Experiment no 1

Power measurement in balanced 3 phase circuits and power factor improvement

1 Power in Single Phase Circuits

Let $v = V_m \cos(\omega t) = \sqrt{2}V \cos(\omega t)$ is the voltage applied to a R-L circuit and $i = I_m \cos(\omega t - \theta) = \sqrt{2}I \cos(\omega t - \theta)$ is the current flowing in it (V and I are the rms values of the voltage and current respectively).
The power at any instant of time is

$$p = vi = V_m I_m \cos(\omega t) \cos(\omega t - \theta)$$

$$p = \frac{V_m I_m}{2} \cos\theta + \frac{V_m I_m}{2} \cos(2\omega t - \theta)$$

$$p = \frac{V_m I_m}{2} \cos\theta + \frac{V_m I_m}{2} \cos(2\omega t) \cos\theta + \frac{V_m I_m}{2} \sin\theta \sin(2\omega t)$$

A careful study of the above equation reveals the following characteristics:

- The average value of power = P = $\frac{V_m \ I_m}{2} \ \ \cos\theta = V \ \ I \ \ \cos\theta$ Watts.
  In AC circuits, when we talk of power rating, we are usually referring to the average power. For example, a “100 W” bulb implies that *average* power output of the bulb is 100 W.

- The frequency of instantaneous power is twice the frequency of the voltage and current. Note that instantaneous power may be negative for a portion of each cycle, even if the load is passive. In a passive network, negative power at a given instant implies that energy stored in inductors or capacitors is being given back to the supply at that instant.
  The fact that the instantaneous power varies with time explains why some single phase motor driven appliances such as refrigerators, which are fed from single phase supply experience vibration, and hence require resilient mountings to prevent excessive vibration of the equipment.

- If the load is purely resistive, the voltage and current are in phase, which means that $\theta = 0$. The above equation reduces to $p = P + P\cos(2\omega t)$. In this case instantaneous real power can never be negative, i.e., power cannot be given back to the supply from a purely resistive network.

- If the circuit is purely reactive (either capacitive or inductive, $\theta = \pm 90^o$), the expression for instantaneous power is $p = \frac{V_m I_m}{2} \sin(2\omega t)$. The average power is zero. Therefore in a purely reactive circuit there is no average power dissipation. Energy is drawn from the supply for a part of a cycle is stored, and given back in another part of a cycle. However, since there is a current flow, the supply system must be designed to source such currents. Therefore it is useful to define a quantity called “reactive power” as follows:

$$Q = \frac{V_m I_m}{2} \sin\theta = VI \sin\theta$$

- Dimensionally P and Q are same. However, in order to distinguish between average (also called “real power”) and reactive power, we use the term ‘VAr’ for reactive power. Q is positive for inductive load and negative for capacitive load. In other words inductors demand or absorb reactive power while capacitors furnish or deliver the reactive power. For purely resistive circuits, Q=0.

If v and i are represented by phasors $\overline{V}$ and $\overline{I}$, then it is easily seen that

$$\overline{S} = P + jQ = \overline{V}\ \overline{I}^*$$
$$\cos\theta = \frac{P}{\sqrt{P^2+Q^2}}$$

$\overline{S}$ is called the complex power and $\cos\theta$ is called the power factor. Power factor is said to be leading if θ is negative (capacitive circuits), and lagging for if θ is positive (inductive circuits).
Dimensionally, complex power is the same as real and reactive power. However, in order to distinguish complex power from real and reactive power, we use the term 'volt amps' or 'VA'. The magnitude of complex power ($|\overline{S}| = S = |\overline{V}\ \overline{I}^*| = \sqrt{P^2+Q^2} =$ VI), is referred to as apparent power.
S indicates the capacity of the source required to supply the load. The apparent power specifications of source and load equipment can be more important than the average power specifications. This is because any electrical equipment requires appropriate design of conductor size, amount of dielectric (insulation) and magnetic material to handle both current and voltage *magnitudes*. Thus S has a direct bearing on size and cost of any electrical equipment. Since average power represents the useful output of the load equipment (essentially energy converting devices like motors, heaters, lighting), operating such equipment close to unity power factor is desirable (i.e, P should be as close to S as possible, or Q should be minimized).
The vector diagram for a lagging load is shown in Fig.1 (a). The current vector lags the voltage vector by and angle θ. In Fig. 1(b) the current phasor is resolved along x and y axes and in Fig.1(c) these components are multiplied by V. The resulting triangle is known as power triangle. The sides of the triangle are P, Q and S, where,

$$\text{P} = VI\cos\theta \quad \text{Watt}$$
$$\text{Q} = VI\sin\theta \ \ \text{VAr}$$
$$\text{S} = VI \quad \text{VA}$$

1.1 Measurement of Power in single phase circuit

Power consumed by single phase load can be measured using a wattmeter. This meter comprises of the following:

- Two identical current coils. Depending upon the magnitude of load current these coils are connected either in series or in parallel (if the current rating of one coil is less than the load current, these coils are connected in parallel, otherwise they are connected in series). The two ends of these coils are marked as 'M' which stands for Mains, and 'L' for load. The current coils are connected in series with the load.

- A voltage coil with different voltage tapings. Depending upon the voltage applied to the load suitable taping is used. The two ends of this coil are marked as 'C' which stands for common and 'V' stands for voltage. This coil is connected across the load. The terminals C and M are connected together.

The reading of this meter is proportional to

$$V_{app}\ I_{Fl} \quad \cos\angle\ (\overline{I}_{Fl} \quad \& \quad \overline{V}_{app})$$

where, V_{app} is the voltage applied to voltage coil, & I_{Fl} is current flowing through the current coil.

2 Three Phase System

The generation, transmission, distribution and utilization of large blocks of electric power are accomplished by means of three-phase circuits. A balanced three phase system consists of three sinusoidal voltages of identical amplitudes and frequency but are out of phase with each other by 120^o. In discussing three-phase circuits, standard practice is to refer the three phase as A, B, and C (or R,Y, B). Furthermore, the A-phase (or R-phase) is almost always used as the reference phase. Because the phase voltages are out of phase by 120^o, two possible phase relationships can exist between the A phase (or R phase) voltage and the B and C phase voltages (Y and B). One possibility is for the B phase to lag the A phase by 120^o (phase C will be lagging B phase by 120^o, or lead A phase by 120^o). In this case the phase relationship is known as ABC (or RYB) phase sequence. The only other possibility is for the C phase to lag A phase (or B phase to lead A phase by 120^o). This phase relationship is known as ACB sequence. In phasor notation, two possible sets of balanced phase voltages are:

$$\overline{V}_a = V\angle 0; \qquad \overline{V}_b = V\angle{-120^o}; \qquad \overline{V}_c = V\angle{-240^o};$$

and $$\overline{V}_a = V\angle 0; \qquad \overline{V}_c = V\angle{-120^o}; \qquad \overline{V}_b = V\angle{-240^o} = V\angle{+120^o}.$$

An important characteristic of balanced three phase voltages is that the sum of the voltages is zero ($\overline{V}_a + \overline{V}_b + \overline{V}_c = 0$). Three phase voltage sources can be either Y (star) or delta connected. These connections are shown in Fig.2 (a) and (b) respectively. Let $\overline{V}_{an}$, $\overline{V}_{bn}$ and $\overline{V}_{cn}$ are the phase voltages (the voltage between line and neutral). Now there are 4 wires - three for three lines and fourth one for the neutral. All the single phase loads are connected between any one of the lines and neutral. The relationship between the line-line voltage ($\overline{V}_{ab}$, $\overline{V}_{bc}$ and $\overline{V}_{ca}$) and phase voltage can be derived as follows:
Referring to Fig.2(a), the line-line voltages for ABC sequence are:

$$\overline{V}_{ab} = \overline{V}_{an} - \overline{V}_{bn} = V\angle 0 - V\angle{-120^o} = \sqrt{3}V\angle 30^o$$

Similarly, $$\overline{V}_{bc} = \sqrt{3}V\angle{-90^o} \qquad \overline{V}_{ca} = \sqrt{3}V\angle{-210^o}$$

In three phase system the load is said to be balanced if the magnitude and phase of the load impedance connected to each phase is the same. For the Fig.2 (b), the phase current (the current in each phase of the load) is

$$\overline{I}_A = \frac{\overline{V}_{an}}{Z_{an}} = \frac{V\angle 0}{Z\angle\theta} = I\angle{-\theta}$$
$$\overline{I}_B = \frac{\overline{V}_{bn}}{Z_{bn}} = \frac{V\angle{-120}}{Z\angle\theta} = I\angle{-(120+\theta)}$$
$$\overline{I}_C = \frac{\overline{V}_{cn}}{Z_{cn}} = \frac{V\angle{-240}}{Z\angle\theta} = I\angle{-(240+\theta)}$$

Line current is the current in each phase of the line. In star connected system, phase currents & line currents are identical. The complete vector diagram for a three phase system feeding a star connected load is shown in fig.3(a).
For delta connected system shown in Fig. 2(b), line to line voltage is the same as phase voltage. However, the relationship between the phase currents and line currents can be determined as follows: The phase currents are given by:

$$\overline{I}_{ab} = \frac{\overline{V}_{ab}}{Z_{ab}} = \frac{V\angle 0}{Z\angle\theta} = I\angle{-\theta}$$
$$\overline{I}_{bc} = \frac{\overline{V}_{bc}}{Z_{bc}} = \frac{V\angle{-120}}{Z\angle\theta} = I\angle{-(120+\theta)}$$
$$\overline{I}_{ca} = \frac{\overline{V}_{ca}}{Z_{ca}} = \frac{V\angle{-240}}{Z\angle\theta} = I\angle{-(240+\theta)}$$

We can write the line currents in terms of the phase currents by direct application of KCL:

$$\overline{I}_A = \overline{I}_{ab} - \overline{I}_{ca} = I\angle{-\theta} - I\angle{-(240+\theta)} = \sqrt{3}I\angle{-(30+\theta)}$$

$$\overline{I}_B = \overline{I}_{bc} - \overline{I}_{ab} = \sqrt{3}I\angle{-(150+\theta)} \quad \& \quad \overline{I}_C = \overline{I}_{ca} - \overline{I}_{bc} = \sqrt{3}I\angle{-(270+\theta)}$$

The complete vector diagram for a three phase system feeding a delta connected load is shown in fig.3(b).

2.1 Power in three phase circuits:

In a balanced three phase system, the magnitude of each line-to-neutral voltage (also line-line) is the same, as is the magnitude of each phase current. Therefore, the expression for total power in terms of phase current and phase voltage is given by:

$$P = 3\ V\ I\ \cos\theta \quad \text{Watt}, \qquad \theta = \angle(\overline{I}\&\overline{V})$$

In-terms of line voltage & line current the above expression becomes:

$$P = \sqrt{3}\ V_L\ I_L\ \cos\theta \quad \text{Watt}, \qquad \theta = \angle(\overline{I}\ \&\ \overline{V})$$

In the above expression V and I are the rms values of the phase voltage and phase current respectively. We can also calculate reactive power (Q) and complex power (S). For balanced load, the expressions for Q and S are given by:

$Q = \sqrt{3}\ V_L\ I_L\ \sin\theta$ VAr, $\quad \theta = \angle(\ \overline{I}\ \&\ \overline{V}),\quad S = \sqrt{3}\ V_L\ I_L$ VA

All the above equations are valid for both the connections (Y or Delta).

2.2 Measurement of Power in Three phase circuit

Real power in balanced (or unbalanced) 3 phase circuits can be measured by using two wattmeters connected in any two lines of a three-phase three wire system. In Fig.4(a) the current coils are connected in lines A and C, with the voltage coil reference connections in line B. The current flowing through the current coil of the wattmeter connected in line A is $\overline{I}_A$ and that in line C is $\overline{I}_C$. Similarly, the voltage applied to the voltage coils is $\overline{V}_{ab}$ and $\overline{V}_{cb}$ (and not $\overline{V}_{bc}$) respectively. Their readings will be:

$$W_A = V_{ab}\, I_A\ \cos\angle(\ \overline{I}_A\ \&\ \overline{V}_{ab}) \qquad \text{and} \qquad W_B = V_{cb}\, I_C\ \cos\angle(\ \overline{I}_C\ \&\ \overline{V}_{cb})$$

From Fig.3 (a or b) angle between V_{ab} and I_A is $(30+\theta)$ and between V_{cb} and I_c is $(30-\theta)$. Therefore the wattmeter readings will be:

$$W_1 = \sqrt{3}\ \ V\ \ I_A\ \ \cos(30+\theta) \qquad W_2 = \sqrt{3}\ \ V\ \ I_C\ \ \cos(30-\theta)$$

$$W_1 + W_2 = 3\ \ V\ \ I\ \ \cos\theta \quad = \quad \sqrt{3}\ \ V_L\ \ I_L\ \ \cos\theta \ \ \text{Watt}$$

Note that if θ is greater than 60^o, W_1 will be negative. In actual power measurement it is possible to encounter such a situation when one of the wattmeters has negative reading. The point to remember is that the total power in three phase circuit is obtained by adding the two wattmeter readings, taking the signs of the readings into account.

It may be worthwhile to identify the following cases:

- If θ is zero (load is purely resistive), $W_1 = W_2$ and both are positive.
- For $\theta = 60^o$ lag, $W_1 = 0$. Similarly for $\theta = 60^o$ lead, $W_2 = 0$.

Note that you will be using a **Power analyzer** to measure power. It is also possible to measure other quantities such as voltage, current, Q, S, power factor etc. using this equipment.

3 Power factor Improvement:

Electrical service to industrial customers is given as a three-phase supply as opposed to the single phase power supplied to residential and small commercial customers. Most electric loads are reactive in nature and have lagging power factor (less than unity). Transmission lines, transformers and generators of the electric power utility have to carry the lagging reactive power of the load. Transformers, the distribution systems and the generators are all rated in kVA or MVA. An improvement in the power factor leads to a reduction in KVA for the same real (average) power supplied. This leads to a release in some of the generation and transmission capability so that it can be used to serve more customers. Generally, power is distributed through transmission lines (in the city of Mumbai, power is distributed through underground cables) and the voltage at one end of these lines is maintained constant. These transmission lines have finite resistance and inductance. From Fig.1 it can be inferred that as the power factor falls, for a fixed amount of power, the magnitude of current flowing through these lines increases. As a result the voltage at the load end drops. Also, loss in the transmission line increases thereby decreasing the overall efficiency.
In order to discourage the bulk consumers drawing a large amount of reactive power from the source, the utilities charge higher tariff if the power factor falls below a specified value. Hence, to improve the power factor, capacitors in three-phase banks are connected to the system, such that the combination of the plant load and the capacitor banks presents a load to the serving utility which is nearer to unity power factor. This is explained with the help of Fig.5. In the Fig.5(a), a R-L load is being supplied by the source and a capacitor is connected across the load. The vector diagram for this combination is shown in Fig.5(b). It is known that the capacitor draws a leading current (or supplies lagging current) from the source. If the magnitude of the current drawn by the capacitor is equal to the quadrature component of the load current ($I_y = I_L \sin\theta$), the source will then supply only the active component of current (I_x). In that case there is a significant reduction in the current flowing through the transmission line (without the capacitor the current flowing in the transmission line is 'I_L' and with the capacitor it is $I_L \cos\theta$). This results in the decrease in voltage drop and power loss in the transmission line.

Note to TAs/RAs: Explain the following:
• wattmeter connection and the procedure for determining the multiplying factor.
• various features of power analyzer and various parts of energy meter.

4 Laboratory Work

4.1 Part- I Star Connected Load:

- Connect the incandescent bulbs in Y & complete the circuit connection as shown in Fig. 4(a).
- Set the output voltage of the autotransformer (also called as variac)to zero and switch on the 3 phase 415, 50 Hz supply.
- Slowly increase the output voltage of the variac by turning the regulating handle till the voltmeter reads 400 V. The corresponding voltage across each bulb will be 230 V (Note that one can directly apply 400 V to this star connected load. We carry out the above procedure just as a precautionary measure). Note down all the meter readings and determine the load power factor.
- Observe the current and voltage waveforms (line-line) on the power analyzer and measure the angle between these two waveforms.

