting torque, a starting winding is used. The starting winding is displaced from the main winding by 90 degrees (electrical) in space. A capacitor is connected in series with the starting winding to provide 90 degrees time-phase difference between the currents in the two windings. The starting winding may be disconnected from the supply with the help of a centrifugal switch after the motor picks up speed.

The equivalent circuit of single-phase induction motor, based on rotating field theory, is shown in Fig. 4.5.1.

Here,

r_1 is the resistance of the main winding of the stator,

x_1 is the leakage reactance of the main winding of the stator,

r_o is the no-load loss resistance,

x_o is the magnetizing reactance

r_2' is the rotor circuit resistance referred to stator,

x_2' is the rotor circuit leakage-reactance referred to stator, and

s is slip of the motor with respect to the forward-rotating field.

The parameters of the equivalent circuit can be determined from blocked-rotor and no load tests.

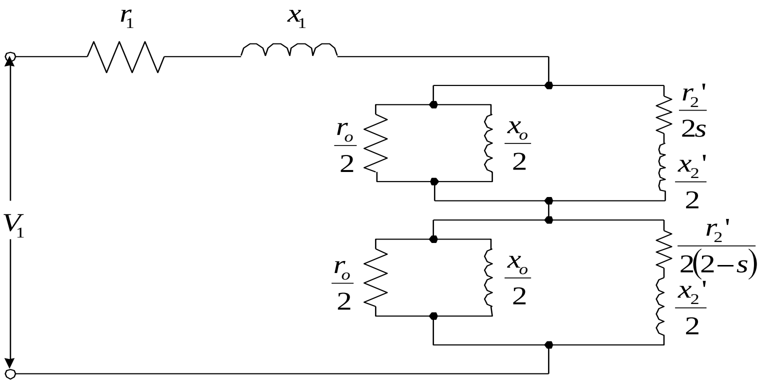


Fig. 4.5.1 Equivalent circuit of single-phase induction motor

Blocked-rotor test

In this method, the starting winding of the motor is disconnected and a reduced voltage (V_{BR}) is applied to the main winding such that it draws a current (I_{BR}) equal to or less than the rated current of the motor. As the starting winding is not connected, the motor remains stationary (blocked). The forward slip (*s*) as well as the backward slip (*2-s*) are unity under this condition. With reduced voltage applied to the motor, the current drawn by the shunt branch is very small and may be neglected. With this approximation, the equivalent circuit of the motor under blocked-rotor condition is simplified, as shown in Fig. 4.5.2. The series parameters of the equivalent circuit may be evaluated from the simplified circuit.
The short-circuit impedance of the motor is given by

$$Z_{sc} = \frac{V_{BR}}{I_{BR}} \tag{4.5.1}$$

The equivalent resistance is given by

$$R = r_1 + r_2' = \frac{P_{BR}}{I_{BR}^2} \tag{4.5.2}$$

Where, P_{BR} is the input power of the motor under blocked-rotor condition.

The main winding resistance r_1 may be determined by conducting dc test. In this test, a small dc voltage V_{dc} is applied across the main winding of the motor such that it draws a small current I_{dc}. The resistance r_1 may be evaluated as:

$$r_1 = 1.15 \times \frac{V_{dc}}{I_{dc}} \tag{4.5.3}$$

Here the factor 1.15 is incorporated to take care of skin effect.

