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# **THE UNIVERSITY OF ZAMBIA**

**SCHOOL OF ENGINEERING**

**DEPARTMENT OF ELECTRICAL AND ELECTRONIC ENGINEERING**

## **EEE 3351 – ELECTROMECHANICS AND MACHINES**

### **LAB MANUAL LIST**

- 1. IRON CORED INDUCTOR**
- 2. SINGLE PHASE TRANSFORMER**
- 3. POWER MEASUREMENTS IN THREE PHASE SYSTEMS**
- 4. AC AND DC GENERATOR TESTS**
- 5. DC SHUNT MOTOR**
- 6. HOPKINSON TEST**

THE IRON CORED INDUCTOR

Console EE321  
C14

Background work

The iron-cored coil has a non linear characteristic. This can be seen immediately by examining experimentally the relationship between B the magnetic flux density and H the magnetizing force. A graph of B plotted against H yields the familiar hysteresis loop shown in Fig 1.

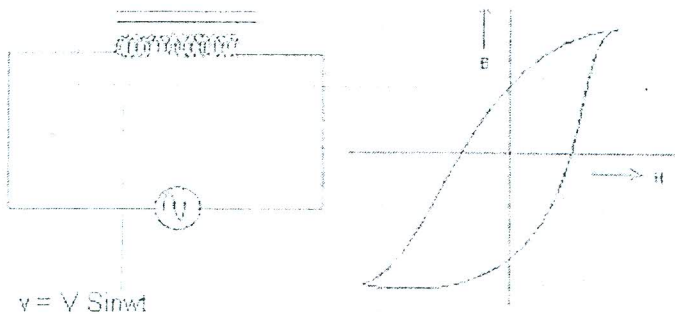


Figure 1

The voltage applied to the coil and the resulting magnetic flux are related by the equation (Faraday's Laws).

$$v = N d\Phi/dt$$

Where  $\Phi$  is the flux and N is the number of turns on the coil

Now  $\Phi = BA$

Where A is the cross-sectional area of the magnetic circuit, hence the above equation may be written as

$$v = NA dB/dt$$

It follows that if the time variation of V is sinusoidal that the corresponding time variation of B is also sinusoidal.

The current in the coil is related to the magnetising force by the equation

$$\Phi = lI/N$$

Where l is the length of the magnetic path and hence the instantaneous value of the current is directly proportional to the instantaneous value of H.

It follows from the above theory that the relationship between V and i is non-linear and hence if the applied voltage is sinusoidal the corresponding current will be non-

sinusoidal. The iron cored coil like a semiconductor diode is a non-linear element and the use of such non-linear elements in electrical circuit poses many problems.

The following diagrams Fig 2 shows the variation of H when the the flux density in the core has a sinusoidal time variation. The time variation of the coil current will be identical to that of the magnetising force since these two quantities are directly proportional to one another.

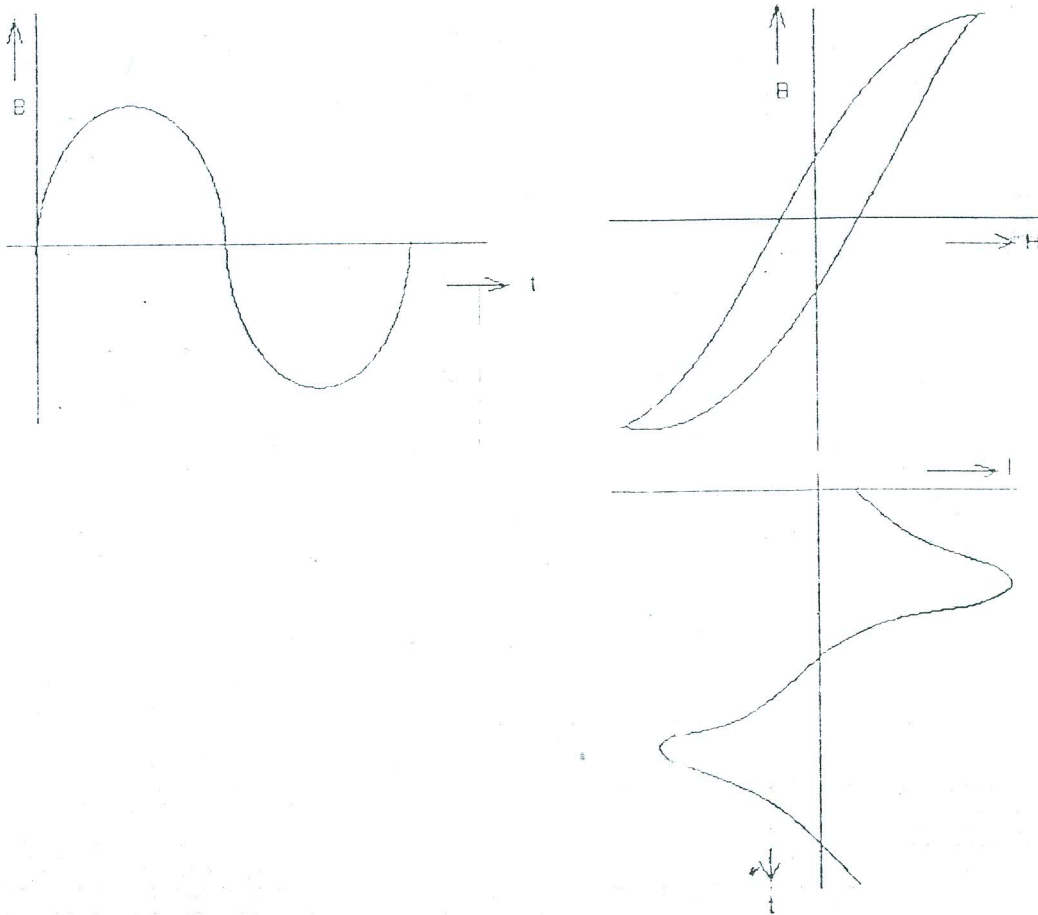


Figure 2

The equation for the inductance of a coil

There are two equations for the self induced voltage appearing across the ends of a coil when the current through the coil is varying with time.

They are:

$$v = L \frac{di}{dt}$$

And  $v = N \frac{d\Phi}{dt}$

And hence  $L = N \frac{d\Phi}{di}$

In other words the inductance may be defined as the flux linkages/amp.

Now  $m.m.f = \text{flux} \times \text{reluctance}$

$$NI = \Phi \times l / \mu_0 A$$

Where  $\mu_0$  = permeability of free space

And substituting for  $\Phi$  in the previous expression for inductance we get

$$L = \mu_0 N^2 A / l \quad \text{Henries}$$

Considering the case of an iron-cored coil the above expression now has to be written in terms of the relative permeability of the core  $\mu_r$ . Hence

$$L = \mu N^2 A / l$$

Where  $\mu = \mu_0 \mu_r$

But  $B = \mu H$

In other words the permeability is the slope of the B.H curve and as can be seen from Fig 1 the value of  $\mu$  varies for different values of B and the inductance of an iron cored coil varies for different operating conditions. It is normal to define an average value of  $\mu$  in terms of the peak to peak swings of B & H as shown in Fig 3.

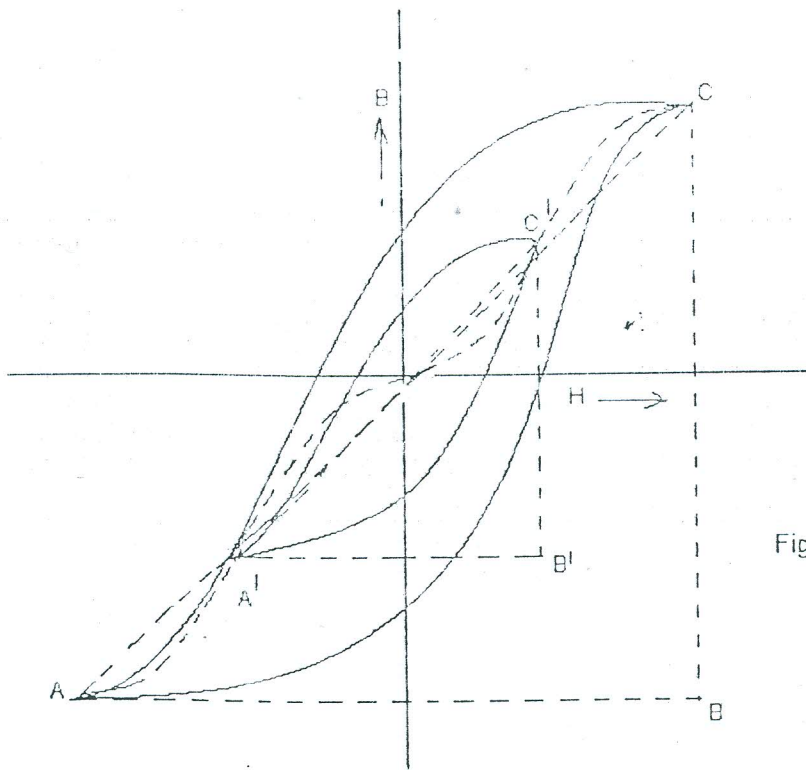


Figure 3

$$\mu = \frac{\text{peak-to-peak swing of B}}{\text{peak-to-peak swing of H}} = \frac{BC}{AB} = \text{slope of line AC}$$

If hysteresis loops for a given iron core coil are determined with different maximum values of the flux density they are found to lie within one another and furthermore the value obtained for an average  $\mu$  is different. Hence for the inner hysteresis loop shown in Fig 3:

$$\mu = BC^1/AB^1$$

And clearly  $\mu$  has a lower value in this case than for the outer hysteresis loop.