- Reduce the output voltage of the variac to zero & switch off the supply.

4.2 Part II Delta Connected Load

- Connect the bulbs in delta without disturbing other part of the circuit. Switch on three phase supply.
- **Slowly increase the output voltage of the variac by turning the regulating handle till the voltmeter reads 230 V.** Note down all the meter readings. Determine the power factor and compare the meter reading with those of Part-1.
- Reduce the output voltage to zero and switch off the supply.

4.3 Part III Powerfactor Improvement:

- Connect the circuit as shown in Fig.6. Ensure that the load (three phase induction motor) is connected in delta and switches S_1, S_2 and S_3 are open.
- Switch on the 3 phase supply. Keep an eye on the ammeter needle and gradually increase the output voltage till the voltmeter reads 230 V (You will observe initially a high current flows through the motor. As the motor accelerates this current reduces automatically. The reason for this behaviour will be explained by the instructor who teaches EE-218 at the appropriate time). Note down all the meter readings. **Reduce the applied voltage to the load to zero**.
- There are three delta connected capacitor banks each of 10μF per phase. These banks can be connected across the load by closing S_1, S_2 & S_3. Connect the first capacitor bank across the load by closing S_1.
- Gradually increase the output voltage of the variac to 230 V. Note all the meter readings. **Reduce the voltage to zero**.
- Close S_2 and S_3 in steps and for each case repeat the above step. **Please ensure that the applied voltage to the load is zero before closing the switches.**
- Open S_1, S_2 and S_3.
- Determine the source powerfactor for all the cases.

− − − − ∗ ∗ ∗ ∗ − − −−

5 Questions to be answered

A With all three capacitor banks connected across the load, the source powerfactor might be now leading. How can you infer this from the readings? Are there any advantages of overcompensating the load?

B You might have observed the voltage & current waveforms on the power analyzer (step-iv in 'section 4.1'). Why is the angle between these two waveforms is 30^o even though the load is purely resistive?

C What is the reason for reducing the voltage to zero every time before switching on the capacitors?

D You have been given thick and thin wires for connections. Which one will you use for connecting (i) an ammeter and (ii) a voltmeter? Justify your answer.

E During the late hours of the night you might have observed the intensity of the incandescent bulb is much higher compared to that during 7-8pm. What could be the reason?

F Why do the single phase motor driven appliances experience vibration?

G You might have observed the power sockets with two pins while, some of them with three pins. What is the difference between these power sockets?

H Utilities use energy meters to measure the energy consumed by consumers. Energy is given by

$$E = \int P \;\; dt$$
$$E = \int (VI\cos\theta) \;\; dt$$

where P is the power consumed by the load. From Fig. 1 it can be inferred that though the consumer is drawing 'I' A of current, he/she is being charged only for $I\cos\theta$. In other words there is no apparent advantage of improving the power factor to unity. Is this correct? Justify your answer.

I Suppose (3+j4) kVA load is being supplied at 230 V (load voltage) and the transmission line has an impedance of $(1 + j1)\Omega$. Determine the following:

(a) voltage at the source terminals

(b) power loss in the transmission line

(c) the required kVAR rating of the capacitor to compensate the load fully (source supplies only the active component of current).

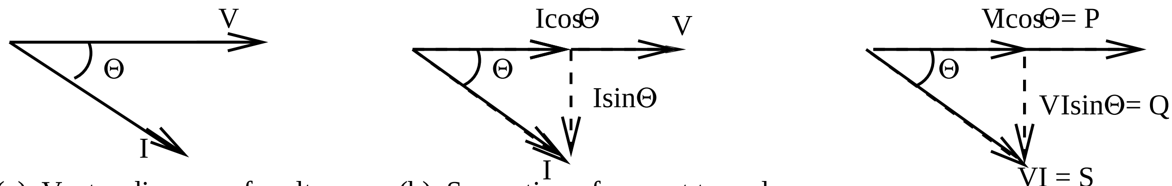
(d) source current, drop is the transmission line, power loss in the transmission line after compensation.

J Find the per phase capacitance necessary to improve the powerfactor to unity in Part-III (section-iv) for the following capacitor connections:

i Star

ii Delta

– – – – * * * * – – – –



(a) Vector diagram of voltage and current for lagging load

(b) Separation of current to real and reactive components

(c) Active and reactive power for corresponding currents

Figure 1: Vector Diagram for an Inductive load

Activity: Validating Two-Wattmeter Method Results through Analysis of Generalized V-I Data Obtained using Oscilloscope

- In this experiment, students will be given data of instantaneous voltage and current readings for a predetermined load, captured using a digital oscilloscope. Utilize Excel/Matlab programming to perform calculations for W1, W2, active power, reactive power and power factor based on the acquired data.
- Afterwards, compare the computed results with readings obtained through the Two-Wattmeter method.
- Generate a comprehensive report that includes the percentage of error observed and an in-depth explanation for any discrepancies encountered during the comparison.
- The oscilloscope data is given as the .csv file on the moodle.

Questions:

1. When using the capacitors for power factor correction, plot the capacitor currents using a DSO. Are the current waveforms through the capacitors sinusoidal? If not, why?

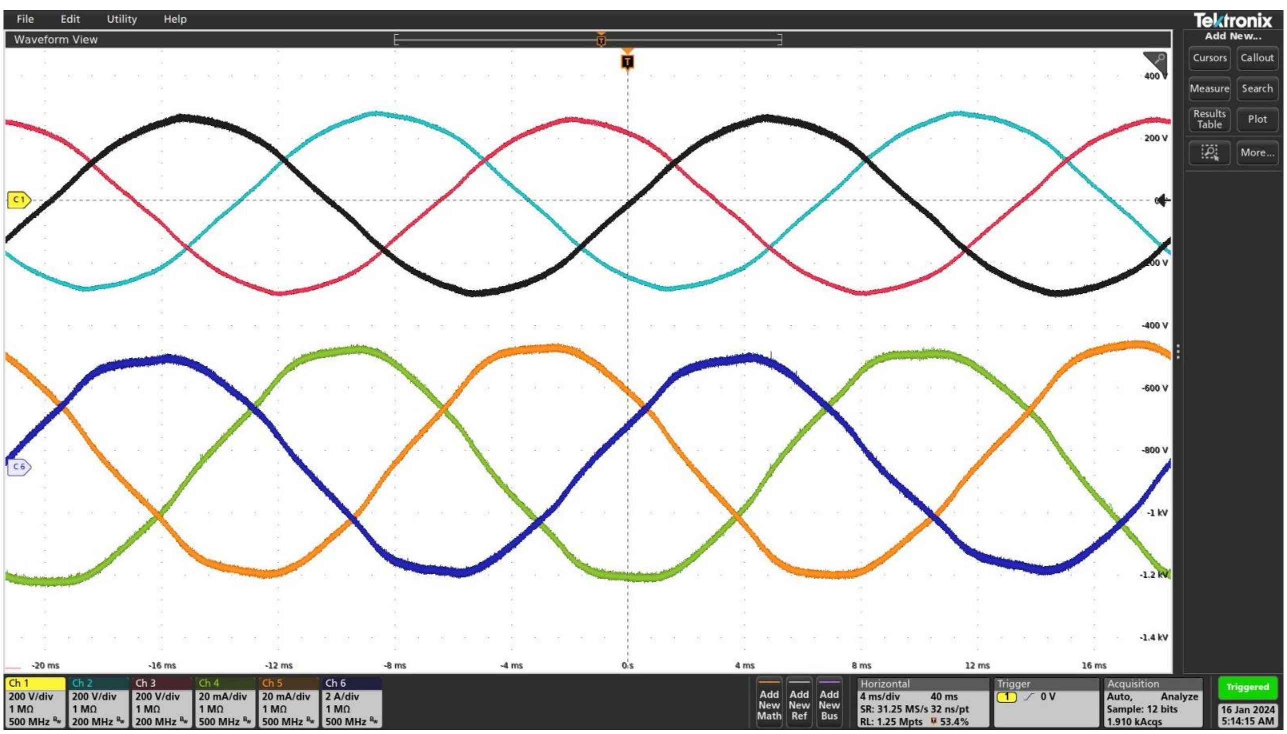


Fig1. Load Voltage and load currents in normal condition

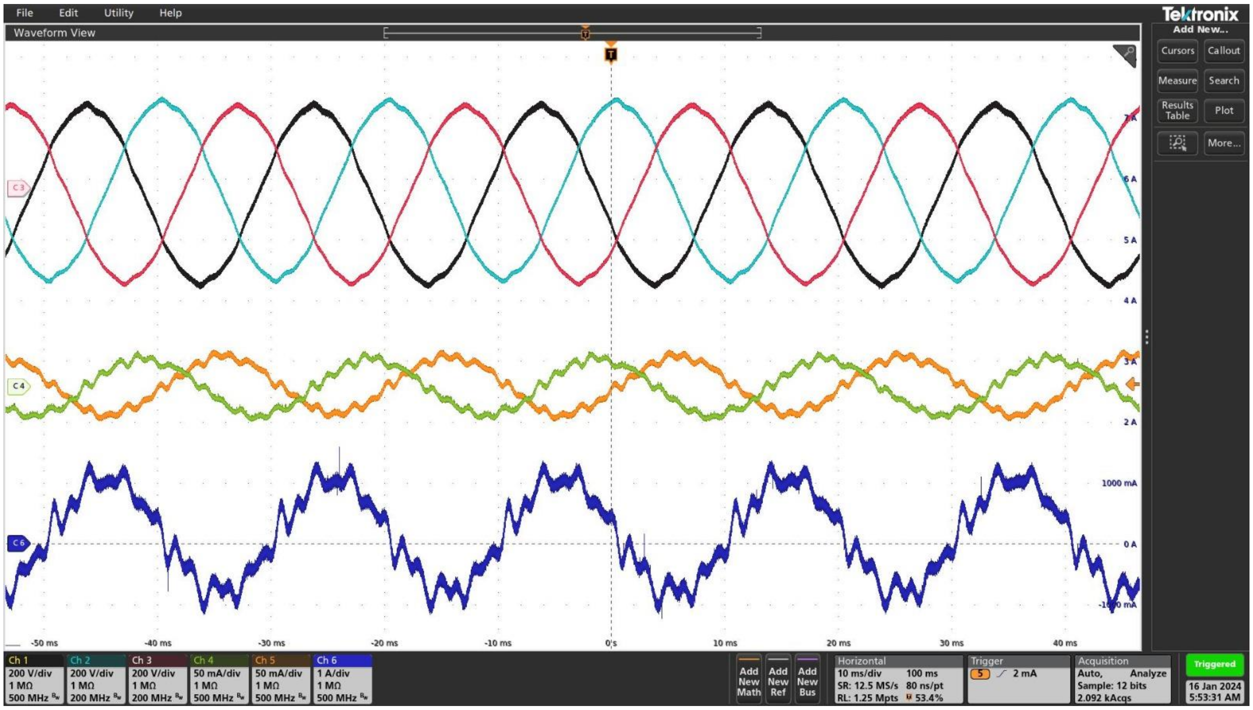


Fig2. Load voltage and load current with capacior bank (Capacitor current in blue)

2.Measure the power meter readings for a particular loading of the induction motor :

Irms, Vrms (line-line), W1, W2

The corresponding instantaneous samples of measurements of Vab, Vbc, Vca (line voltages) and the instantaneous line currents have been given in the file, with time values.

Plot these voltages and currents with respect to time.

Numerically compute the rms values of Vrms (line-line), Irms, and total three-phase instantaneous power using Excel/Matlab.

Compare with those obtained from the 2 wattmeter readings.

3. The current drawn by a computer is as shown in fig3. Can you explain the nature of the waveform? Comment upon the power factor in this case. Can the power factor be improved by adding capacitor bank?