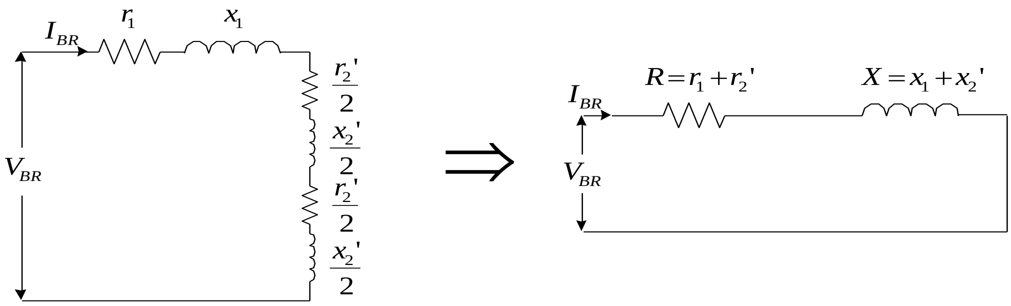


Fig. 4.5.2 Equivalent circuit under blocked-rotor condition

The rotor circuit resistance referred to stator side is calculated as

$$r_2' = R - r_1 \tag{4.5.4}$$

The equivalent leakage- reactance is given by

$$X = x_1 + x_2' = \sqrt{Z_{sc}^2 - R^2} \tag{4.5.5}$$

If x_1 and x_2' are assumed to be equal then

$$x_1 = x_2' = \frac{X}{2} \tag{4.5.6}$$

No-load test

In no-load test, the motor is run on no-load at rated voltage (with starting winding connected). A centrifugal switch disconnects the starting winding when the motor attains the normal speed. As the motor is on no-load, the motor runs at a speed close to synchronous speed of the machine. The forward slip s approaches zero and the backward slip becomes almost equal to two. Under this condition, the rotor circuit impedance for the forward field $(\frac{r_2'}{2s} + j\frac{x_2'}{2})$ tends to infinity. Therefore, the rotor circuit branch for the forward field may be neglected. As the backward slip is very high (close to 2), the rotor circuit impedance becomes so low that it almost shunts the exciting branch. Therefore, the exciting branch may be omitted. With these approximations, the equivalent circuit of the motor for the no-load condition may be drawn as shown in Fig. 4.5.3. From the circuit, the exciting branch parameters may be evaluated.
The equivalent no-load impedance is given by

$$Z_o = \frac{V_o}{I_o} \tag{4.5.7}$$

Where

V_o is the voltage applied under no-load condition and
I_o is the current drawn by the motor under no-load condition.

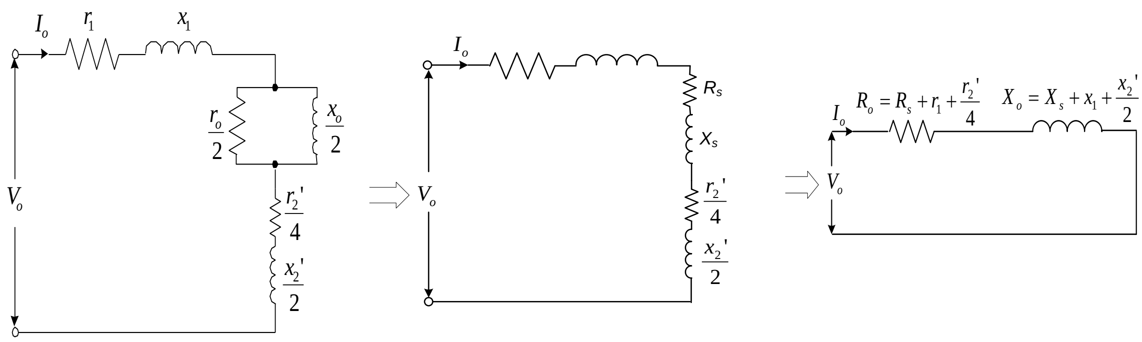


Fig. 4.5.3 Equivalent circuit under no-load condition

The equivalent no-load resistance is given by

$$R_o = R_s + r_1 + \frac{r_2'}{4} = \frac{P_o}{I_o^2} \tag{4.5.8}$$

Where

P_o is the power drawn by the motor under no-load condition and

R_s is the series equivalent resistance of the parallel circuit formed by $r_o/2$ and $x_o/2$.