The power loss in an iron cored coil.

The power loss in an iron cored coil depends upon three factors

- The winding resistance of the coil
- The hysteresis loss in the core
- The eddy current loss in the core.

These three effects can be lumped together in a parameter called the effective resistance of the coil which may be defined by the equation.

$$R_{eff} = P/I^2$$

Where  $P$  is the power as measured on a wattmeter &  $I$  is the r.m.s value of the current.

A warning note should be sounded here. It is usual to measure the power on a dynamometer wattmeter which normally has a frequency range of 150Hz. In the experiment the voltage waveform is sinusoidal whilst the current waveform is non-sinusoidal and has a strong third harmonic content; hence the wattmeter will give an indication of the true power in the coil to a fair degree of accuracy. However, the current is measured by a moving iron instrument. Theoretically the instantaneous torque of this instrument is proportional to the square of the instantaneous current and hence

$$\text{Average torque} \quad T \propto I^2$$

And it would appear that the moving iron instrument should read the true r.m.s value of the current, however, the non-linearity of the B-H curve for the moving iron parts of the instrument means that the deflecting torque is not exactly proportional to the square of the current. Thus whilst theory shows that the instrument once calibrated in r.m.s values should indicate r.m.s values whatever the waveform, this result will not in practice be realized.

The power factor of the coil can be defined by the following equation

$$\text{Power factor} \quad \cos\theta = P/VI$$

Where  $V$  is the r.m.s value of the voltage applied to the coil and  $I$  is the r.m.s value of the current in the coil. However, it should be realised that in this case power factor has no physical significance in the sense that it does not represent the phase difference between

the current & voltage waveforms. It is not possible to define phase angle when dealing with non sinusoidal waveforms.

The loss due to the winding resistance of the coil  $P$  is proportional to  $V^2$  where  $V$  is the r.m.s. value of the applied voltage hence

$$P \propto V^2$$

The hysteresis loss is found to be proportional to  $(B_{\max})^x$  where  $B_{\max}$  is the peak value of the flux density in the iron core. But since the applied voltage is sinusoidal we may write

$$P_h \propto (V)^x$$

Where  $P_h$  is the hysteresis loss and  $x$  is called the Steinmetz index and has an empirical value in the range  $x = 1.5-2.5$ .

The eddy current loss is proportional to  $(B_{\max})^2$  but since the applied voltage is sinusoidal we may write

$$P_e \propto V^2$$

where  $P_e$  is the eddy current loss.

It is usual to limit the eddy current loss by laminating the core but in the case of a solid core then the eddy current loss would be the dominant factor in the total loss.

The total loss  $P$  is given by

$$P = P_r + P_h + P_e$$

## EXPERIMENTAL WORK

### Apparatus

- 1 × Choke coil having laminated and non-laminated cores
- 2 × Voltmeters (ac/dc)
- 1 × low voltage d.c supply 0-30V 1 amp
- 1 × 8A Russian variac
- 1 × low power factor wattmeter 150V or 300V, 1A or 2A
- 1 × 5A Wattmeter 75, 150 or 300V
- 1 × oscilloscope
- 1 × Isolating Transformer
- 1 × Cambridge Instrument Decade Box

(1) MEASUREMENT OF D.C RESISTANCE  
PROCEDURE

- (a) The circuit connections are as shown in fig 4. (ensure that the laminated core is inside the coil)

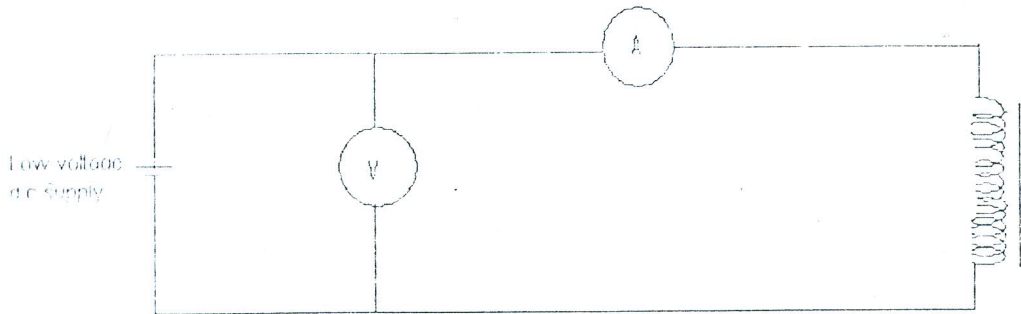


Figure 4

- (b) Tabulate discrete values of current between 0A and 1A.  
(c) By varying the voltage using the coarse and fine knobs on the d.c supply unit, obtain readings of V corresponding to the tabulated current values.  
(d) Repeat steps (b) and (c) for the non-laminated core.

(2) MEASUREMENT OF POWER FACTOR  
PROCEDURE

- (a) The circuit connections are shown in fig 5.

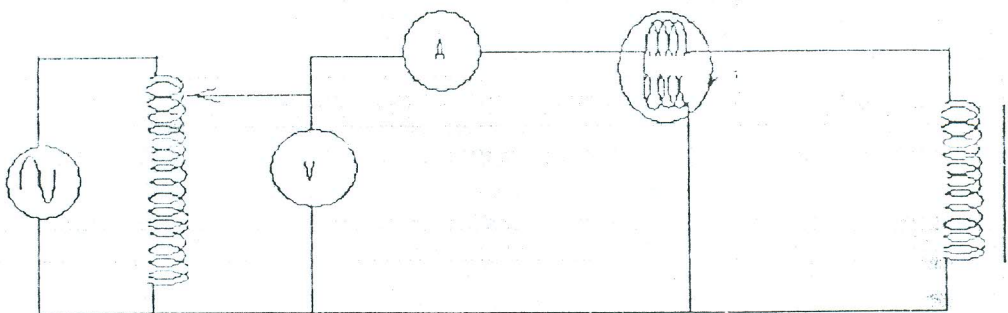


Figure 5

(N.B. Ensure that before switching on power, the variac is at zero.)

- (b) Using the knob on the variac, slowly adjust the supply voltage to 250V.  
(c) At this voltage, record the readings of W, V, I for both the laminated and non-laminated cores.  
(d) Calculate the power factor in each case.

(3) VARIATION OF INDUCTANCE WITH VOLTAGE  
PROCEDURE

- (a) The circuit connections are as shown in fig 5.  
 (b) Using the non-laminated core vary the voltage in steps of 25V ranging from 0-250volts and take corresponding readings of W and I.  
 Tabulate your results as shown in the following table.

P watts	V volts	I amps	Z ohms	$R_{eff}$ $P/I^2$ ohms	$X_L = \sqrt{Z^2 - R_{eff}^2}$ ohms	$L = X_L / 2\pi f$ henries	$V^2$

- (c) Plot graphs of L and  $R_{eff}$  against V and also plot P against  $V^2$

(4) VARIATION OF INDUCTANCE WITH THE POSITION OF THE CORE.  
PROCEDURE

The circuit connections are shown in fig 5. The non-laminated core has been marked at 2cm intervals. For a fixed voltage of 100volts, vary the position of the core and take corresponding readings of P and I. Tabulate your results as shown in the following table.

d distance of core out of coil	P watts	V volts	I amps	Z ohms	$R_{eff}$ ohms	$X_L$ ohms	L henries

Plot a graph of inductance L against the distance d.

(5) EXAMINATION OF COIL CURRENT WAVEFORM.

PROCEDURE

The circuit connections are shown in fig 6.