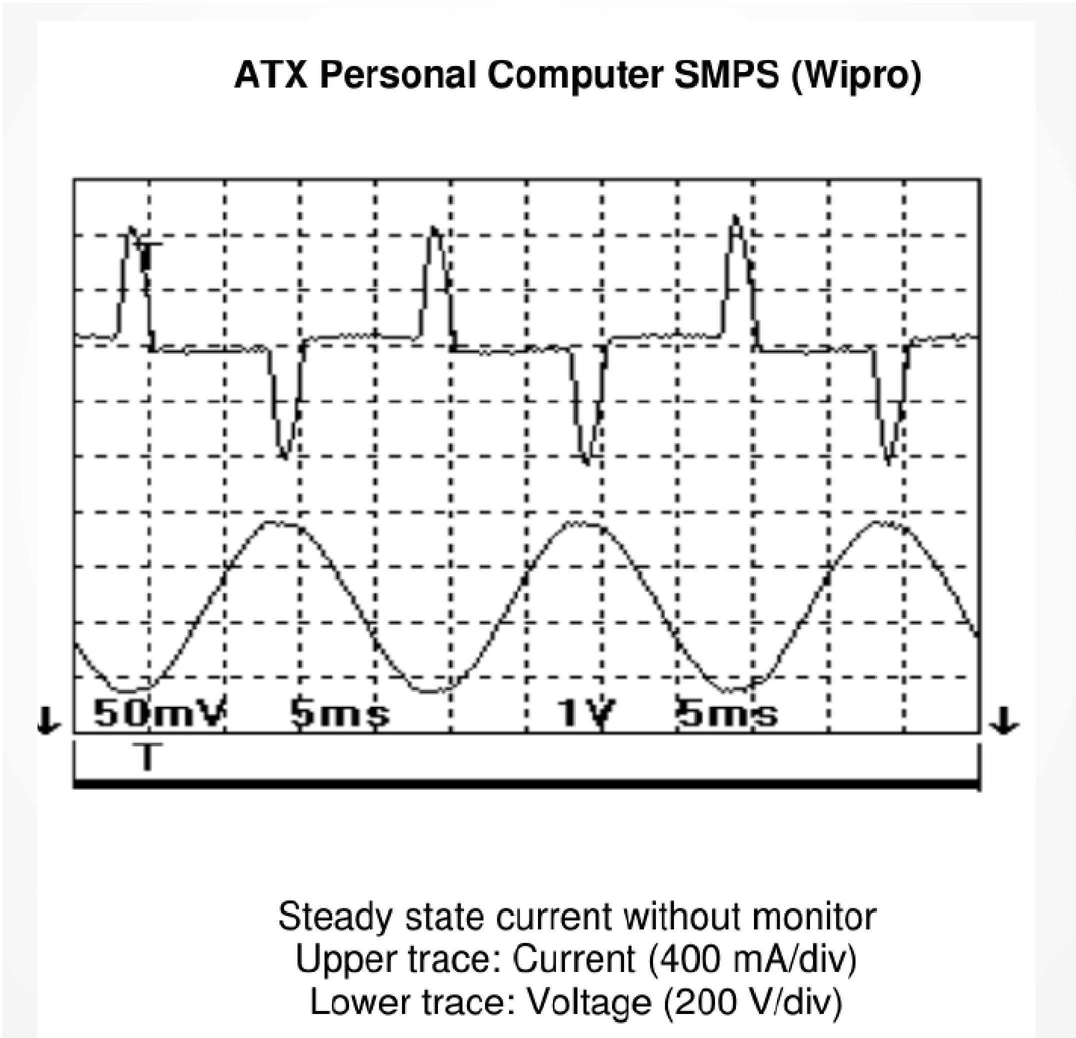


Fig3. Computer SMPS current

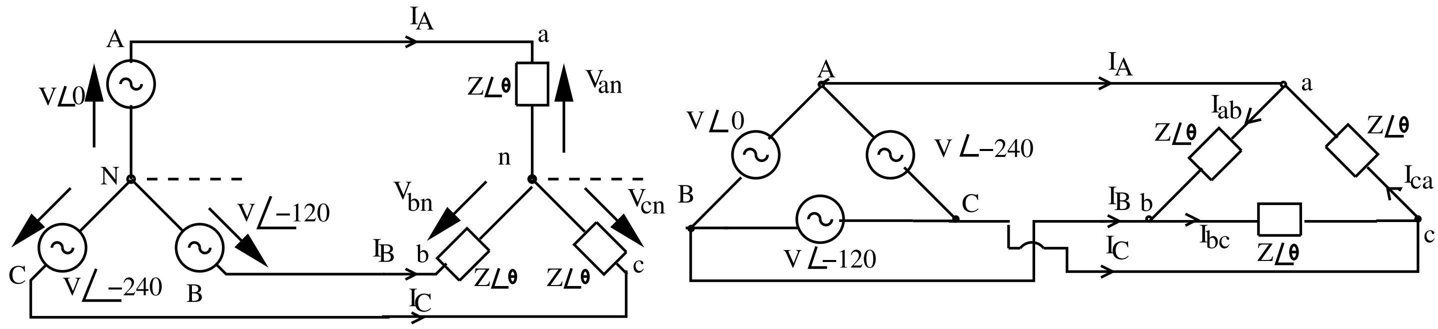


Fig. 2(a) Star – Star System

Fig. 2(b) Delta – Delta System

Figure 2: Schematic configuration of star – delta supply and load system

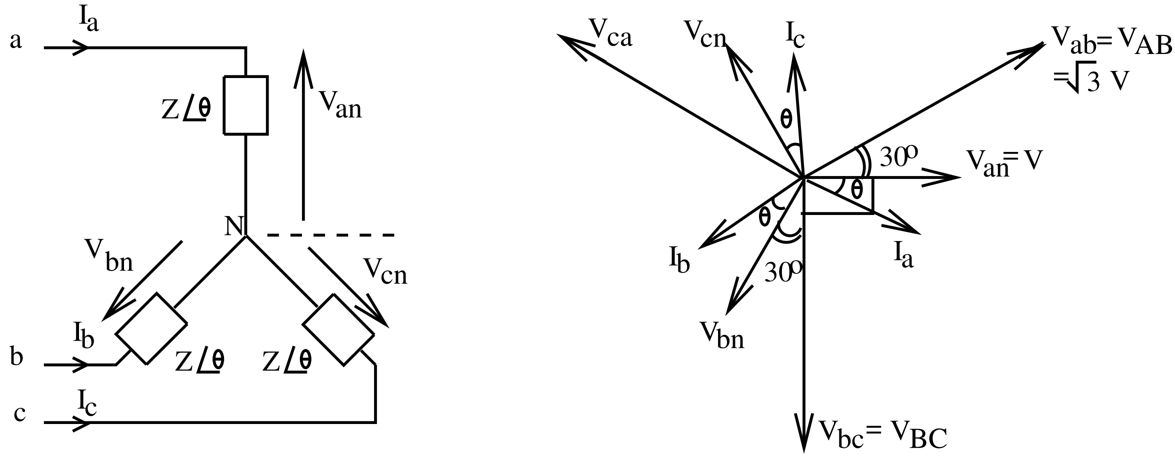


Fig. 3(a) Vector Diagram for a 3–phase system supplying
a balanced star connected load

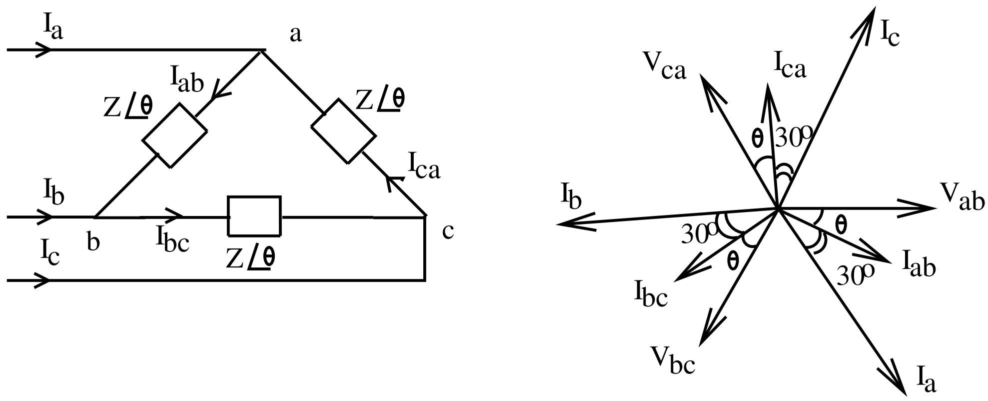


Fig. 3(b) Vector Diagram for a 3–phase system supplying
a balanced delta connected load

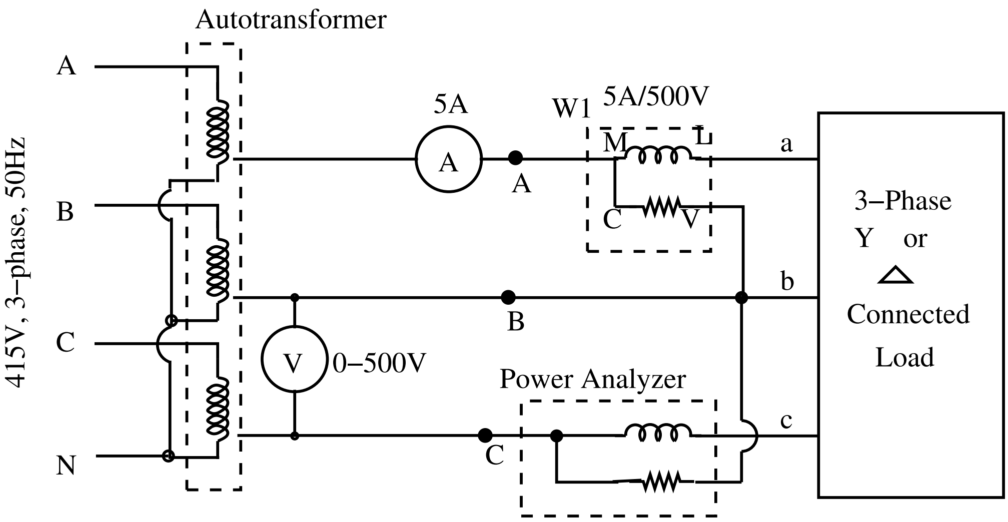


Fig. 4(a) Circuit Diagram to measure power consumed by 3−phase Load
using 2−Wattmeter method

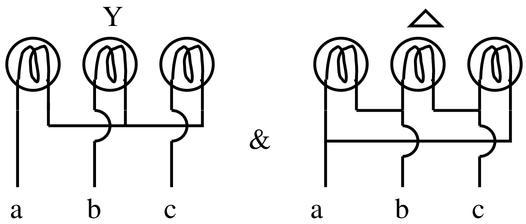
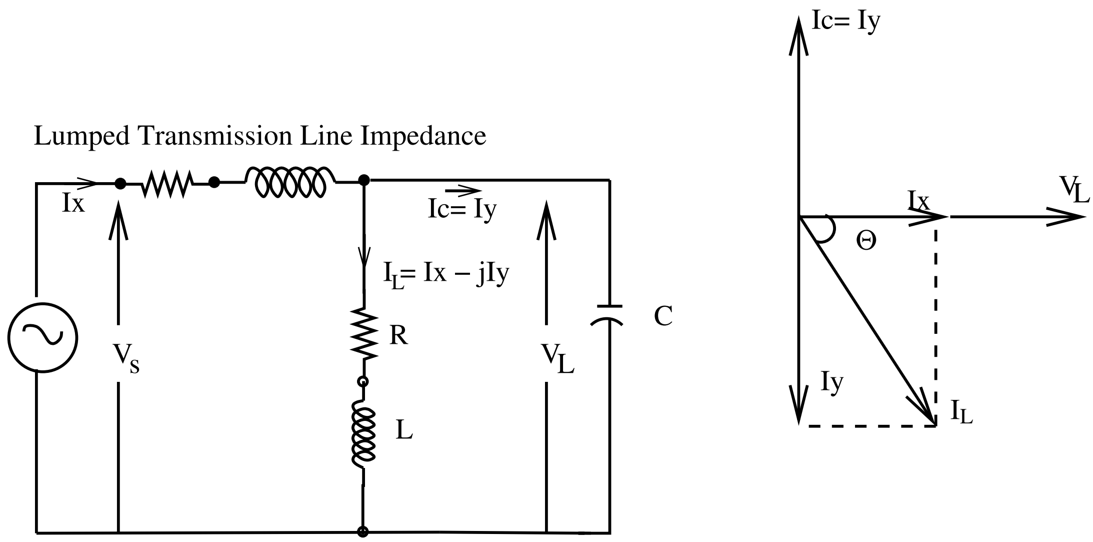


Fig. 4(b) 3−Phase Load connection: Star & Delta



(a) Schematic Diagram

(b) Phasor Diagram

Figure :5 Power Factor Improvement

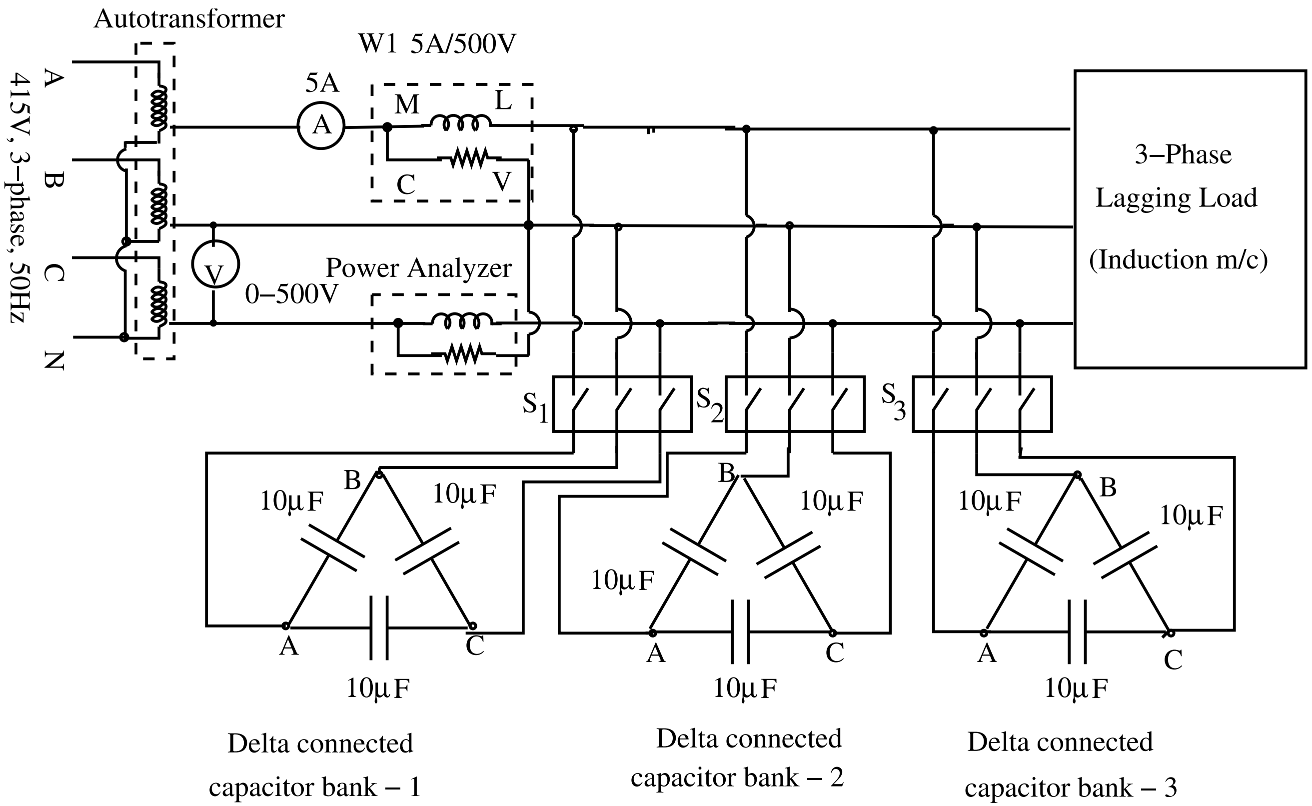


Fig.6 Circuit diagram for Power factor improvement

Experiment No: 2

Open circuit and short circuit tests on single phase transformer

1 Aim

- To understand the basic working principle of a transformer.
- To obtain the equivalent circuit parameters from OC and SC tests, and to estimate efficiency & regulation at various loads.

2 Theory

The physical basis of the transformer is mutual induction between two circuits linked by a common magnetic field. Transformer is required to pass electrical energy from one circuit to another, via the medium of the pulsating magnetic field, *as efficiently and economically* as possible. This could be achieved using either iron or steel which serves as a good permeable path for the mutual magnetic flux. An elementary linked circuit is shown in Fig.1. The principle of operation of this circuit can be explained as follows:

Let an alternating voltage v_1 be applied to a primary coil of N_1 turns linking a suitable iron core. A current flows in the coil, establishing a flux ϕ_p in the core. This flux induces an emf e_1 in the coil to counterbalance the applied voltage v_1. This e.m.f. is

$$e_1 = N_1 \tfrac{d\phi_p}{dt}.$$

Assuming sinusoidal time variation of the flux, let $\phi_p = \Phi_m \sin \omega t$. Then,

$$e_1 = N_1 \omega \Phi_m \cos \omega t, \quad \text{where} \quad \omega = 2\pi F$$

The r.m.s. value of this voltage is given by:

$$E_1 = 4.44 F N_1 \Phi_m$$

Now if there is a secondary coil of N_2 turns, wound on the same core, then by mutual induction an emf e_2 is developed therein. The r.m.s. value of this voltage is given by:

$$E_2 = 4.44 F N_2 \Phi'_m$$

where Φ'_m is the maximum value of the (sinusoidal) flux linking the secondary coil (ϕ_s).

<u>If it is assumed that $\phi_p = \phi_s$</u> then the primary and secondary e.m.f.'s bear the following ratio:

$$\tfrac{e_1}{e_2} = \tfrac{\overline{E}_2}{\overline{E}_1} = \tfrac{N_2}{N_1}$$

Note that in actual practice, $\phi_p \neq \phi_s$ since some of the flux paths linking the primary coil do not link the secondary coil and similarly some of the flux paths linking the secondary coil do not link the primary coil. The fluxes which do not link both the coils are called the "leakage fluxes" of the primary and secondary coil.

In a practical transformer a very large proportion of the primary and secondary flux paths are common and leakage fluxes are comparatively small. Therefore $\phi_p \approx \phi_s = \phi_{mutual}$ and therefore $\Phi_m \approx \Phi'_m$.
If in addition, winding resistances are neglected – being usually small in a practical transformer, then

$$\overline{V}_1 \approx \overline{E}_1$$

Similarly,

$$\overline{V}_2 \approx \overline{E}_2$$

Although the iron core is highly permeable, it is not possible to generate a magnetic field in it without the application of a small m.m.f.(magneto-motive force), denoted by M_m. Thus even when the secondary winding is open circuited, a small magnetizing current (i_m) is needed to maintain the magnetic flux. The current of the primary circuit on no-load is of the order of 5% of full load current.
Also, the pulsation of flux in the core is productive of core loss, due to hysteresis and eddy currents. These losses are given by:

$$P_h = K_h B_{max}^{1.6} F, \qquad P_e = K_e B_{max}^2 F^2 \qquad \text{and } P_c = P_h + P_e$$

where P_h, P_e and P_c are hysteresis, eddy current and core losses respectively, K_h and K_e are constants which depend on the magnetic material, and B_{max} is the maximum flux density in the core. These losses will remain almost constant if the supply voltage and frequency are held constant. The continuous loss of energy in the core requires a continuous supply from the electrical source to which the primary is connected. Therefore, there must be a current component i_c which accounts for these losses. It should be noted that magnetizing current (i_m) and core loss component of current(i_c) are in phase quadrature. The resultant of these two currents is the no-load current i_o. Generally the magnitude of this current is very small compared to that of the rated current of the transformer (may be of the order of 5% of the rated). This current makes a phase angle ζ_o of the order of ($\cos^{-1}(0.2)$) with the applied voltage.