The equivalent no-load reactance is given by

$$X_o = X_s + x_1 + \frac{x_2'}{2} = \sqrt{Z_o^2 - R_o^2} \tag{4.5.9}$$

Where X_s is the series equivalent reactance of the parallel circuit formed by $r_o/2$ and $x_o/2$.

The values of r_1, r_2', x_1, and x_2' are already determined from blocked-rotor test. Using these values, R_s and X_s can be determined from equations (4.5.8) and (4.5.9). The exciting branch parameters can be determined using the following equations.

$$r_o = \frac{2\left(R_s^2 + X_s^2\right)}{R_s} \tag{4.5.10}$$

$$x_o = \frac{2\left(R_s^2 + X_s^2\right)}{X_s} \tag{4.5.11}$$

The proof of equations (4.5.10) and (4.5.11) has been left for the reader.

PROCEDURE

DC test

Apply a small dc voltage across the main winding of the motor with the help of a potential divider so that the winding draws a current less than its rated current. Note down the applied voltage V_{dc} and the current drawn I_{dc}.

Blocked-rotor test

(i) Make the connections as shown in Fig. 4.5.4 using instruments of appropriate ratings. Do not connect the starting-capacitor.

(ii) Gradually increase the voltage applied to the motor with the help of the autotransformer till the motor draws a current equal to or less than its rated current. Record the readings of the instruments.

No-load test

(i) Connect the starting capacitor and complete the connections as shown in Fig. 4.5.4.

(ii) Apply rated voltage to the motor with the help of the autotransformer. The centrifugal switch S that was closed at the time of starting will be disconnected as the motor attains its no-load speed. Record the readings of the instruments.

OBSERVATIONS

DC test

Voltmeter reading V_{dc}=….

Ammeter reading I_{dc}=…..

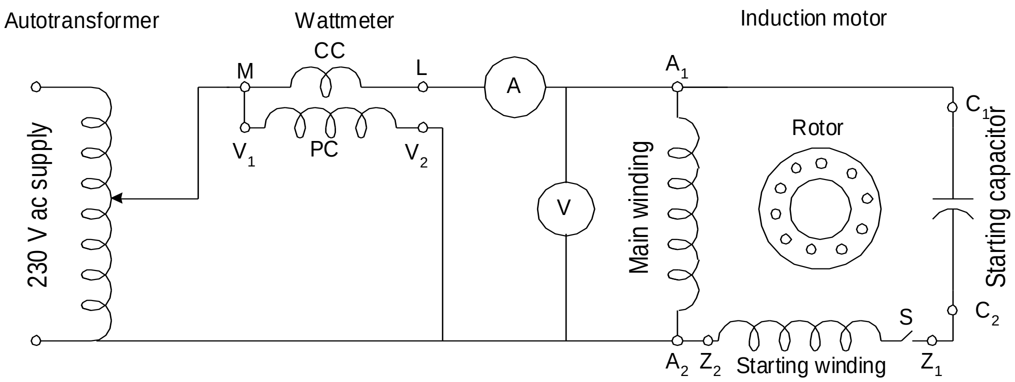


Fig. 4.5.4 Circuit diagram for the blocked-rotor and the no-load tests

OBSERVATIONS

DC test

Voltmeter reading V_{dc}=….

Ammeter reading I_{dc}=…..

Blocked-rotor test

Voltmeter reading V_{BR}=….

Ammeter reading I_{BR}=…..

Wattmeter reading P_{BR}=…..

No-load test

Voltmeter reading V_o=….

Ammeter reading I_o=…..

Wattmeter reading P_o=…..

REPORT

Use the relevant equations given in the theory, to evaluate the parameters of the induction motor.

SAMPLE QUESTIONS

1. Why is a single-phase induction motor not self-starting?
2. What is the function of the capacitor in the auxiliary winding circuit of a single-phase induction motor?
3. What is the principle of operation of a shaded-pole motor and explain the advantages of capacitor-start motor over a shaded-pole motor.