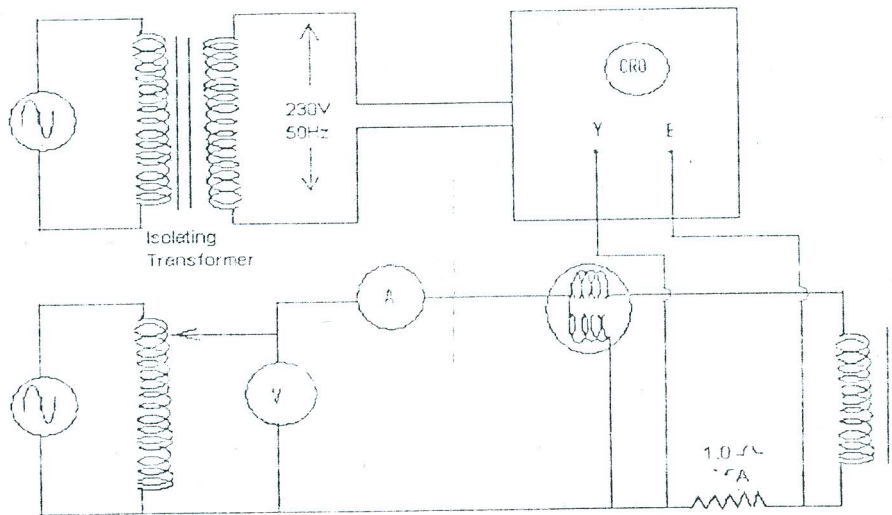


Figure 6

Using the non-laminated core, examine the circuit waveform on the oscilloscope for different values of the applied voltage and sketch the oscillograms for perhaps three different voltages.

# ELECTRICAL ENGINEERING LABORATORIES

## THE SINGLE-PHASE TRANSFORMER

### 1. OBJECT

- To determine the turns ratio of a transformer.
- To derive an equivalent circuit of the transformer.
- To examine the behaviour of the transformer on load.

### 2. BACKGROUND THEORY

A single-phase transformer has two windings on a common magnetic circuit. To keep losses small, the windings are made of a high conductivity material, usually copper, and the magnetic circuit is made of a suitable quality of laminated steel. One winding, the "primary", is connected to the a.c. power supply; the other, the "secondary", is connected to the load. The main purpose of a power transformer is to change voltages as desired, and its power efficiency can be made close to 100%.

The behaviour of a real transformer may be examined in two stages:

- by considering an IDEAL transformer, defined below, which brings out the main features, and then
- by including the effects of real materials not considered in (a), which introduce several important secondary effects.

An IDEAL transformer is defined as one where:

- the windings have no resistance, so  $R_1 = 0$ ,  $R_2 = 0$ , and the copper loss  $P_{Cu} = 0$ .
- There are no iron losses, so  $P_{Fe} = 0$ .
- The magnetic circuit has no reluctance, so  $S = 0$ .
- There is no leakage of magnetic flux between the two windings, so  $\phi_1 = \phi_2$ .

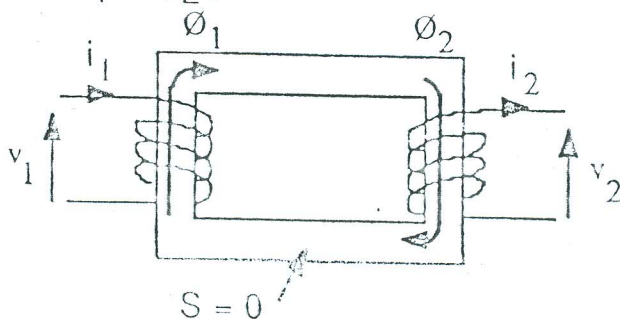


Figure 1: Ideal Transformer

For this ideal transformer, shown in figure 1, applying Faraday's law to winding 1 with  $N_1$  turns,  $v_1 = N_1 d\phi_1 / dt$   
and to winding 2,  $v_2 = N_2 d\phi_2 / dt$

Dividing these two equations, remembering  $\phi_1 = \phi_2$ ,

gives 
$$\frac{v_1}{v_2} = \frac{N_1}{N_2} \text{ at every instant}$$

In terms of RMS phasor voltages,

$$\frac{V_1}{V_2} = \frac{N_1}{N_2} \quad (1)$$

Now, applying Ampere's Law to the magnetic circuit,

$$N_1 i_1 - N_2 i_2 = \phi S$$

Hence, with  $S = 0$ ,

$$\frac{i_1}{i_2} = \frac{N_2}{N_1}$$

or, for RMS phasor currents,

$$\frac{I_1}{I_2} = \frac{N_2}{N_1} \quad (2)$$

We see that for our ideal transformer, the voltage ratio equals the turns ratio and the current ratio equals the inverse of the turns ratio. Note that as the turns ratio is a pure number (a numeric), then the two voltages are in phase and also the two currents are in phase.

A REAL transformer may be represented by the equivalent circuit of figure 2, where:

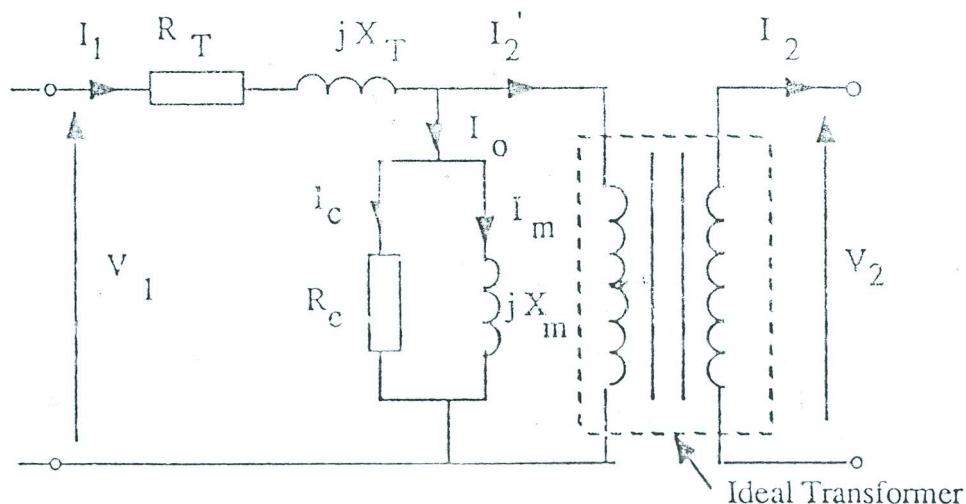


Figure 2: Equivalent Circuit of a Real Transformer.

- (i)  $R_T$  represents the total effective winding resistance, namely  $R_1$  plus  $R_2'$  (the secondary resistance referred to the primary).
- (ii)  $R_c$  is a resistance which gives the core power loss  $\frac{V_1^2}{R_c}$
- (iii)  $X_m$  is the reactance of the primary winding and
- (iv)  $X_T$  is the "leakage reactance" which represents the effect of leakage flux.

The no-load and the short-circuit tests are done to determine values for the parameters, based on some assumptions.

## 2.1 Open-Circuit Test

On no load, the current  $I_2$  is zero and so  $I_1 = I_0$ . Also, if it is assumed that the voltage drops due to the leakage reactance and winding resistance are negligible, the equivalent circuit for the no-load condition may be simplified to fig.3. whose phasor diagram is shown in fig.4.

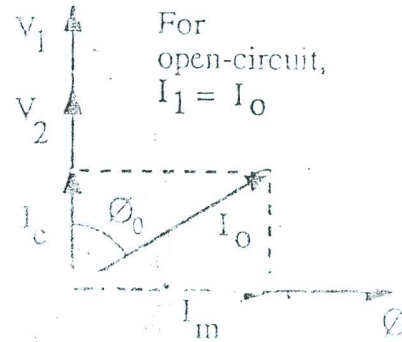
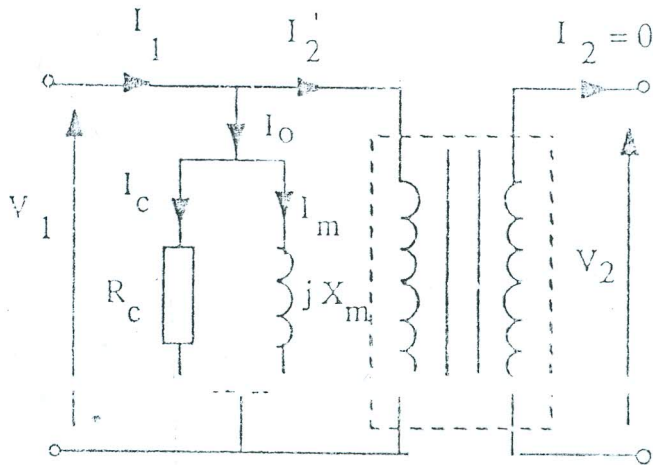