If a load of finite impedance is connected across the second coil, a current i_2 will flow through it. This tends to alter the mmf and thereby the flux in the core. But this is prevented by an immediate and automatic adjustment of the primary current i_1, thereby maintaining the flux ϕ at the original value. This value of flux is required to produce the emf of self induction e_1. Any reduction of the flux would cause a reduction of e_1, leaving a voltage difference between v_1 and e_1 which would be sufficient to increase the primary current and thereby re-establish the flux. Thus any current which flows in the secondary causes its counterpart to flow in the primary so that the flux ϕ (and therefore the mmf - M_m) shall always be maintained at a value such that the voltage applied v_1 to the primary terminals shall be balanced by the induced emf e_1 (neglecting voltage drops due to resistance and leakage flux effects). Thus if current flows in the secondary (i_2), then $i_1 = i_o + \frac{N_2}{N_1} i_2$ so that effective mmf in the core remains at M_m. In phasor notation:

$$\overline{I}_1 = \overline{I}_o + \frac{N_2}{N_1}\overline{I}_2$$

$\overline{I}_o$ is quite small compared to the rated current and is usually neglected if transformer is loaded. Thus:

$$\overline{I}_1 \approx \frac{N_2}{N_1}\overline{I}_2$$

It is therefore, evident that energy is conveyed from the primary to secondary by the flux: the primary stores the energy in the magnetic field, and an extraction of some of this for the secondary load is made up by the addition of energy from the primary, which consequently takes an increased current.

Thus by making the assumptions :

- Winding resistances are small
- Magnetising current is small
- Core losses are small
- Leakage fluxes are small

we can infer that (for an "ideal transformer"):

$$\frac{\overline{I}_1}{\overline{I}_2} = \frac{N_2}{N_1} = \frac{\overline{E}_2}{\overline{E}_1} = \frac{\overline{V}_2}{\overline{V}_1} \tag{1}$$

2.1 Equivalent Circuit of a practical Transformer

The practical transformer has coils of finite resistance. Though this resistance is actually distributed uniformly, it can be conceived as concentrated. Also, all the flux produced by the primary current cannot be confined into a desired path completely as an electric current. Though a greater proportion links both the coils(known as mutual flux), a small proportion called the leakage flux links one or other winding, but not both. It does not contribute to the transfer of energy from primary to secondary. On account of the leakage flux, both the windings have a voltage drop which is due to 'leakage reactance'. The transformer shown in Fig.1 can be resolved into an equivalent circuit as shown in Fig.2 (a) in which the resistance and leakage reactance of primary and secondary respectively are represented by lumped R_1, X_1, R_2 and X_2. This equivalent circuit can be further simplified by referring all quantities in the secondary side of the transformer to primary side and is shown in Fig.2(b). These referred quantities are given by:

$$R_2' = R_2(\tfrac{N_1}{N_2})^2 \qquad X_2' = X_2(\tfrac{N_1}{N_2})^2 \qquad I_2' = I_2(\tfrac{N_2}{N_1}) \qquad V_2' = V_2(\tfrac{N_1}{N_2})$$

Generally the voltage drops I_1R_1 and I_1X_1 are small and magnitude of $\overline{E}_1$ is approximately equal to that of $\overline{V}_1$. Under this condition, the shunt branch (comprising X_m and R_o) can be connected across the supply terminals. This approximate equivalent circuit (shown in Fig.3) simplifies the computation of currents and other performance characteristics of a practical transformer.

2.2 Determination of Equivalent Circuit Parameters

The equivalent circuit shown in fig.2(b) or 3 can be used to predict the performance of the transformer. All the circuit parameters must be known so that the equivalent circuit can be used for the above purpose. These parameters can be easily determined by performing tests that involve little power consumption. Two tests, a no-load test(or open circuit test) and short circuit test will provide information for determining the parameters of the equivalent circuit.

2.2.1 Open circuit (OC) test

The shunt branch parameters can be determined by performing this test. Since, the core loss and the magnetizing current depend on applied voltage, this test is performed by applying the rated voltage to one of the windings keeping the other winding open (generally HV winding is kept open and rated voltage is applied to LV winding). The circuit diagram to conduct this test is shown in Fig.4. Since, the secondary terminals are open (no load is connected across the secondary), current drawn from the source is called as *no load current*. On no-load, the approximate equivalent circuit shown in Fig.3 can be further reduced and is shown in Fig.5 (a). Under no-load condition the power input to the transformer is equal to the sum of losses in the primary winding resistance R_1, (refer fig.2b) and core loss. Since, no load current is very small, the loss in winding resistance is neglected. Hence, on no load the power drawn from the source is dissipated as heat in the core. If I_o and P_i are the current and input power drawn by the transformer at rated voltage V_1 respectively, then

$$\cos\zeta_o = \frac{P_i}{V_1.I_0}$$

From fig.5(b),

$$I_c{=}I_0\cos\zeta_o, \qquad I_m{=}I_0\sin\zeta_o,$$

Therefore,

$$R_0 = V_1/I_c, \qquad X_m = V_1/I_m$$

2.2.2 Short circuit (SC) test

Consider the circuit shown in Fig.3. Suppose the input voltage is reduced to a small fraction of rated value and secondary terminals are short-circuited. A current will circulate in the secondary winding. Since a small fraction of rated voltage is applied to the primary winding, the flux in the core and hence the core loss is very small. Hence, the power input on short circuit is dissipated as heat in the winding. The circuit diagram to conduct this test is shown in Fig.6 (a). In this test, the LV terminals of the transformer are short circuited. The primary voltage is gradually applied till the rated current flows in the winding. Since, the applied voltage is very small (may be of the order of $5-8\%$), the magnetizing branch can now be eliminated from the equivalent circuit. The modified equivalent circuit is shown in Fig.6(b). If V_{sc} is the applied voltage to circulate the rated current (I_2') on short circuit, and P_c is the power input to the transformer then,

$$Z_{sc} = \frac{V_{sc}}{I_2'} \qquad \cos\theta = \frac{P_c}{V_{sc}.I_2'}$$

Therefore,

$$(R_1 + R_2') = Z_{sc}\cos\theta, \qquad (X_1 + X_2') = Z_{sc}\sin\theta$$

2.3 Efficiency

Efficiency of the transformer is defined as:

$$\eta = \frac{\text{output power}}{\text{input power}}$$

Interms of losses,

$$\eta = \frac{\text{output power}}{\text{output power+ iron losses+copper losses}}$$

Let 'S' be the rated VA of the transformer, 'x' is the fraction of full load the transformer is supplying, and ζ is the load power factor angle. Under this condition the output power of the transformer is $= x.S.\cos\zeta$. If P_c is the copper loss (loss in winding resistance) at rated current, the corresponding loss while supplying the fraction of load is $= x^2.P_c$. With transformers of normal design, the flux in the core varies only a few percent between no-load to full load. Consequently it is permissible to regard the core loss (iron loss) as constant, regardless of load. Let this loss be P_i. Therefore equation becomes :

$$\eta = \frac{x.S.\cos\zeta}{x.S.\cos\zeta + P_i + P_c.x^2}$$

2.4 Regulation

From Fig.3 it can be seen that if the input voltage is held constant, the voltage at the secondary terminals varies with load. Regulation is defined as the change in magnitude of secondary (terminal) voltage, when the load is thrown off with primary voltage held constant. Since, the change in secondary voltage depends only on the load current, the equivalent circuit is further simplified and is shown in Fig.7. The vector diagrams for lagging, unity and leading powerfactor loads are shown in Fig.8. It can be proved that angle σ is very small and can be neglected. In that case, the expression for regulation is given by

$$\%regulation = \frac{I_2'.R_{eq}.\cos\zeta \pm I_2'.X_{eq}.\sin\zeta}{V_2'} \times 100 \tag{2}$$

where

I_2'=load current, $R_{eq} = R_1 + R_2'$, $X_{eq} = X_1 + X_2'$, '+' sign for lagging pf & '-' for leading pf.

Note to TAs/RAs: Open the cover of the transformer and show the students HV and LV terminals, conductors used for LV and HV winding. Also show them E & I laminations, and ferrite core. Also, conduct the no-load test on high frequency ferrite core transformer at

• 50 Hz (using single phase ac source). Ask the students to observe the deflection on the ammeter as you increase the voltage. Observe the current waveform on the power analyzer. Note down the magnitude of applied voltage.

• about 10 kHz (use the signal generator) and observe the waveforms on the storage oscilloscope. Note down the magnitude of applied voltage.

3 Procedure

Note down the name plate readings and determine the rated currents for both the windings.

3.1 No-Load Test:

- Connect the circuit as shown in fig.4.
- Apply voltage to the LV side in steps upto the rated voltage and for each case record primary current and power drawn from the source. Also, observe the current waveform on the power analyzer.
- Increase the applied voltage by 10% and repeat the above step.
- Reduce the output voltage of the variac to zero and switch-off the supply.

3.2 Short-Circuit Test:

- Connect the circuit as shown in Fig.6(a). Set the autotransformer output to zero. **It is extremely important to note that a low voltage is to be applied to the primary winding.**
- Adjust the output of the autotransformer such that rated current flows through the windings. Record the applied voltage, current and input power.
- Reduce the output voltage of the autotransformer to zero and put off the supply.

3.3 Voltage regulation test

- Load the 230 V side of the transformer with the bulb arrangement connected at the bench and energize the transformer from the 115 V side. (Ensure that the current rating of the transformer is not violated)

- Measure the load side voltage (230V) with and without load using multi-meter and measure current and power factor using the power analyser.

- Calculate the voltage regulation using the equivalent parameters derived from the no-load and short-circuit tests, employing the formula mentioned in the manual.

- Determine the voltage regulation from the load and no-load voltage measurements taken previously.

- Report the percentage error in the voltage regulation between step 3 and step 4 and mention the reason for the error.

4 Report

- Determine the equivalent circuit parameters from the test results.
- Using equivalent circuit parameters compute the following:
  - regulation at 25%, 75% and full load for powerfactor = 1, 0.6 lag and 0.6 lead.
  - efficiency at 25%, 50%, 75% and full load for powerfactor = 1, 0.8 lag, and 0.6 lead.
- Plot the variation of
  - Efficiency with load VA for each power factor
  - Regulation with powerfactor.

$- - - - * * * - --$

5 Questions to be answered

- Which winding (LV or HV) should be kept open while conducting OC test? Justify your answer.
- Assume that the given transformer has the following name plate ratings:
  40 kVA, 440 V/11 kV, 50 Hz.
  What do these numbers imply?
- Comment on the nature of the current waveform drawn from the source during OC test for (i) 50%, (ii) 100% and (iii) 110% of the rated voltage.
- Can the regulation be negative? What does it signify?
- Assume that you have been given a transformer manufactured in the US (The supply voltage and frequency are 110 V and 60 Hz respectively). What voltage will you apply if this transformer is to be used in this country? Justify your answer.
- What is the reason for high no load current at lower-than-rated voltage for the no load test on high frequency transformer which was demonstrated to you by the TAs ?
- Assume that you have been given two transformers of identical VA, and voltage ratings. But one of them is a 10 kHz transformer and another is a 100 Hz transformer. Just by inspection, how would you identify which one is the high frequency transformer? Justify your answer.
- What is an 'impedance matching' transformer? Name one instrument of everyday use, in which this transformer being used.

$- - - - * * * - --$

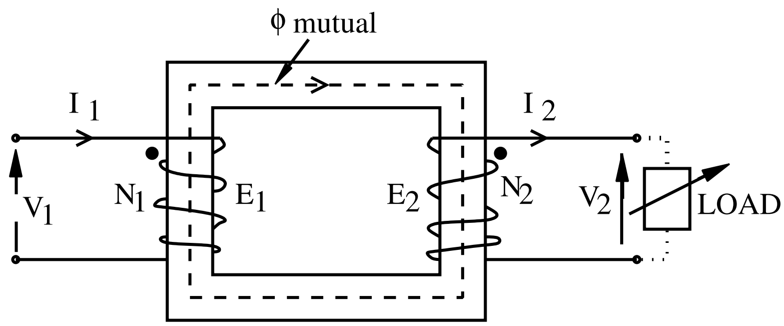
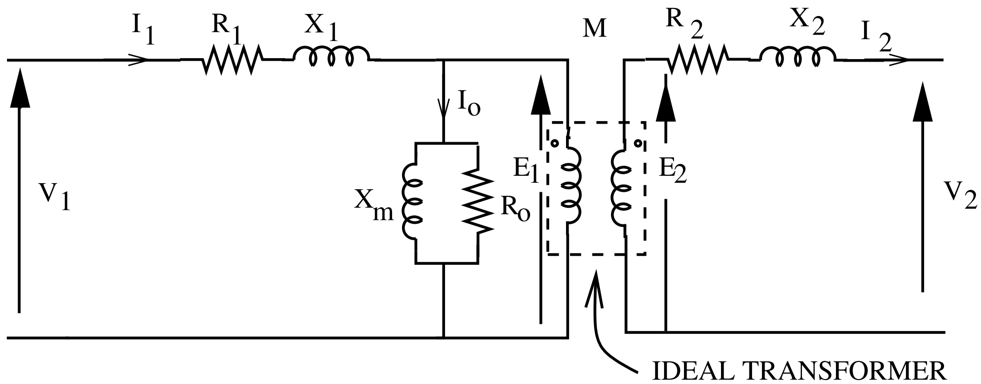
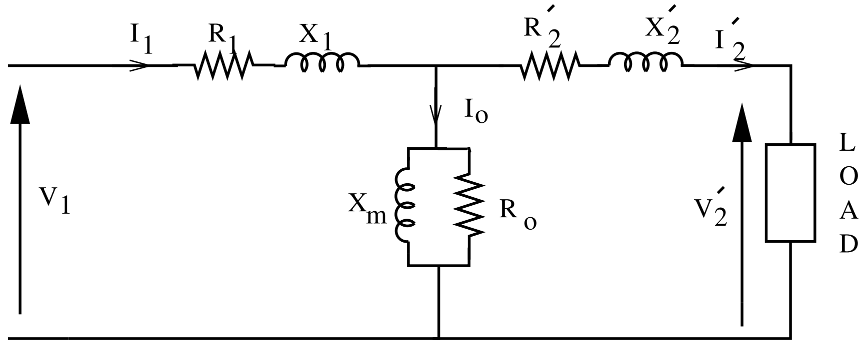


Fig.1 Elementary Transformer



(a)



(b)

Fig.2 Development of Transformer Equivalent Circuit

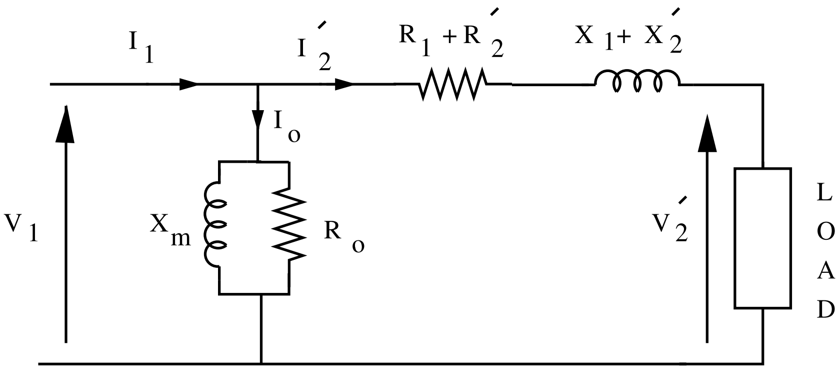


Fig.3 Approximate equivalent circuit of transformer

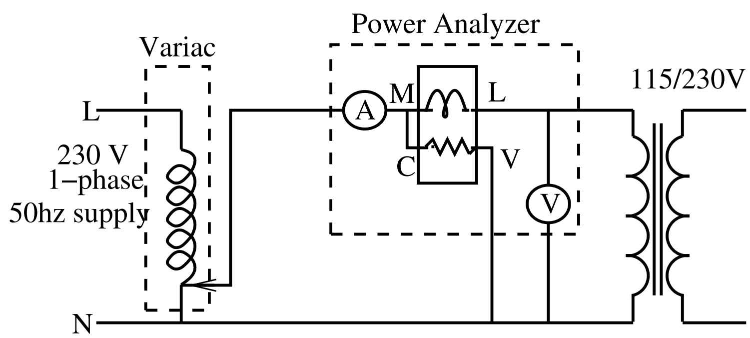
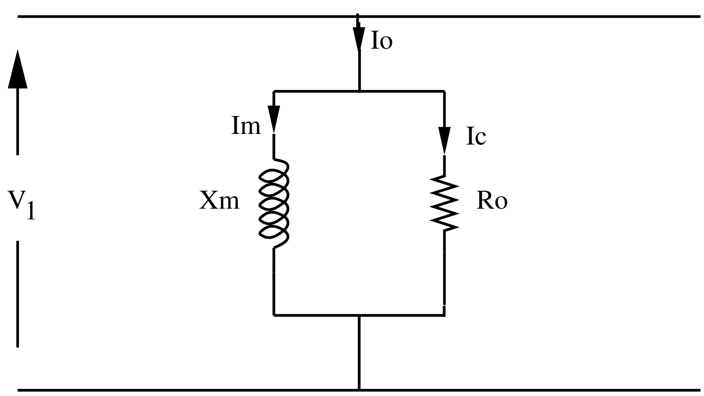