Fig 3: Equivalent Circuit for Open-Circuit Diagram

Fig 4: Phasor Diagram

The input power  $P_1 = V_1 I_0 \cos \phi_0 = V_1 I_1 \cos \phi_0$

and so 
$$\cos \phi_0 = \frac{P_1}{V_1 I_1} \quad (3)$$

It also follows from the phasor diagram that

$$I_c = I_1 \cos \phi_0 \quad (4a)$$

$$I_m = I_1 \sin \phi_0 \quad (4b)$$

The values of  $P_1$ ,  $V_1$ ,  $I_1$  may be measured and the values of  $I_c$  and  $I_m$  calculated from equations, (3) and (4). Hence obtain

$$R_c = \frac{V_1}{I_c} \quad \text{and} \quad X_m = \frac{V_1}{I_m}$$

## 2.2 Short Circuit Test:

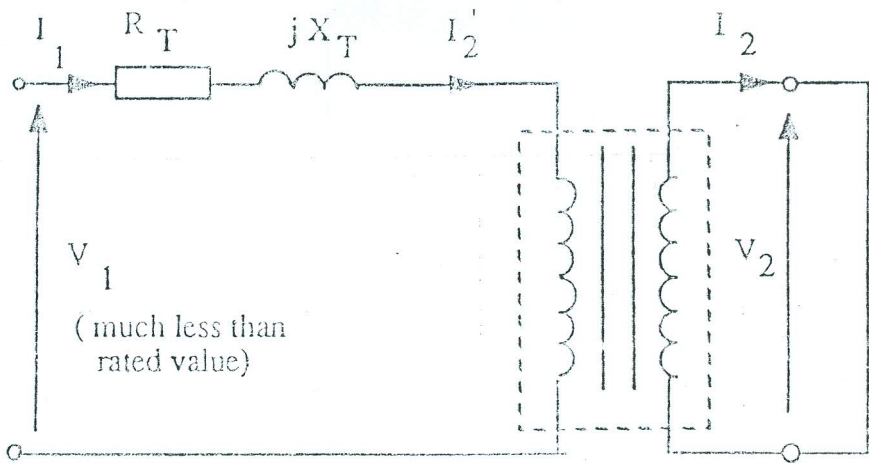


Figure 5: Equivalent Circuit for Short-Circuit Test.

The value of the equivalent resistance  $R_T$  and reactance  $X_T$  can be found by short circuiting the output of the transformer. The applied primary voltage  $V_1$  should be only a few per-cent of the rated value so that the current flowing through the primary windings does not exceed the rated value. At this condition, the current taken by the parallel components  $R_C$  and  $X_M$  is considered negligible. Hence the equivalent circuit simplifies to fig 5. Since no power is dissipated in the reactance

$$P_1 = I_1^2 R_1, \quad \text{giving} \quad R_1 = \frac{P_1}{I_1^2} \quad (5)$$

$$\text{The total impedance is } Z_T = \frac{V_1}{I_1} = \sqrt{R_T^2 + X_T^2}, \quad (6)$$

and so  $X_T$  may be obtained.

### 3. ITEM BEING TESTED

Single-phase transformer ( Feedback TT179, dissectable Transformer)

Primary: 120 V, 50 Hz, 270 turns ( with center tap)

Secondary: two identical windings, each 60 V, 2 A, 148 turns.

### 4. APPARATUS

"Transformer Trainer" (TT 179 Feedback ) ( with range of voltmeters, ammeters, and protection)

Power Supply (PS 189 ) 0-135 V, 5 A ( make sure on a.c setting)

Electronic Wattmeter (EW 604)

Load unit (LU 178)

Mercury thermometer (0 °C to 100 °C)

Watch or stop watch.

### 5. PROCEDURE

Connect the circuit as shown in fig 6.

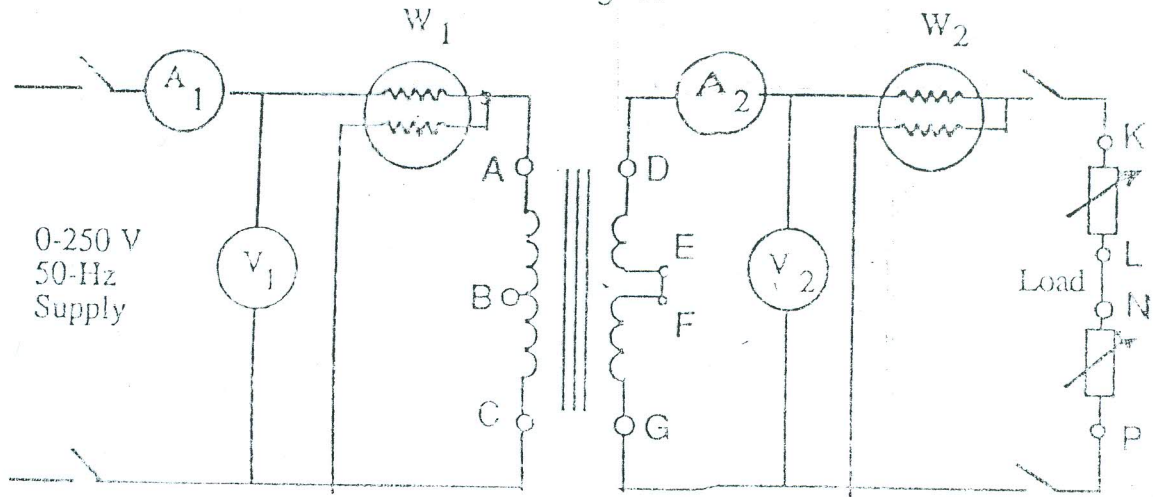


Figure 6: Circuit Diagram

5.1 Determination of turns ratio of the given transformer:  
For different values of input voltage  $V_1$ , measure the output voltage  $V_2$  on no load.

5.2 Open Circuit Test:  
The secondary is left open-circuit. For the rated voltage  $V_1$ , measure the values of input current  $I_1$ , input power  $P_1$ , and secondary voltage  $V_2$ .

5.3 Short Circuit Test:

Short circuit the transformer output. Starting with the input voltage equal to zero increase the input voltage  $V_1$  slowly until the rated  $I_2$  (2 A) is flowing. Record  $V_1$ ,  $I_1$  and  $P_1$ .

WARNING. Immediately after this test, remove the short circuit.

5.4 Load Test (for full-load conditions).  
Connect the load to the transformer output.

WARNING. Check that the load is connected (not a short circuit) and the ranges of all instruments are appropriate:

Adjust  $V_1 = 120$  V. Adjust  $I_2 = 2$  A (by varying load resistance). Measure  $I_1$ ,  $P_1$ ,  $V_2$ ,  $I_2$ ,  $P_2$ , temperature  $T_{\text{core}}$  and time  $t$ , over 30 minutes or longer.

## 6. DERIVED RESULTS AND DISCUSSION

- 6.1 For experiment 5.1 plot input voltage  $V_1$  against output voltage  $V_2$ .
- What is the gradient of the curve.
  - Hence determine the turns ratio.
  - Calculate the turns ratio from the stated numbers of turns
- 6.2 (i) From your open circuit and short circuits tests, determine,
- $R_C$  and  $X_m$  (o/c test)
  - $R_T$  and  $X_T$  (s/c test)
- (ii) Draw the and equivalent circuit for the transformer, and the phasor diagram on no load. On the circuit show the values of resistances and reactances that have been determined.
- 6.3 Determine the regulation of the transformer:
- from load test results.
  - by prediction from the parameters of your equivalent circuit.
- 6.4 Calculate the efficiency of the transformer:
- from load test results.
  - by predictions from the parameters of your equivalent circuit.
- 6.5 Plot the temperature of the core,  $T_{core}$ , against time,  $t$ . Calculate the efficiency for all values of  $T_{core}$  and plot the efficiency against time. What causes the decrease in efficiency.

In your discussion compare the predicted values with the measured values for both regulation and efficiency. Comment on variations of the load test measurements with time.

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POWER MEASUREMENT IN 3-PHASE SYSTEMS

EE323

**Object**

To investigate methods of measuring real power and reactive power in balanced and unbalanced 3-phase circuits.

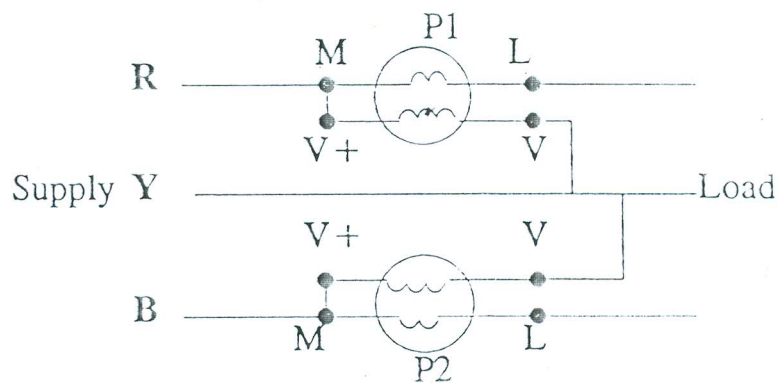
**Background**

In general, if there are  $n$  wires connected to a load then the total power is the sum of  $n-1$  wattmeters. Thus

$$P_T = \sum_{j=1}^{n-1} P_{mn,j}$$

where  $P_{mn,j}$  indicates that the voltage is measured between lines  $m$  and  $n$  and the current coil is in line  $i$ . Thus for a 3-phase 3-wire system two wattmeters are needed, whereas for a 3-phase 4-wire system three wattmeters must be used. These general rules may be relaxed if the system is known to be balanced, for then only one wattmeter need be used to measure the power in one phase, and then multiply by the number of phases to obtain the total power. The most common connections are as follows:

**1. Two-wattmeter Method for Unbalanced 3-phase 3-wire System**

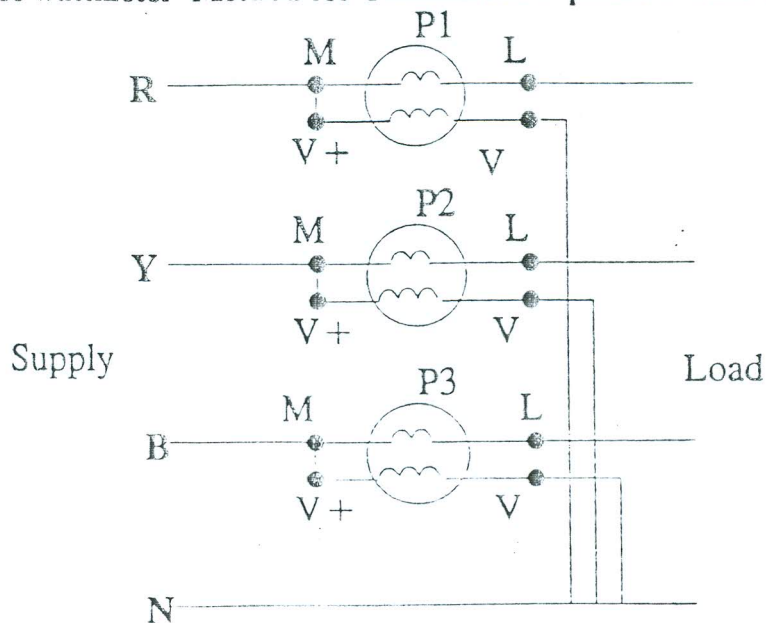


$$P_T = P_1 + P_2$$

Fig 1 : Two wattmeter Method

If the meter reads backwards, reverse the current connections and count the reading as negative.

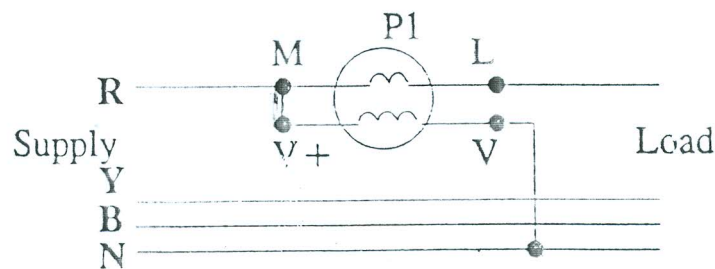
## 2. Three wattmeter Method for Unbalanced 3-phase 4-wire System



$$P_T = P_1 + P_2 + P_3$$

Fig 2: Three wattmeters

## 3. One-wattmeter Method for Balanced System (with neutral available)



$$P_T = 3P_1$$

Fig 3: One wattmeter method

### Power Factor

Considering only a balanced system (fig 3)

$$\cos \phi = \frac{P_T}{\sqrt{3}V_L I_L}$$

If the two wattmeter method is used (fig 1) then

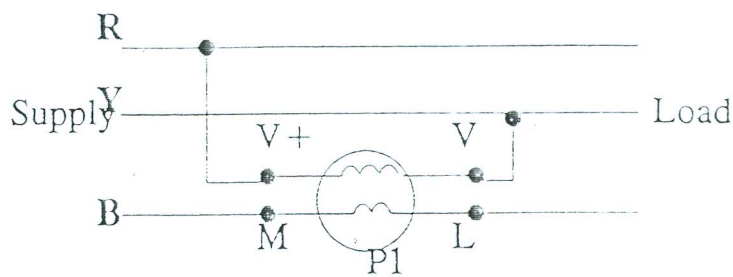
$$\tan \phi = \frac{\sqrt{3}(P_1 - P_2)}{P_1 + P_2}$$

### Reactive Power

Considering only a balanced system (fig 3)

$$Q_T = \sqrt{3}V_L I_L \sin \phi = P_T \tan \phi$$

This can easily be calculated from earlier readings. Alternatively, one wattmeter connected as  $W_{RY,B}$  as shown in fig.4 can be used directly to measure reactive power.



$$Q_T = \sqrt{3} P_1$$

Fig 4: Reactive Power Measurement

Notice that this is the only case where neither end of the voltage coil is connected to a current coil terminal.

### Phase Separation

By feeding an oscilloscope with a scaled down voltage of the 3-phase supply, it is possible to observe the waveforms, phase separation and phase sequence of the 3-phase system.

An approximate measurement of the phase angle of separation can be performed by first determining the duration of a complete cycle and then the time separation of the peaks of the two voltage waves on the two traces as shown below.

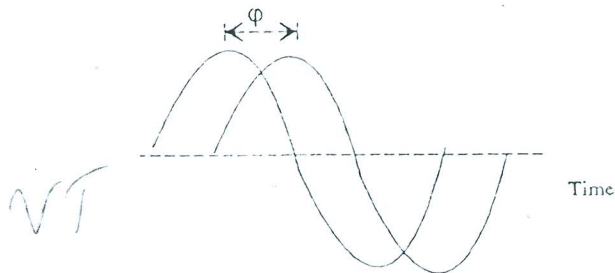


Fig 5: Display of phase separation

A more accurate method for phase angle measurement uses the Lissajous figure. A Lissajous figure (elliptical display) is formed by applying one phase voltage to the X-input and the other phase voltage to the Y-input of the oscilloscope to obtain a display as in fig 6.

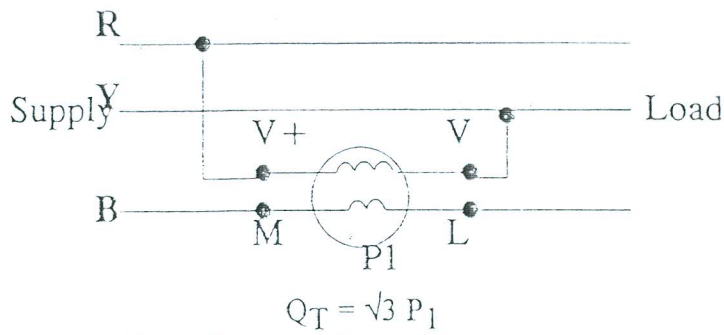


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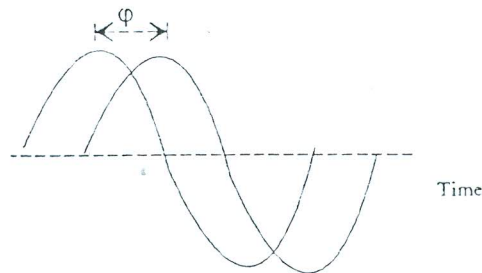
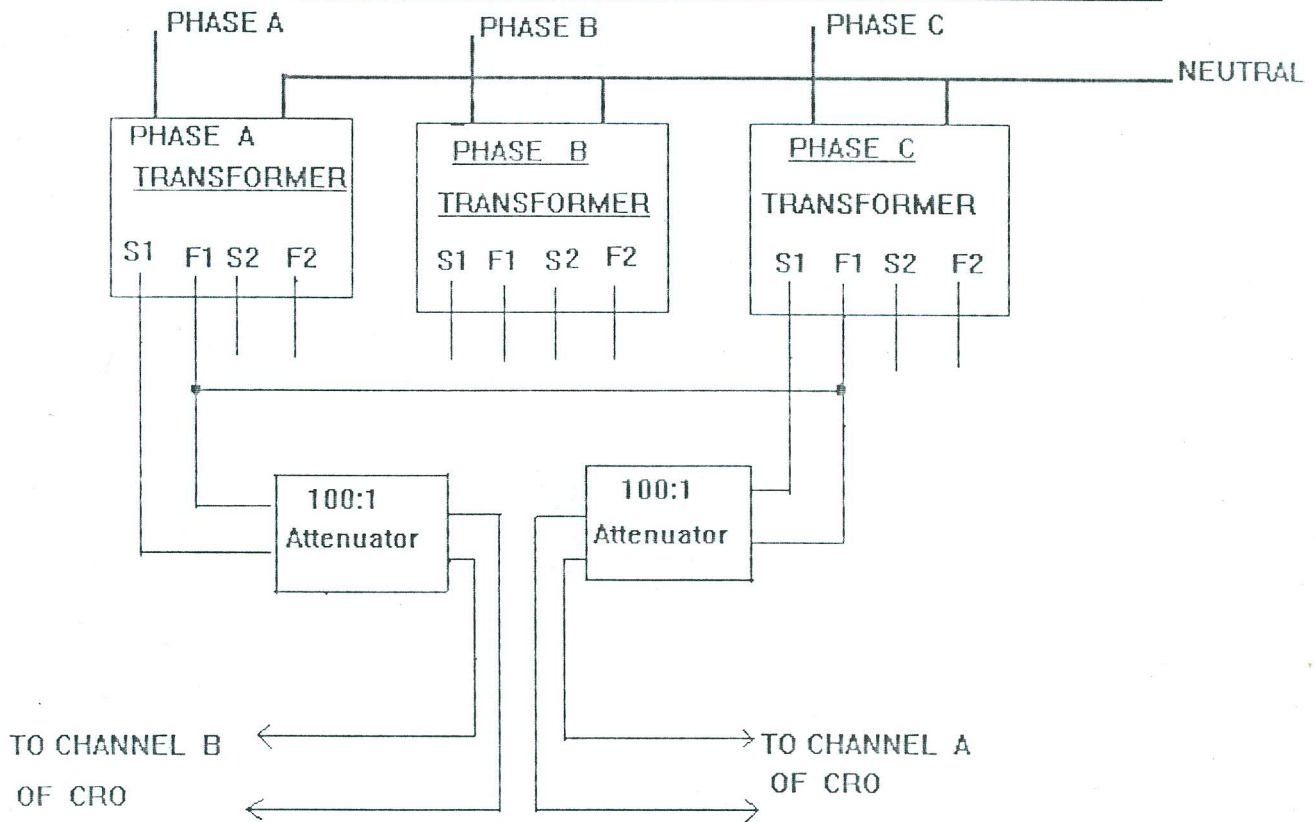