Fig.4 Circuit Diagram for No−Load Test



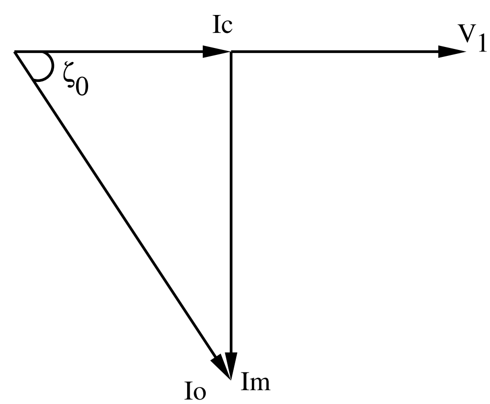


Fig.5(a) Equivalent Circuit on No−Load

Fig.5(b) Phasor Diagram on No−Load

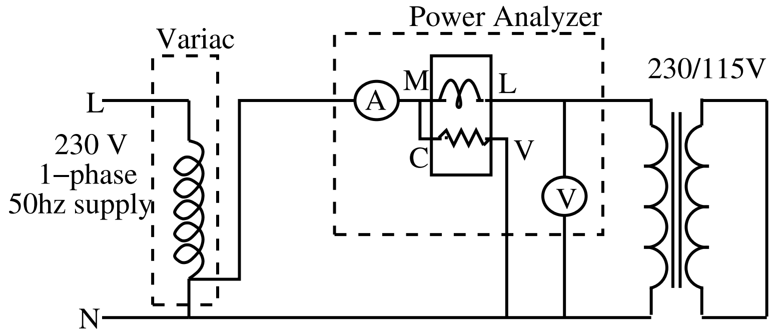


Fig.6(a) Circuit Diagram for Short−Circuit Test

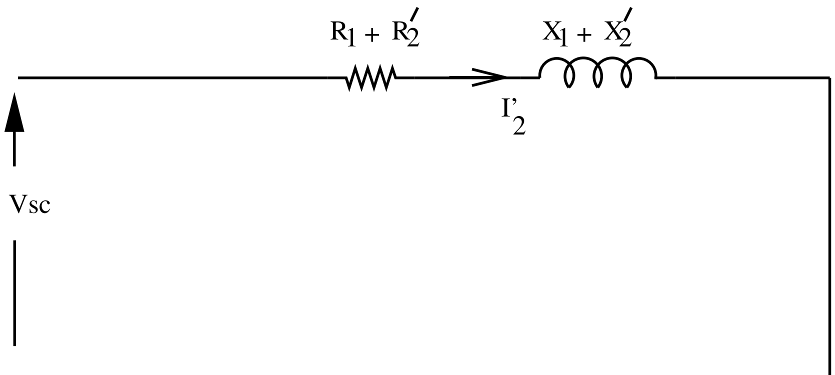


Fig.6(b) Equivalent Circuit on Short Circuit

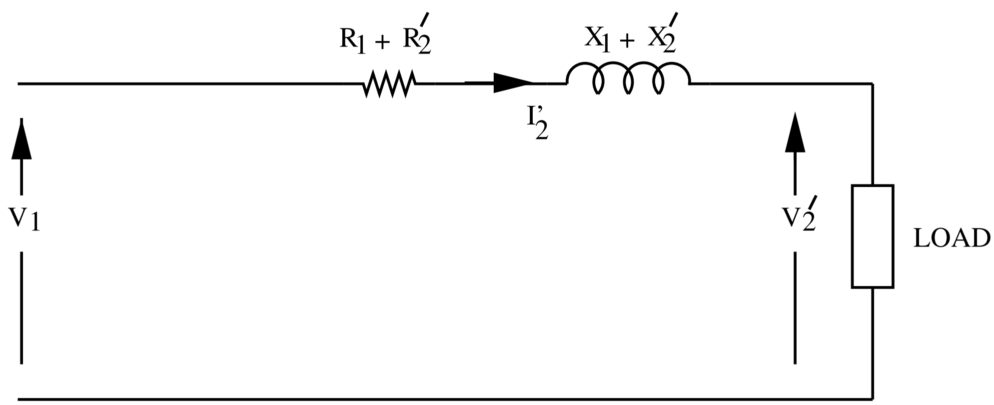
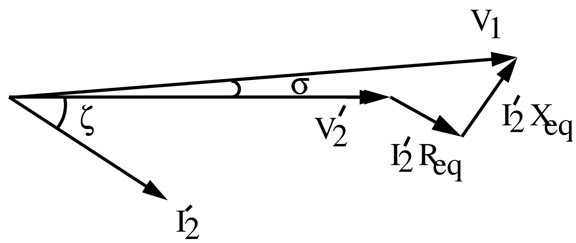
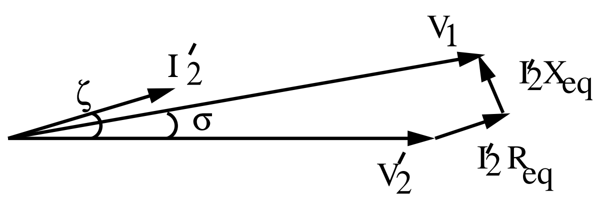


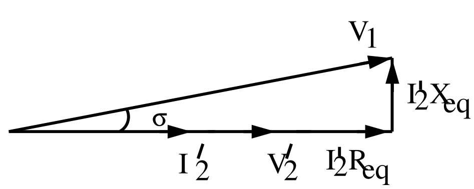
Fig.7 Equivalent Circuit to determine Regulation



(a) Lagging Power Factor



(b) Leading Power Factor



(c) Unity Power Factor

Fig.8 Vector diagram for various load conditions

Experiment No: 4

Characteristics of Separately Excited DC motor

1 Aim

To study the variation of speed with
- Armature Voltage
- Field Current

and to obtain the performance characteristics (T-ω) of a separately excited (S.E.) DC motor.

2 Theory

One of the unique features of the DC motor which has helped to maintain its supremacy over other electric drive systems, is its ability to provide a smooth and wide range of speed control with relative ease. This is because the mmf (magneto-motive force) produced by field coil and that produced by armature coil are always at quadrature, and hence they can be controlled independently. As shown in Fig.1, field mmf (F_s) is taken along the x-axis (also known as direct or d-axis) and the armature mmf (F_a) is along the y-axis (quadrature or q-axis). The generalized torque expression can be written as:

$$T_e \propto F_s F_a sin\angle(F_s \& F_a)$$

Since this angle is 90^o, the expression becomes $T_e \propto F_s F_a$. Now, F_s and F_a are proportional to field current (I_F) and armature current (I_a) respectively. Therefore $T_e \propto I_F I_a$. Since the angle between I_F and I_a is always 90^o, the ratio ($\frac{T_e}{I_a}$) is maximum. This is another important feature of the DC machine (in other machines, additional control is required to achieve this feature). Generally, it is assumed that the magnetic circuit is linear. Therefore, Φ is proportional to I_F. Hence, the torque expression becomes T_e = K ΦI_a, where K is constant.

2.1 Speed Control

The other basic equations governing the steady-state operation of the DC motor are:

$$V_a = I_a R_a + E_b, \qquad E_b = K\phi\omega, \qquad \text{and} \qquad I_F = \frac{V_F}{R_F}$$

Alternate method of deriving the expression for torque is as follows:
Multiplying the first equation by I_a we get, $V_a I_a = I_a^2\ R_a + E_b\ I_a$
The first term in the above equation is the power input to the armature, second term is the power lost as heat in the armature resistance and the last term is the power developed in the armature. This power should be equal to the mechanical power ($T_e\ \omega$) if mechanical losses (friction and windage) are neglected.
Equating $E_b\ I_a$ = (K $\phi\ \omega$) $I_a = T_e\ \omega$
Therefore T_e = K $\phi\ I_a$
Substituting for I_a in terms of torque and flux, the relationship between T_e and ω is given by:

$$\omega = \frac{V_a}{K\phi} - \frac{T_e R_a}{(K\phi)^2}$$

If the armature terminal voltage V_a and airgap flux ϕ are held constant, the above equation can be written as:

$$\omega = \text{A} + \text{B}\ T_e,$$

where A and B are constants. This is an equation of a straight line wherein, A is the y-axis intercept and (-B) is the slope. The y-axis intercept represents the no-load speed which depends only on the

terminal voltage and air gap flux. The variation of speed with torque is shown in Fig.2. Generally, the drop in speed with increase in torque is small (it is desirable that the speed of rotation is independent of load coupled to the motor shaft). A point to be noted is that in an actual machine, armature reaction helps in maintaining the speed almost constant. Therefore if V_a and ϕ are held constant, the speed of a separately excited dc motor will remain almost constant and it is independent of torque applied to the shaft. Hence in order to vary the speed of rotation over a wide range, the no-load speed (magnitude of 'A') should be varied. This can be achieved by the following methods:
• By controlling the voltage applied to the armature terminals of the machine
• By controlling the flux produced by the field winding

2.1.1 Armature Voltage control:

The schematic diagram for this control technique is shown in Fig.3(a). In this method, the field current (hence ϕ) is held constant at its rated value and V_a is varied. The speed-torque characteristics for this method are shown in Fig.3(b). These characteristics are drawn for various values of V_a and fixed value of ϕ. This method of speed control is used for speed below the rated value. In addition, the following point may be noted:

* Since ϕ is held constant, the speed of rotation changes linearly with V_a. Motor will draw a constant armature current I_a from the source if it is driving a constant torque load ($T_e = K\phi I_a$). Under this working condition, the power (P) drawn by the motor varies linearly with the speed. This mode of operation is known as **constant flux** or **constant torque mode.** The variation of the various quantities with speed is shown in Fig.3(c).

2.1.2 Field Control:

The schematic diagram for this control technique is shown in Fig.3(d). In this method, the armature voltage is held constant at its rated value and the field current is reduced. The speed of the motor changes in inverse proportion to ϕ. The $T - \omega$ characteristics for this method are shown in Fig.3(b). These characteristics are drawn for various values of ϕ and fixed value of V_a. It should be noted that the reduction in speed with torque is higher compared to that in the previous method. This method of speed control is used for speed above the rated value. In addition, the following point may be noted:

* non-linear inverse speed control of motor speed. This method also changes the value of developed torque for a given armature current. If the armature current is held constant at the rated value, the input power and therefore output power remains approximately constant (assuming that frictional and windage losses remain constant). Hence, this operating zone is known as either **constant hp (horse-power)** or **field weakening zone**. Generally the maximum speed of rotation is kept within 150% of the rated value.

2.2 Variable Voltage DC Source:

Both armature voltage and field control methods require a variable voltage dc source. If a fixed-voltage dc power supply is available, voltage applied to the armature or field circuits can be varied by connecting a variable resistance in series with these circuits. However, this results in increased losses, heat and poor efficiency Nowadays, power electronic controllers are increasingly being used to obtain variable dc (or ac) voltage supply from ac source. The advantages are smooth & flexible control, and high efficiency (one such example is elegant, light weight miniature size fan regulator. This regulator is mounted inside the switch board, while 'old' fan regulators are mounted on the switch board. Apart from larger size, the old regulators dissipate heat at low speed of operation).

Fig.4 shows the output voltage waveform of a full wave diode bridge. If the input voltage to the bridge is $V_m \sin \omega t$, then the average value of the output voltage is given by:

$$V_{av} = \frac{2V_m}{\pi}$$

From the output voltage waveform, it can be observed that the waveform is continuous and the instantaneous value is always finite and positive. Hence the average value of the output voltage depends only on the peak value of the input voltage. An autotransformer is now required to vary the output dc voltage by varying the peak input voltage.

The average value of the output voltage can also be reduced if the instantaneous value of the output voltage is made either zero or negative. This is possible by using power semiconductor devices other than diodes (e.g. thyristors). This results in the reduction of size and cost, and improvement in efficiency. However, the applied voltage to the armature is continuously pulsating. In order to reduce the pulsation in the current drawn by the motor, (developed torque depends not on the applied voltage but on armature current and flux) an inductor is connected in series with the armature. Since the current flowing through the inductor is dc, the average voltage drop across it is zero at steady state. However, the current becomes almost constant (property of an inductor- current can not change instantaneously).

2.3 Starting:

From the basic equation governing the steady state operation of dc motor, we have the following:

$$I_a = \frac{(V_a - K\phi\omega)}{R_a}, \qquad \text{and} \qquad T_e = K\phi I_a$$

The torque developed at starting is determined by the product of total flux and armature ampere-turns. This torque is utilized partly in overcoming friction, partly in accelerating the armature, and partly in accelerating the load. The value of starting torque required from a motor will then depend very largely on the load. At standstill there is no back emf, so that to circulate full load current in the armature a very small voltage is required. Neglecting the effect of armature inductance, the voltage that must be applied to the armature at starting depends only on armature resistance. Since, this resistance is very small, a large current will flow if the rated voltage is directly applied to the armature (for the given machine whose parameters are given below, this current is approximately $\frac{180}{2} = 90A$, while the full load rated current is of the order of 10.5 A!). The starting current can be limited to a safe value by the following methods:

- including external resistance only in the armature circuit so that machine develops necessary starting torque. As the motor speeds up, the back emf is generated and the current falls. Generally a large resistance is necessary to limit the starting current. If this resistance is left in the circuit, the steady state speed would be very low and in addition there would be waste of power in the resistance. It is therefore becomes necessary to cut out the whole of the resistance so that rated speed is obtained.
- applying a low voltage by using a variable dc power supply. This voltage is increased as the machine accelerates.

The developed torque and the rate at which back emf is generated depends on the air gap flux. In order to have faster acceleration rated voltage is applied to the field winding while starting.

3 Procedure:

There are three machines mounted on the stand, out of which two of them are dc machines. Note the name plate ratings of these machines and use one of them as a dc motor and the other as a separately excited dc generator. The parameters are:

- 1.5 kW dc machine: $R_a = 2.04\Omega$, $R_F = 415\Omega$, Friction & windage loss at 1500 rpm = 53 W.
- 1.1 kW dc machine: $R_a = 2.1\Omega$, $R_F = 415\Omega$, Friction & windage loss at 1500 rpm = 53 W.

3.1 Precaution:

* **Always start the motor by applying a low input voltage (V_a) to the armature, else the power electronic controller may get damaged due to heavy inrush current. Also, apply the rated voltage to the field winding of the motor. In case the drive has tripped, bring back the voltage control knob on the power controller feeding armature of the dc motor to 'zero position' and then press the 'green' button.**

3.2 Armature Voltage control:

A. Connect the circuit as shown in Fig.5. In this experiment the motor is loaded by loading the generator. Put off all switches of the lamp load and open the main switch 'S' connected between the load and the armature of the DC generator. Also, **open switches S_1, S_2 and S_3**. These are on machine stand.

B. Switch on the AC supply to the power electronic controller supplying power to the field winding of the motor. Using the knob on the controller, apply the rated voltage to the field winding.

C. Switch on the AC supply to the power electronic controller supplying power to the armature of the motor. Using the knob on the controller, slowly increase the voltage to the armature till the rated value. Also, apply the rated voltage to the field winding of the generator (the output terminals are at the rear side of the controller feeding the armature of the motor). Note down the meter readings, speed and direction of rotation.