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PHASE SEPARATION ETL 171A THREE PHASE TRANSFORMER



Drawn 28.5 96 Chilombo

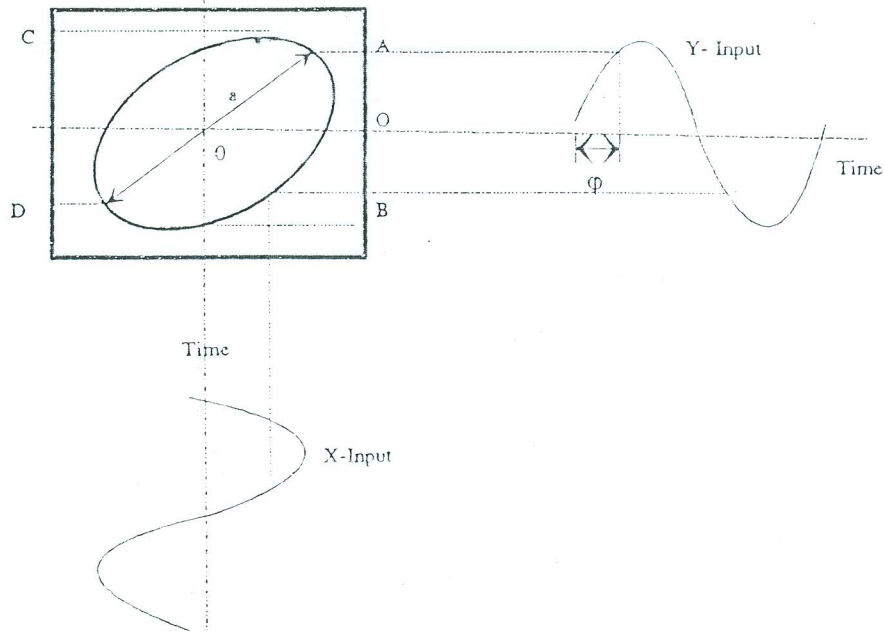


Fig 6: A lissajous figure

For the case shown in the figure, at the time the X-input is zero the Y-input has an amplitude  $OA$ , where,  $OA = OC \sin \phi$  and  $\sin \phi = \frac{OA}{OC} = \frac{AB}{CD}$  and 'a' is the axis of the lissajous figure.

**PROCEDURE**

The basic circuit is as shown in Fig 7.

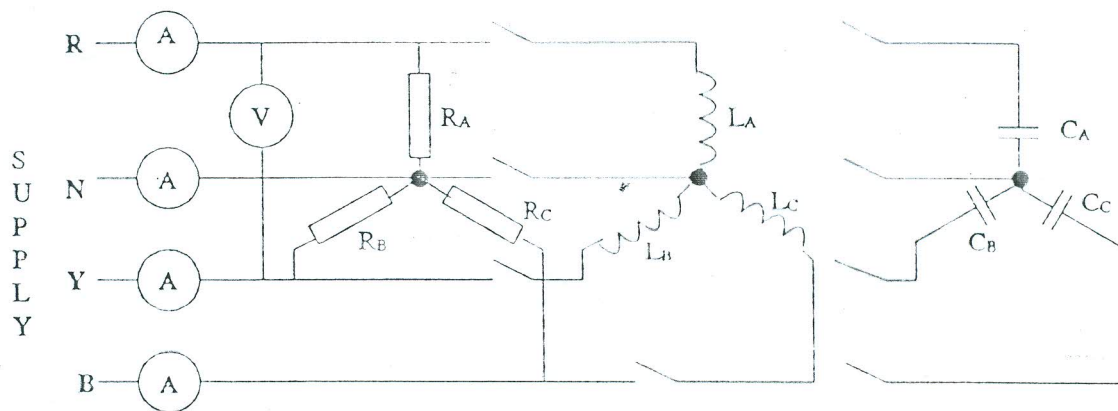


Fig 7: Basic Test Circuit

**Part I Phase Separation**

Before connecting the loads and the meters to the supply confirm the phase separation and phase sequence of the 3-phase supply for the ETL 171A Three Phase Supply Unit on an oscilloscope with 60 V phase voltage. Use both the time waveform display and the Lissajous figure methods and compare the results.

**Part II Balanced System**

- (a) Switch the inductor/capacitor load switch to L

- (b) To obtain a sufficient load current at 60 V phase voltage set the resistances to  $60 \Omega$  and the inductor cores to position 6.
- (c) After switching on supply check that the supply (three phase and neutral) is balanced by taking the readings of  $V_{AN}$ ,  $V_{BN}$ ,  $V_{CN}$  and  $V_{AB}$ ,  $V_{AC}$ ,  $V_{BC}$ .
- (d) Check that the line currents are equal and that  $I_N = 0$ .
- (e) Using the one-wattmeter method (Connect the power factor meter as well in the same manner as the wattmeter) obtain the total power and read  $V_L$  and  $I_L$  and hence find the power factor.
- (f) Read the power factor from the meter and compare with the calculated value.
- (g) Switch the inductor/capacitor load switch to C with the  $20 \mu\text{F}$  capacitor switched in and repeat (e) and (f).
- (i) Using the two wattmeter method, with load switch set to L, again obtain the total power and power factor and compare with the results of (e).
- (h) Set the load switch to C and repeat (i).
- (j) Measure the reactive power for the cases when load switch is set to L and to C.
- (k) Calculate the total reactive power from a knowledge of  $P_T$ ,  $V_L$ ,  $I_L$  and power factor for both the inductive and capacitive load and compare with measured values.
- (l) Draw a complete phasor diagram.
- (m) If the load were a pure  $R$  and a pure  $L$  in parallel in each phase, calculate their values.

### Part III Unbalanced Load 3-phase 3-wire (Neutral Open)

- (a) Set the load switch to L.
- (b) Open the neutral and unbalance the load by setting  $R_A=60 \Omega$ ,  $R_B=80 \Omega$ ,  $R_C=100 \Omega$  and  $L_A$  at 8,  $L_B$  at 6 and  $L_C$  at 10.
- (c) Switch on power and note ammeter readings,  $V_{AN}$ ,  $V_{BN}$ ,  $V_{CN}$ ,  $V_{AB}$ ,  $V_{AC}$  and  $V_{BC}$ .
- (d) Measure the total power by the two wattmeter method and compare with (h).
- (e) Reverse phase rotation to the load and repeat (c).
- (f) Qualitatively explain with the aid of phasor diagrams the results of (c) and (e).
- (g) Draw an accurate phasor diagram for case (c) showing all voltages and currents.
- (h) Predict from the phasor diagram what readings to expect on wattmeter  $P_1 = P_{AB,B}$  and  $P_2 = P_{AC,C}$ .

### Part IV Unbalanced Load 3-Phase 4-Wire ( Neutral closed)

- (a) Close the neutral
- (b) Note the four ammeter readings
- (c) Would you expect these four ammeter readings to depend on phase rotation? Check and explain.

## Discussion

Discuss your results, especially where cross-checks would be made. Consider sources of errors in the various readings and in the phasor diagrams. Would you expect all voltages and currents to be sinusoidal? Would you expect harmonics to invalidate any of the theory used?