E. Close switch S and load the generator in steps till it reaches full load. For each load keep the input voltage to the armature constant & note down all the meter readings and speed. **You may find that beyond a certain load, it is not possible to keep the armature input voltage constant. Do not increase the load beyond this point**. Switch off the load and open S.

F. Now apply 85% of the rated voltage to the armature and repeat the above step. Do not switch off the supply.

3.3 Field Control:

A. Using the power electronic controller apply the rated voltage to the armature of the DC motor.

B. Using the power electronic controller suppling power to the field of the DC motor, reduce the field current to 0.4 A.

C. Close S and load the generator in steps till full load. For each load keep the input voltage to the armature and field current constant, and note down all the meter readings and speed. **You may find that beyond a certain load, it is not possible to keep the armature input voltage constant. Do not increase the load beyond this point**. Switch off the load and open S.

D. Now reduce the field current to 0.38A with armature voltage unchanged at its rated value. Repeat the above step.

E. Reduce the voltage applied to the armature to zero.

3.4 Reversal of Direction of Rotation

A. Without disturbing other parts of the circuit interchange the supply terminals to the armature of motor. Apply the rated voltage to the field winding of the motor, and slowly increase the voltage to the armature till the rated value. Note down the speed and direction of rotation.

E. Reduce the voltage applied to the armature of the motor to zero and put off the supply to both the power electronic controllers.

3.5 Plotting of $T - \omega$ Characteristics:

* Using the plot of efficiency vs output power of the generator, for each output determine the input to the generator.

* Assuming 100% coupling efficiency, the above input power is the output of the motor. Knowing the speed of the motor, determine the torque. Plot T-ω characteristics.

− − − ∗ ∗ ∗ ∗ − − − −

4 Questions to be answered:

* The condition to develop steady torque is that the relative speed between the two fields (in this case F_s and F_a) should be zero. In other words, the two fields should be stationary w.r.t each other. In dc motor, the speed of F_s is zero (stator coil is stationary and it is excited by dc current), while the armature is rotating. Explain how is the above condition satisfied?

* Explain why the full field and reduced armature voltage is applied to dc motor while starting.

* Whether the speed is independent of the direction of rotation? If it isn't what could be the reason?

* 'Armature reaction improves the speed regulation' Is this statement true? Justify your answer.

* What may happen if the field circuit gets open circuited during motoring?

* Which type of motor is most suitable for electric traction?

* What are the limitations of S.E. dc motor?

* Why is it mentioned in section-2.1.2 that the maximum speed of operation is about 150% of the rated speed?

* In dc series motor the field winding is connected in series with the armature. Can a separately excited motor be converted to series motor by connecting the field in series? Justify your answer.

− − − ∗ ∗ ∗ ∗ − − − −

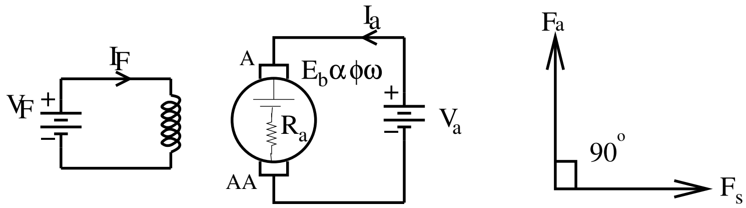


Fig 1 Separately Exicited DC Motor

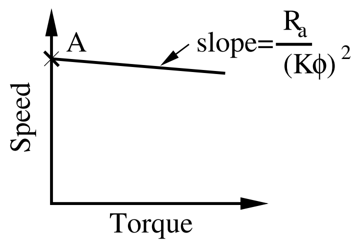


Fig.2 T−ω characteristics of Separately
Excited DC Motor

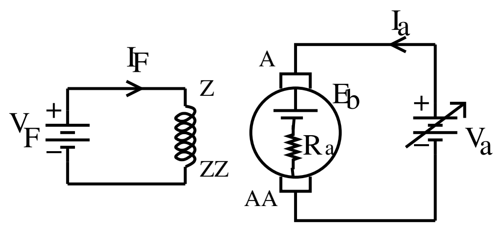


Fig.3 (a) Schematic diagram for armature
voltage control

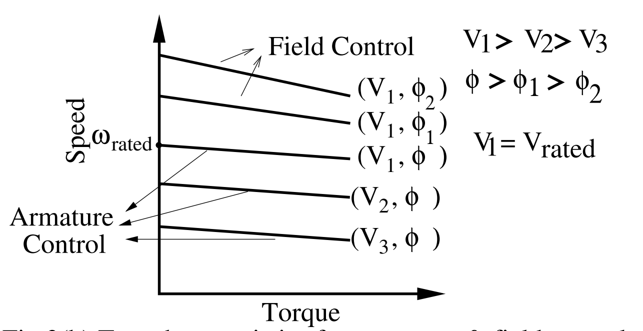


Fig.3(b) T−ω characteristics for armature & field control

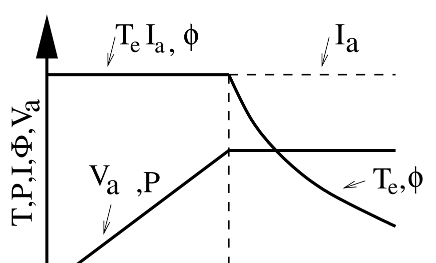


Fig.3(c) Variation of various quantities with speed

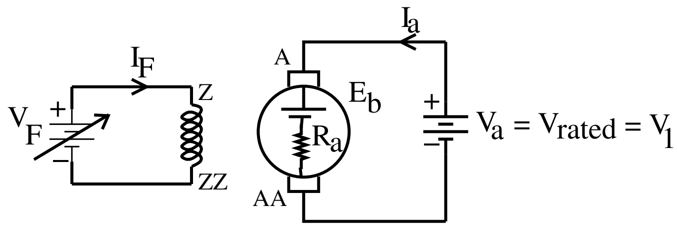


Fig. 3(d) Schematic diagram for field control

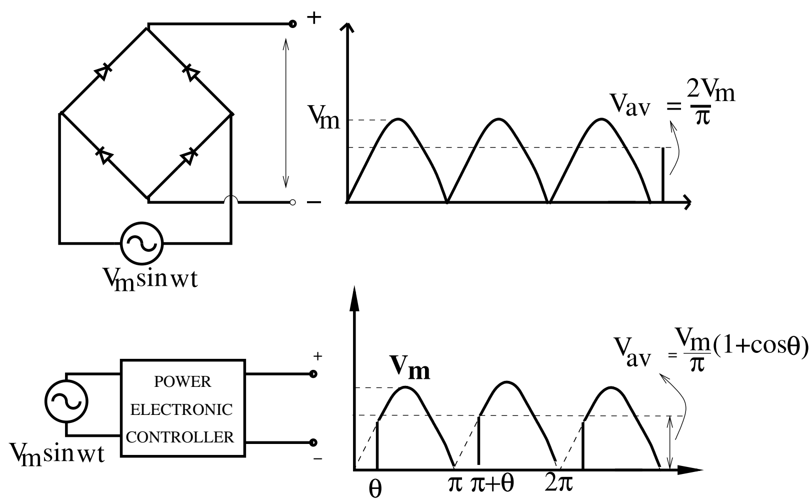


Fig.4 Output voltage waveform of Power Electronic controller

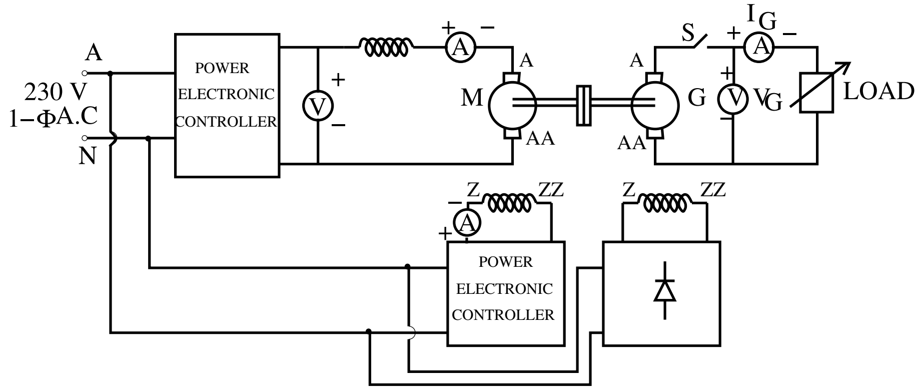
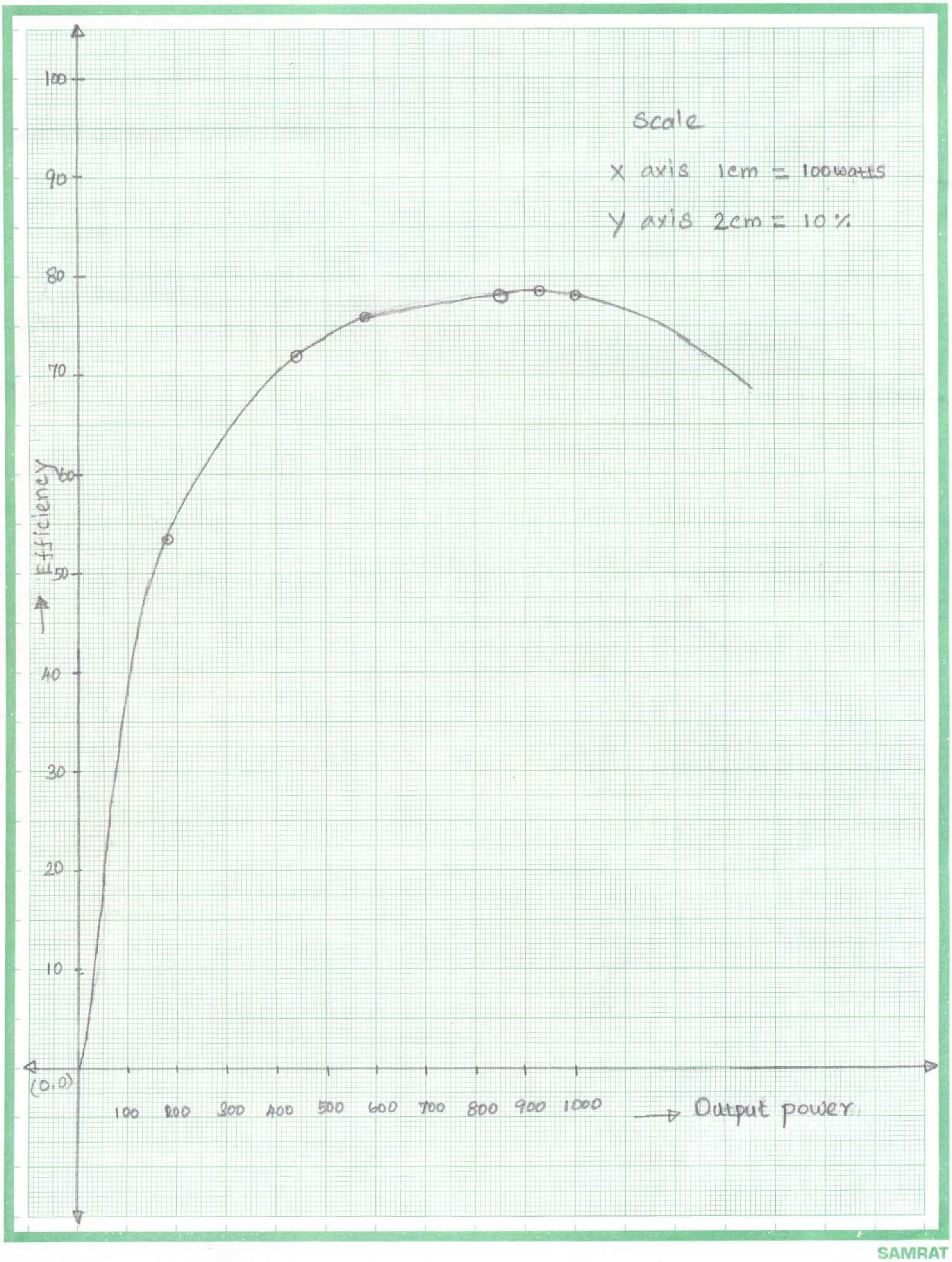


Fig.5 Circuit diagram for speed control of Separately Excited DC Motor

Efficiency Vs Output power of D.C Generator

Date :



Experiment No: 3

Speed Control of 3 Phase Induction Motor

1 Aim

To study the behaviour of inverter fed three phase phase induction motor (IM) and to obtain the performance characteristics (T-N_r) of the motor

2 Theory

In a DC machine, the stator winding is excited by DC current and hence the field produced by this winding is time invariant in nature. In this machine the conversion of energy from electrical to mechanical form or vice versa is possible by one of the following ways:

- rotating the rotor in the field produced by the stator
- feeding external dc current through carbon brushes to the rotor

Now consider three coils A, B and C of N turns each, displaced in space by 120^o degrees and connected to a balanced 3 phase system as shown in Fig.1. (Note that the stator winding of 3 phase IM is distributed in a large number of slots as shown in Fig.2). The expressions for the current drawn by these coils are given by:

$$i_a = I\sin(\omega_s t) \qquad i_b = I\sin(\omega_s t + 120^o) \qquad i_c = I\sin(\omega_s t + 240^o)$$

where $\omega_s = 2\pi F_1$. When this alternating current flows through the coil it produces a pulsating magnetic field whose amplitude and direction depend on the instantaneous value of the current flowing through the coil. Each phase winding produces a similar magnetic field displaced by 120^o degrees in **space** from each other. The steps involved in determining the magnitude and position of the resultant field produced by these coils are as follows:

- Resolve the field produced by individual coil along x and y axes
- Determine $\sum x$ and $\sum y$ components
- Find the magnitude and angle of the resultant magnetic field with respect to the axis of coil-A.

The sum of the x-axis component of the field produced by the three coils is given by:

$$\sum x = Ni_a + Ni_b\cos 120^o + Ni_c\cos 240^o \qquad = Ni_a - (N/2)[i_b + i_c]$$

Since $i_a + i_b + i_c = 0$, the above equation can be written as: $\sum x = (3/2)Ni_a$

Similarly,

$$\sum y = 0 + Ni_b\sin 120^o + Ni_c\sin 240^o \qquad = (\sqrt{3}/2)N[i_b - i_c]$$

The magnitude and angle of the resultant magnetic field are given by:

$$R = \sqrt{\left(\sum x\right)^2 + \left(\sum y\right)^2} \qquad \& \qquad \theta = tan^{-1}\frac{\sum y}{\sum x}$$

Table-I gives the x and y axis components of the field produced by each coil, $\sum x$ and $\sum y$ components, and the magnitude and angle of the resultant magnetic field for various instantaneous values of the input current. It can be observed that the resultant of the three mmf (magneto-motive force or field) vectors is a vector whose magnitude remains constant (1.5 times the amplitude of mmf produced by the individual phases alone) and its position depends on the instantaneous value of input currents.

$\omega_s t$	i_a	i_b	i_c	$\sum x$	$\sum y$	R	θ
0^o	0	$+(\sqrt{3}/2)I$	$-(\sqrt{3}/2)I$	0	(3/2)NI	(3/2)NI	90^o
30^o	I/2	I/2	-I	(3/4)NI	$(3\sqrt{3}/4)NI$	(3/2)NI	60^o
90^o	I	-I/2	-I/2	(3/2)NI	0	(3/2)NI	0^o
180^o	0	$-(\sqrt{3}/2)I$	$+(\sqrt{3}/2)I$	0	-(3/2)NI	(3/2)NI	180^o

When the instantaneous value of phase-A current is zero (corresponding values of phases B and C are $(\sqrt{3}/2)$I and $-(\sqrt{3}/2)$ I respectively) the resultant field is aligned along the y-axis. When the input cycle completes 90^o the resultant field also rotates by the same amount. In other words, **the result of displacing the three windings by 120^o in space phase and displacing the winding currents by 120^o in time phase is a single positive revolving field of constant magnitude**. Under balanced three phase conditions, the three phase winding produces an air gap mmf wave which rotates at synchronous angular velocity determined by the supply frequency alone. The speed of the rotating magnetic field is

$$\omega_m = \omega_s \tfrac{2}{P} \text{ radians (mechanical)/sec.} \qquad \text{since, } 1^o Elec = (\tfrac{2}{P})^o Mech.$$

If N_s is the speed of the stator magnetic field in 'rpm', then

$$\tfrac{2\pi N_s}{60} = (\tfrac{2}{P})2\pi F_1 \qquad N_s = \tfrac{120F_1}{P}$$

where P is the number of poles.
There are two types of rotor construction, one of them being squirrel cage type. In this type of construction, aluminium bars are embedded in the rotor slots and short- circuited at each end by aluminum end rings. When the rotor is at rest, synchronously rotating stator magnetic field induces a voltage of stator frequency in the rotor. This induced voltage produces rotor currents that interact with the air gap field to produce torque. Since the relative speed between the rotor and the stator field is maximum, the magnitude of the induced voltage in the rotor and hence the current is maximum. Similar to a transformer, for any current flowing in the rotor of an induction motor causes its counterpart to flow in the stator. **Therefore if an induction motor is started at rated voltage and frequency, a high current will be drawn from the source. The magnitude of this current could be approximately 6 times the full load current**. If the rotor is free to rotate, the torque will cause it to rotate in the direction of the rotating field. As the rotor speed increases, the relative speed between the rotor and the stator field reduces. The effect is two fold: (a) induced voltage in the rotor and the hence the current falls, and (b) the frequency of the rotor induced voltage and current falls. The rotor will eventually reach a steady-state speed N_r that is less than the synchronous speed N_s. Rotor cannot by itself achieve synchronous speed because at $N_r = N_s$, the rotor conductors would then be stationary with respect to the stator field; no induced voltage would be induced in the rotor, and hence no torque would be produced. The difference between N_s and N_r is commonly referred to as the **slip speed** and the slip 's' is usually expressed as follows:

$$s = \tfrac{N_s - N_r}{N_s} \qquad N_r = (1-s)N_s$$

In terms of frequency

$$s = \tfrac{F_1 - F_3}{F_1} = \tfrac{\omega_s - \omega_r}{\omega_s} = \tfrac{F_2}{F_1} = \tfrac{\omega_2}{\omega_s} \qquad \text{and} \qquad F_2 = sF_1 \text{ Hz} \qquad \text{or} \qquad \omega_2 = s\omega_s \text{ rad/s}$$

where F_3 is the frequency corresponding to the speed of the rotor, and F_2 is the frequency of the voltage induced in the rotor. Now if the motor is running on no-load at a speed very close to synchronous speed, the induced voltage in the rotor winding will be very small, and so will be the currents thereby developing a torque just sufficient to maintain the rotor in motion. Suppose now that a mechanical load is put on the rotor shaft. The rotor will slow down and in doing so it will increase the slip. The induced

voltage in the rotor winding will now increase both in magnitude and frequency, and will produce more current and therefore more torque. The change in speed or slip required is normally small. The value of s for a medium sized motor may vary from 1 (on no load) to 3% (on full load). e.g. For a 4 pole, 50 Hz induction motor, the variation in speed from no-load to full load could be 1485 to 1455 rpm. The induction motor is therefore a machine of substantially constant speed.
With the rotor revolving in the same direction of rotation as the stator field, the frequency of the rotor currents is sF_1 Hz and they will produce a rotating mmf which will rotate at sN_s rpm with respect to the rotor in the forward direction. Since the rotor itself is rotating at N_r rpm with respect to stator, the speed of the field produced by the rotor currents is given by:

$$sN_s + N_r = sN_s + (1-s)N_s = N_s$$

We see that the field produced by rotor currents rotates at N_s with respect to stator and hence in synchronism with the field produced by the stator currents. Because the rotor and stator fields rotate synchronously, they are stationary with respect to each other and thereby the machine develops a steady torque. Recall the generalized torque equation derived in the manual for expt. no:3, $T \propto F_s F_r \sin\delta$, where, F_s & F_r are stator field and rotor field respectively, and δ is the angle between them. One of the major differences between IM and DC motor is that in the case of a DC motor, δ is always 90º while in IM it is a function of load. Its value is approximately zero under no-load condition.

Load $= 0 \Rightarrow \delta_{IM} \approx 0$

2.1 Equivalent Circuit Representation:

The rotor of the induction motor has no electrically conducting connection with the stator supply. The power that it receives and converts to mechanical output at the shaft is transfered inductively - i.e. by transformer action - from stator to rotor by means of mutual flux. Thus, the electrical behaviour of an induction machine is similar to that of a transformer but with the additional feature of frequency transformation (Frequency of rotor current $F_2 = sF_1$). The per phase equivalent circuit of IM looks almost similar to that of a transformer. The steps followed to derive this circuit are almost the same as those in the case of transformer. This circuit is shown in Fig.3 in which
R_s and X_{sl} : stator winding resistance and leakage reactance
R_r' and X_{rl}' : referred rotor resistance and leakage reactance
R_c and X_m : the core loss component and magnetizing reactance
$\frac{R_r'(1-s)}{s}$: the electrical analogue of the mechanical load

Referring to this figure, an induction motor can be thought of as a generator feeding a fictitious resistance. It is fictitious because unlike in a transformer it is not an external resistance connected at the load terminals. The mechanical power developed per phase may be regarded as the ohmic loss in a fictitious secondary resistance $\frac{R_r'(1-s)}{s}$ load. Therefore, power developed by the motor is:

$$P_d = (I_r')^2 R_r'(1-s)/s$$

The rotor copper loss is given by: $P_c = (I_r')^2 R_r'$
The air gap power input (or input to rotor) is:

$$P_a = P_d + P_c = (I_r')^2 R_r'/s$$

An important conclusion can be drawn from the fact, out of the power P_a delivered to the rotor, a fraction 's' is lost as heat in the rotor and remaining (1-s) appears as mechanical power including friction, so that

$$P_a : P_c : P_d = 1 : s : (1-s)$$

Hence, the rotor power will always divide itself in this proportion. It is obviously advantageous to run with as small slip as possible. If the mechanical power developed by the motor is P_d at $n_r = (1-s)n_s$ rps, the total developed torque is:

$$T_d = \frac{3P_d}{\omega_r} = \frac{3P_a(1-s)}{2\pi n_s(1-s)} = \frac{3(I_r^{'})^2 R_r^{'}/s}{2\pi n_s}$$

Thus the torque developed is directly proportional to the air-gap power input, regardless of the speed of rotation. Generally, the voltage drops $I_1 R_s$ and $I_1 X_{sl}$ are small. The magnitude of E_1 is approximately equal to V_S. Under this condition, the shunt branch can be connected across the supply terminals (similar to transformer). The expression for equivalent rotor current $I_r^{'}$ is:

$$I_r^{'} = \frac{V_s}{\sqrt{[R_s + R_r^{'}/s]^2 + [x_{sl} + x_{rl}^{'}]^2}}$$

Therefore,

$$T_d = \frac{3{V_s}^2 R_r^{'}/s}{2\pi n_s[(R_s + R_r^{'}/s)^2 + (x_{sl} + x_{rl}^{'})^2]} \tag{1}$$

$$\propto V_s^2 \text{ if } F_1 \text{ is constant.}$$

At normal speeds close to synchronism, 's' is very small. Therefore, $|R_s + R_r^{'}/s| >> |x_{sl} + x_{rl}^{'}|$ and $|R_s| << |R_r^{'}/s|$. An increase in torque is developed by a nearly proportional increase in 's', giving the machine a $T - N_r$ curve nearly linear. Torque is zero when $N_r = N_s$ and increases linearly. The maximum torque that the motor can develop is determined by the condition $\frac{dT}{ds}$ =0. On differentiating the torque expression, it is found that the condition for maximum torque is

$$s = s_{max} = R_r^{'}/(R_s^2 + x^2)^{\frac{1}{2}}, \qquad x = x_{sl} + x_{rl}^{'}$$

If stator parameters are neglected, $s_{max} = \frac{R_r^{'}}{x_{rl}^{'}}$

At low speeds and at starting, 's' approaches unity. For a normal induction machine, due to the presence of airgap, the leakage flux is quite substantial. The typical value of $\frac{R_r}{x_{rl}} = 0.2$. Therefore $|R_s + R_r^{'}/s| << |x_{sl} + x_{rl}^{'}|$. Torque is inversely proportional to 's'. The $T - N_r$ curve is a rectangular hyperbola, as shown in Fig. 4. The effect of reducing V_s on torque is also shown in this figure.

Also, at normal speed of operation $|R_r^{'}/s| >> |x_{rl}^{'}|$. The rotor impedance angle $(tan^{-1}\{\frac{x_{rl}^{'}}{R_r^{'}/s}\})$ is approximately zero and therefore the rotor power factor (pf) is $\cong 1$ (rotor circuit is almost resistive. This fact can also be argued in the following way: At normal speed of operation, the frequency of rotor current is of the order of 0.5-1.5 Hz. For this very low frequency, $x_{rl} -> 0$ and the circuit becomes resistive. Rotor current is nearly in phase with rotor emf). However, the source has to supply the magnetizing current. Due to the presence of air gap, this current is quite substantial. Therefore, the source pf is always lagging (in case of transformer, the source powerfactor depends on load. It could be unity, lagging or leading). This powerfactor on no-load is very poor (if two-wattmeters are used to measure the input power, one of them would read negative) and improves with load.

2.2 Speed Control:

As mentioned earlier the induction motor is essentially a constant-speed motor. Its speed of rotation is determined by the synchronous speed. Many motor applications, however, require wide variation in motor speed. This can be achieved by varying the stator frequency of the motor thereby varying the synchronous speed. Let us now see the relationship between supply voltage and frequency, and developed torque. The torque equation can also be written as:

$$T_d = 3(\frac{P}{2})\frac{1}{\omega_s}\frac{V_s^2 R_r'/s}{[(R_r'/s+R_s)^2+(x_{sl}+x_{rl}')^2]}$$

Neglecting stator parameters (R_s & x_{sl})

$$T_d = 3(\frac{P}{2})\frac{1}{\omega_s}\frac{V_s^2 s R_r'}{[R_r^2+(s\omega_s)^2 L_{rl}'^2]} \quad \cong 3(\frac{P}{2})(\frac{V_s}{\omega_s})^2\frac{\omega_2}{R_r'}$$

Now, $$I_m = \frac{E_1}{X_m} = \frac{E_1}{2\pi F_1 L_m} \cong [\frac{V_s}{2\pi F_1}]\frac{1}{L_m}$$

Therefore, $$L_m I_m = \phi = \text{Air gap flux linkage} = \frac{V_s}{2\pi F_1}$$

and $$T_d \cong 3(\frac{P}{2})\frac{\phi^2\omega_2}{R_r'}$$

From the above analysis the following observations can be made:

* Developed torque remains constant if ϕ & ω_2 are held constant and is independent of F_1
* Air gap flux will remain constant if $\frac{V_s}{F_1}$ is held constant.
* Generally it is not a good engineering practice to supply a voltage higher than the rated. Therefore air gap flux can be held constant from very low speed to the rated speed.
* $T_d \propto \omega_2$ if air gap flux is held constant. Hence, torque can be controlled by controlling slip speed (ω_2). The shape of $T - N_r$ characteristics remain the same for any frequency below the rated. As F_1 decreases, the value of x-axis intercept decreases while that of y-axis intercept increases. Peak torque developed by the motor remains almost constant.
* Speed above the rated can be increased by keeping V_s at its rated value and increasing F_1. Flux and hence the peak torque capability of the motor reduces (This is also evident from equ.1).

Therefore in order to vary the speed over a wide range, the source should have the following features.
• The magnitude of output voltage should vary with frequency so that $\frac{V}{F}$ remains constant till 50 Hz.
• The magnitude of voltage should remain constant as the frequency is increased above 50 Hz.

$T - N_r$ characteristics of the motor fed from a source having the above mentioned features are shown in Fig. 5. **Since both magnitude and frequency of the source are variable, it is now possible to start the motor at a very low frequency. In that case the speed of the stator field and hence the relative speed between the rotor and the stator field would be low. The machine now draws less current at starting. It could be of the order of full load current and the developed torque of the order of its full load value.**

2.3 Variable Voltage Variable Frequency Source (VVVF)

In the event of a power failure, uninterrupted power supply (UPS) is often used for supplying critical loads such as computers used for controlling important process, etc. (same equipment is also used in residences as a backup in the event of a power failure. This power electronic equipment is also known as **Inverter**). Input power to the UPS (or inveter) comes from the battery bank. In the inverter used for home applications a 12 V Lead acid battery is often used. When the utility power supply is available, power is converted to DC using a rectifier. This dc power is used to charge the battery. In the event of a power failure, stored energy in the battery is used to supply the load. The inverter uses the stored DC power to convert into 50 Hz, 230 V AC. In fact, it is possible to use an inverter to change from dc to any desired frequency, not just 50 Hz.

The block diagram to generate VVVF supply is shown in Fig. 6. The ac power supply is converted to DC and it is filtered using a large capacitor. It maintains a constant voltage at the input of the inverter (similar to a battery) which is converted to AC in such a way that $\frac{V}{F}$ remains constant till F=50 Hz and above this frequency, magnitude of output voltage remains constant.

Note to TAs/RAs: There is a 3 Phase IM which is cut opened. Show the students rotor, rotor bars, end rings, stator coils etc. Also show them stator and rotor laminations.

3 Procedure

A Note down the name plate readings of IM and DC generator. From the name plate readings of the motor determine the net output available at the shaft and number of poles. You may have to justify your answer. **Open S_1, S_2 and S_3.** These are on the machine stand.

B Connect the circuit as shown in Fig.8 (a) and set the output voltage of the autotransformer to zero and switch on the three phase supply.

This part of the experiment is performed to validate the principle that when the VVVF fed motor is started at low frequency, it develops a much higher torque than that developed by the motor when started with reduced voltage at rated frequency. Go through the following steps (C-E) and then perform the experiment.

C Hold the shaft of the motor firmly and gradually increase the applied voltage to the motor till the rated current is drawn by it.

D Decrease the voltage to zero. Connect the circuit as shown in Fig.8(b).

E Set the inverter output frequency to 8Hz and repeat step-C. Did you experience a higher torque in the second case? In case you are not sure you may repeat the above steps.

This part of the experiment is performed to observe various waveforms of VVVF fed induction motor and to conduct the load test.

F Put off all the lamps and open S. Set the output frequency at 20Hz. Load the separately excited DC generator in steps (in constant flux operation, torque capability and not output power of the motor remains unchanged) and for each load note down the various meter readings and speed. Also observe the following on a digital storage oscilloscope.

- Line current
- Line-Line voltage at lower as well as at a higher time base. Make note of the nature of pulses (magnitude, rise and fall time, width etc).

G Repeat the above steps for the inverter output frequency of 40 and 60 Hz (Note that using VVVF source it is possible to increase the speed of rotation above the rated speed).

G Put off all the lamps and open S. Reduce the speed of the motor to zero.

H Interchange any two stator terminals. Put on the supply to the inverter and gradually increase the output frequency of the inverter. Note the direction of rotation.

3.1 Comments on your observations

You might have observed the following:

* Current drawn by the motor fed from a VVVF source is approximately sinusoidal.

* Line-Line voltage waveform is not a sinusoid. It has a large number of pulses of varying width and magnitude ranging from zero to approximately 300 V.

* The variation of magnitude from zero to 300 V and vice versa is very fast.

* The width of the pulses increases with stator frequency.

* Line-Line voltage waveform has a quarter-wave odd symmetry.

The motor is designed for a sinusoidal excitation. When it is fed by a sinusoidal voltage source, it draws a sinusoidal current. The current is still a sinusoid when it is fed from a VVVF source. This can happen only if the Fourier series of the voltage waveform has the following terms:

- Frequency of the first term is same as that of the supply frequency
- Frequency of the next term should be very high compared to the supply frequency (In the inverter provided to you this frequency is of the order of 5 KHz). The motor does not respond to these higher frequency excitation components.

Typical waveform of the line-line voltage and the harmonic spectrum is shown in Fig.7.

3.2 Procedure to determine the torque of the motor

- For each output power of the dc generator, determine the corresponding input power to the dc generator from the given output power vs η plot.
- Assuming 100% coupling efficiency, the above power is the output power of the motor.

− − − − ∗ ∗ ∗ ∗ − − −−

4 Questions to be answered

- You might have observed the intensity of the lamp (either incandescent bulb or fluorescent tube) reducing momentarily when an induction motor of 3-4 HP (or air-conditioner/refrigerator) is switched ON. What could be the reason?
- Why does the direction of rotation reverse when any two stator terminals are interchanged?
- What is the reason for decreasing the speed of the motor to a very low value and then interchanging any two stator terminals in order to reverse the direction of rotation?
- Which type of motor is used in (i) ceiling fan (ii) mixer (iii) vacuum cleaner ?
- What are the advantages of induction motor over separately excited dc motor?
- Why induction motor is also known as asynchronous motor?

− − − − ∗ ∗ ∗ ∗ − − −−

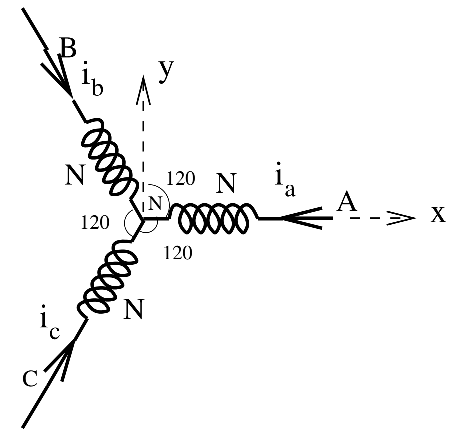


Figure 1: Coil arrangement to produce rotating magnetic field

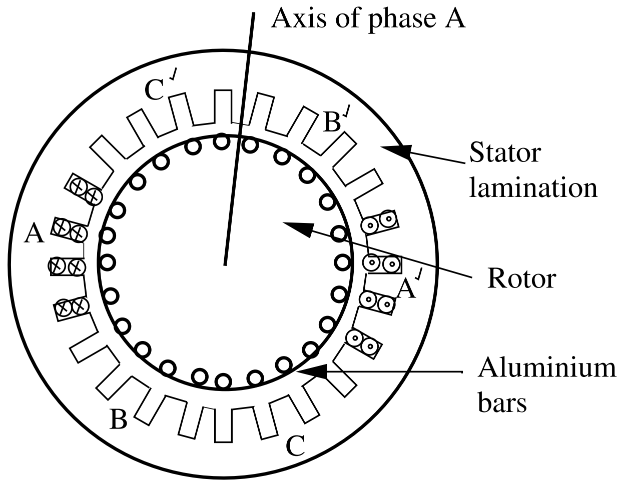


Figure 2: Distributed coil arrangement for 2-pole 3-phase IM

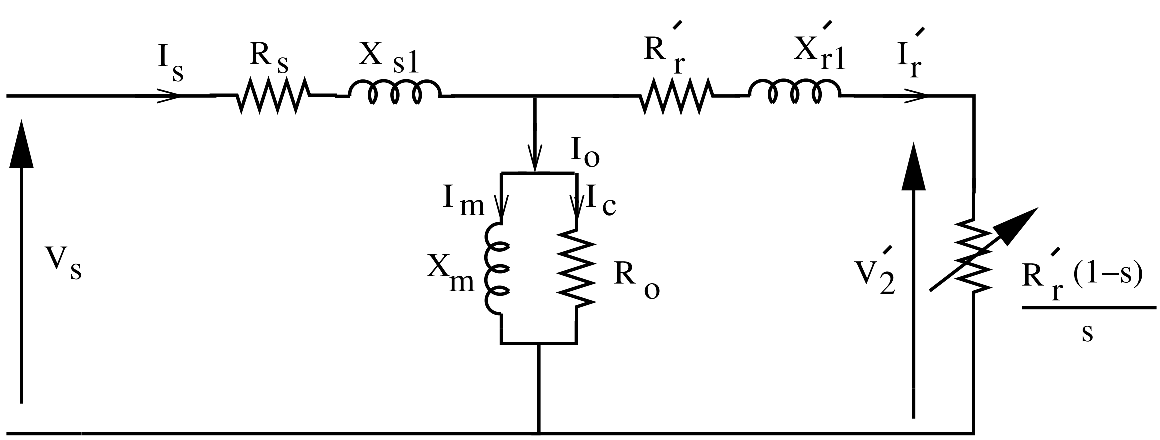


Figure 3: Per phase equivalent circuit of Induction Motor

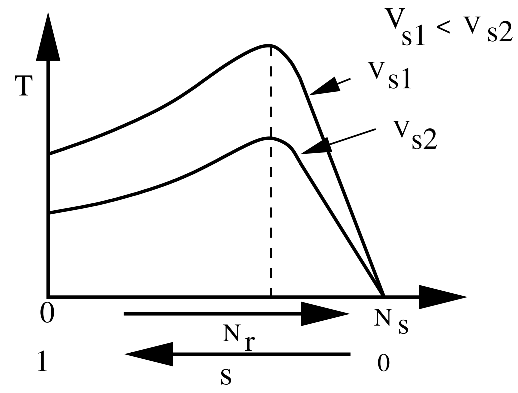


Figure 4: T-Nr characteristic of IM for Variable Voltage Constant Frequency supply

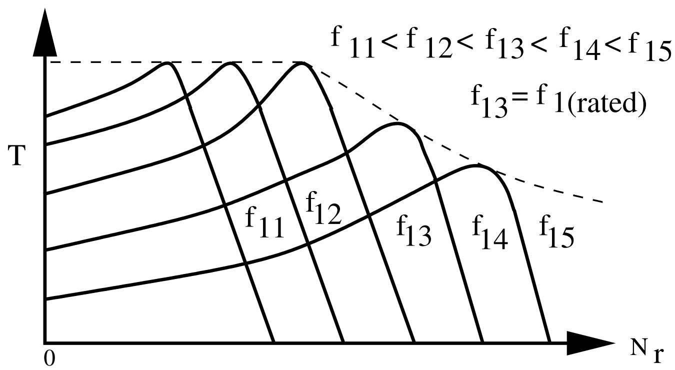


Figure 5: T-Nr characteristic of IM for Variable Voltage Variable Frequency supply

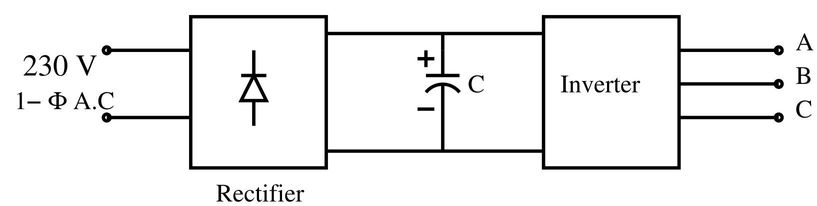


Figure 6: Internal Block Diagram of the VVVF supply (Inverter)

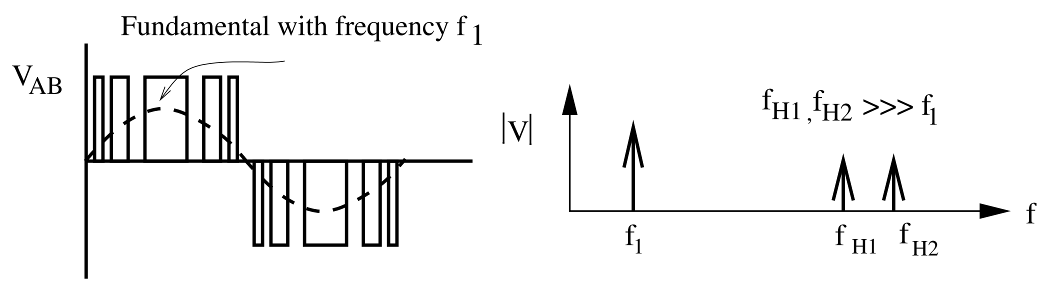
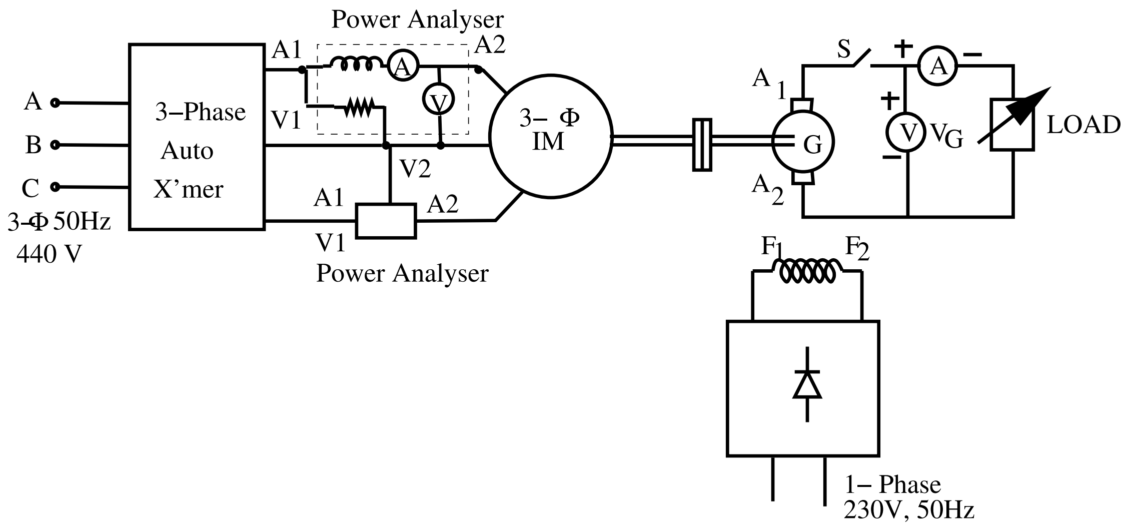
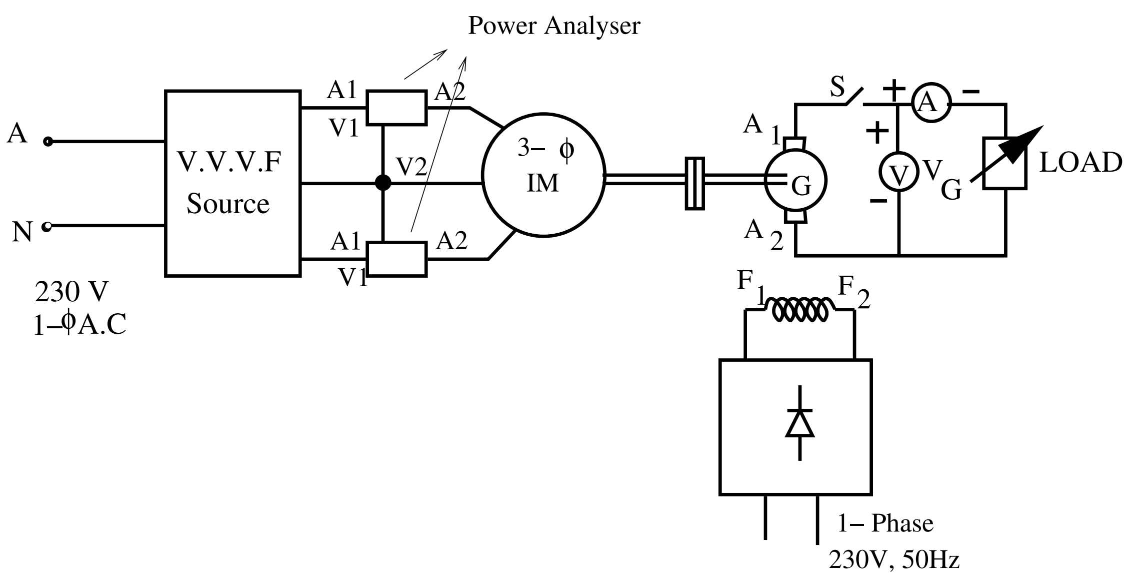


Figure 7: Line-Line voltage waveform and its harmonic spectrum



(a)

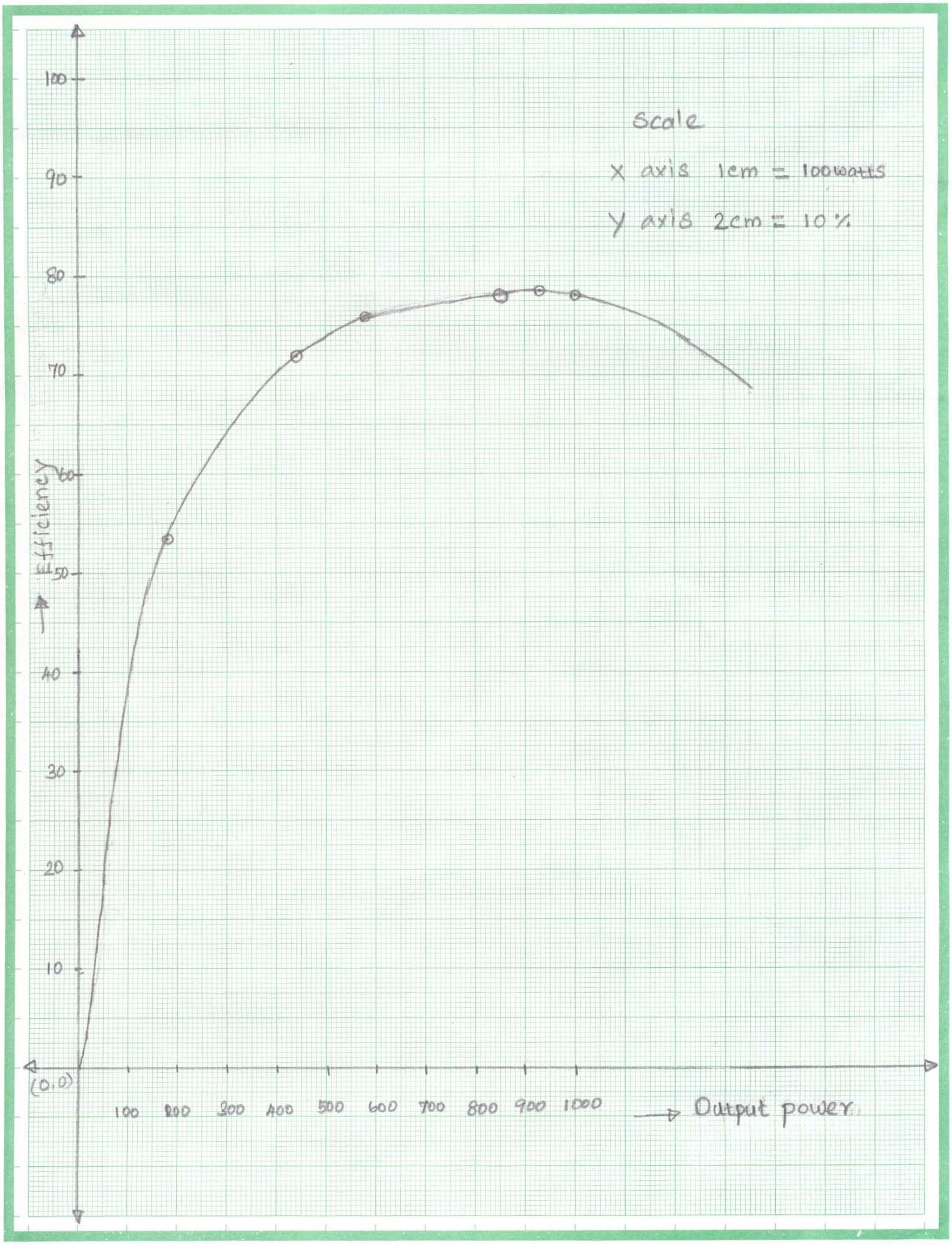


(b)

Figure 8: Circuit Diagram to conduct load test on 3 Phase Induction Motor

Efficiency Vs Output power of D.C Generator

Date :



SAMRAT