## Equipment

ETL 171 A Three Phase Supply Unit  
ETL 171 B Measurement Unit, Includes:  
3 off Voltmeters 150 V ac  
3 off Ammeters 5 A ac  
2 off Wattmeters 300/600 W  
1 off Power factor meter

ETL 171 C Three Phase Load Unit (R, L and C)  
1 off bench ammeter 5 A ac.  
2 off 100/1 Voltage attenuators  
1 off Philips Double Beam Oscilloscope

VT

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24/6/92 Rajamani/Musaba/Mubemba  
22/3/95 A A Zulu.

1. OBJECT:

To investigate the variation of output voltage and waveform with field current and speed, for both an a.c. generator and a d.c. generator.

2. BACKGROUND MATERIAL

All generators produce a voltage by the relative motion of a conductor and magnetic flux. Applying Faraday's Law,  $v = d\Phi/dt$  in the simplest case, we obtain an average value of induced voltage,

$$V_1 = k n \Phi$$

where  $n$  is the speed of rotation,  $\Phi$  is the flux per pole, and  $k$  is a constant dependent on the machine design (e.g. number of conductors in series, number of poles). The magnetic flux  $\Phi$ , is normally associated with the coil carrying the "field current",  $I_f$ . The relationship between  $\Phi$  and  $I_f$  depends on the properties of the magnetic circuit, and in particular the non-linear B-H characteristic of the iron will produce a non-linear magnetisation curve.

Any one conductor in the machine has an alternating voltage induced in it, one half-cycle being produced as it passes a north pole and the other half-cycle of opposite polarity as it passes a south pole. The frequency,  $f$  (Hz), thus depends on the speed of rotation ( $n$  rev/s) and the number of pole-pairs,  $p$ :

$$f = n p$$

In an alternator (ac generator) the designer ensures that the arrangement of a large number of conductors in series and the shape of the magnetic circuit of the poles produce a sinusoidal voltage output. The field is usually provided by the rotor, being excited with d.c. current through sliprings, for then the large a.c. output power comes from permanent connections to the stator windings. However, the roles of rotor and stator may be reversed, for it is the relative motion that is important, and in fact the machine being tested will have d.c. fed to the stator windings and a.c. obtained from the rotor via slip-rings.

In order to obtain d.c. from a generator it is necessary to reverse the connections to the conductor when it is changing from being under a north to under a south pole, and vice-versa, so that the output voltage in the external circuit is always unidirectional. This is achieved by having a stationary field system, and the rotor conductors connected to a commutator (instead of slip-rings in the a.c. case) with its associated brush-gear.

Reference should be made to your recommended text books for more complete practical details.

### 3. EQUIPMENT - (Note main specifications from name plates).

#### 3.1 A.C. Generator test

##### Item under test:

Synchronous machine.: star-connected, 400 V, 4.3 A, 3 kVA,  
3-phase, 50-Hz, 1500 rev/min, phase voltage 230 V,  
manufacturer: BKB.

##### Prime mover:

Schrage Motor 400 V, 3-phase, 50-Hz, 450-2250 rev/min

##### Apparatus:

Voltmeter	0-500 V ac
Ammeter	0-1 A dc
Field Resistor	500 $\Omega$ , 1.0 A
Tachometer	0-5000 rev/min
Attenuator	100 : 1

#### 3.2 D.C. Generator test

##### Item under test:

D.C. generator 220 V, 9.1 A, 1000 rev/min, 2 kW  
(manufacturer AEI)

##### Prime Mover

D.C. shunt motor, 220 V, 14.7 A, 1000 rev/min

##### Apparatus:

2 Voltmeters	0-300 V dc
Ammeter	0-500 mA dc
Resistor R1	1.5 k $\Omega$ , 0.82 A
Resistor R2	1.5 k $\Omega$ , 0.57 A
Tachometer	0-5000 rev/min
Attenuator	100 : 1

### 4. PROCEDURE

#### 4.1 A.C. GENERATOR

Console C20

Make the circuit connections shown in figure 1. The prime-mover, which provides the mechanical rotation, is a Schrage motor. Any other variable-speed motor could have been used in this experiment.

Switch the motor on and the ac generator's field on.

- With the speed constant at 1500 rev/min increase the field current of the generator from 0 A to 0.6 A in steps of 0.1 A, and record the generated voltage for each step.
- With the field current constant of 0.2 A increase the speed from 400 - 2000 rev/min in steps of 400 rev/min and record the generated voltage for each step.

Use the oscilloscope to check if the waveform is sinusoidal and from the knowledge of its time base determine the frequency at any convenient speed, and thereby calculate the number of pole-pairs.

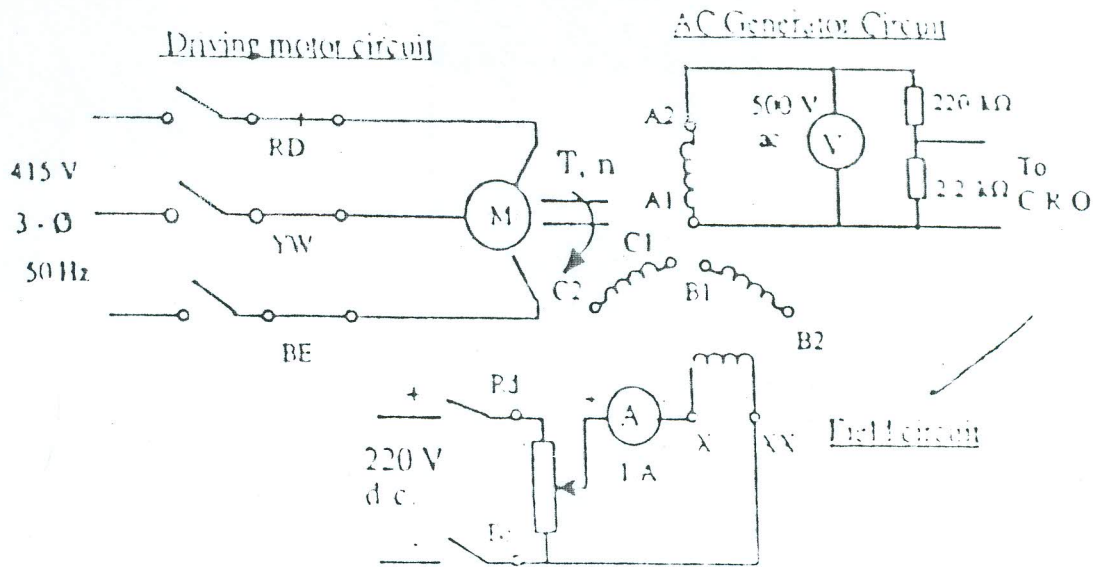


Fig 1: Test Circuit Diagram for ac Generator

## 4.2. D.C. GENERATOR

Console C18

Make the circuit connections shown in Figure 2. The prime-mover is a dc motor whose field is connected in the shunt mode. The variable resistance in the field circuit of the motor will be used to control the speed of the motor. To start the driving motor gradually move the starter handle until it latches in the extreme position.

- With the speed constant at 1000 rev/min increase the field current of the dc generator from 0.15 A to 0.5 A and record the generated voltage.
- Then with the field current constant at 0.2 A, increase the speed from 1000 to 1800 rev/min and record the generated voltage. Examine the voltage on the oscilloscope, set to "d.c." and then to "a.c."

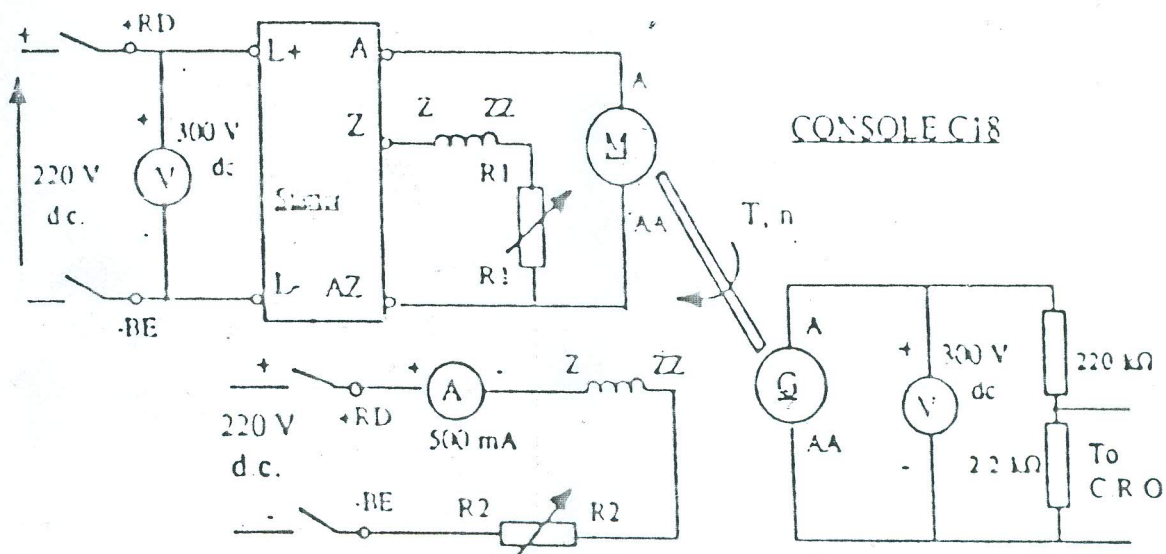


Fig 2: Test Circuit Diagram for dc Generator

## 5. REPORT

Include in your report the following points:

- 5.1. Plot the necessary graphs and compare with theory. Make use of equations and be to the point.
  - 5.2. Comment on the wave-forms of both generators.
  - 5.3. From your reading, make a few comments on the use of these generators in practice, and possible difficulties in operation.
- 

## PREPARATION

THE ANSWERS TO THE FOLLOWING QUESTIONS HAVE TO BE GIVEN TO THE TUTOR AT THE BEGINNING OF THE LAB-SESSION. FAILURE TO DO SO WILL LEAD TO A PENALTY

### 1. AC GENERATOR:

Explain what would occur when you :

- (a) Increase the field current while keeping the speed constant?  
Sketch the expected graph.
  - (b) Increase the speed while keeping the field current constant.  
Sketch the expected graph.
- 2 Calculate the speed of the AC-Generator, if it has two pairs of poles and gives an output frequency of 50-Hz.

### 3. DC GENERATOR

ANSWER QUESTIONS 1.(a) AND 1(b) for the DC-GENERATOR

- 1 How do you expect the generated voltage of the DC-generator to look like? MAKE A GRAPH OF IT.

1. OBJECT

To determine the variation of the speed of a d.c. shunt motor with field current and armature voltage, on no-load; also to measure the torque-speed and efficiency-output characteristics.

2. BACKGROUND MATERIAL

The rotating armature of a d.c. machine has an e.m.f.  $V_i$  induced in its windings according to Faraday's Law:

$$V_i = k n \Phi \quad (1)$$

where  $k$  is a constant of the machine depending on its number of poles, the number of armature conductors, and the details of the armature winding connections;  $n$  is the speed of rotation; and  $\Phi$  is the magnetic flux/pole produced by the stator, which depends on the field current,  $I_f$ , according to the "magnetisation curve" of the machine. This curve is non-linear because of the non-linear B-H characteristic of iron.

In an ideal machine the terminal armature voltage  $V_a$  would equal  $V_i$ , but in a real machine there are several causes (such as the resistance of the windings) producing small internal voltage drops which add up to  $I_a R_a$ , where the effective resistance  $R_a$  may (at this introductory level) be assumed constant. Thus

$$V_a = V_i + I_a R_a \quad (2)$$

It should be realised that the machine designer ensures that  $I_a R_a$  is much less than  $V_i$  even under full-load conditions.

Eliminating  $V_i$  from equations (1) and (2)

$$V_a = k n \Phi + I_a R_a \quad (3)$$

On no-load the  $I_a R_a$  term may be neglected, and so

$$V_a = k n \Phi \quad (4)$$

Under load conditions.

The electrical input power to the "ideal" machine,  $P_i = V_i I_a$ , is converted to mechanical output power of  $2 \pi n T$ , where  $T$  is the torque, and hence

$$T = V_i I_a / 2 \pi n \quad (5)$$

In the real machine the useful output torque  $T_{out}$  will be a little less than  $T$  because of windage and friction losses. Eliminating  $V_i$  from equations (1) and (5)

$$T = k I_a \Phi / 2 \pi \quad (6)$$

The torque-speed relationship, with constant  $V_a$  and  $\Phi$ , can be predicted from equations (3) and (6). From (3) we see that

$$n = (V_a - I_a R_a) / k \quad (7)$$

and so with  $V_a$  constant,  $n$  will decrease slightly with increasing  $I_a$ . As  $T$  is proportional to  $I_a$  (equation (6)), we expect  $n$  to decrease slightly with increasing torque.

The shunt configuration of the dc motor is when the field circuit is "shunted" across the motor. A variable resistor may be included in this circuit to vary the field and therefore the speed of the motor.

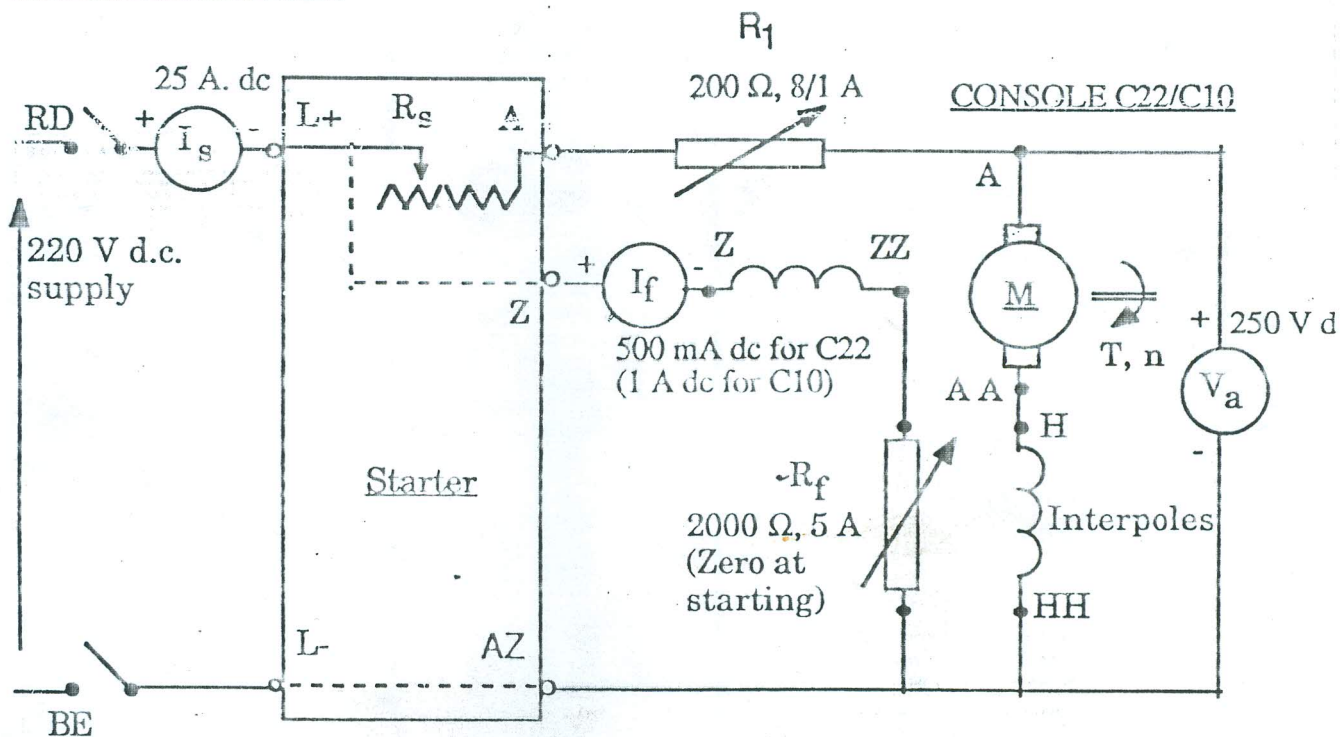
### 3. ITEM UNDER TEST

Console C10	Compound machine, used as a d.c. shunt motor Higgs, 2.2 kW., 220 V, 13.2 A, 1500 rev/min.
Console C22	Compound machine, used as a d.c. shunt motor EI, 2.6 kW., 220 V, 14.7 A, 1000 rev/min.

### 4. APPARATUS

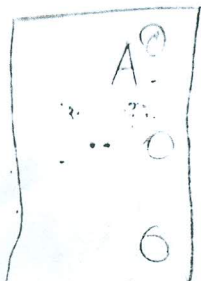
Armature starting resistance, $R_s$ ,	within starter.
Series resistance	200 ohm, 8/1 A.
Field resistance $R_f$	2000 ohm, 1 A.
Voltmeter, $V_a$ .	250 V, d.c.
Ammeter, $I_f$ .	1A, d.c.(500 mA console C22)
Tachometer,	2,000 rev/min.
Ammeter, $I_s$ ,	25 A, d.c.
J.J. Eddy current dynamometer,	26 Nm

### 5. PROCEDURE



N.B. On C22, the interpoles are connected internally.  
Also, the field connections Z and ZZ are reversed.

Figure 1: D.C. Shunt Motor Test Circuit Diagram



### 5.1. Connections.

With reference to the circuit diagram, fig 1., ensure that you connect the interpoles and armature in series in the sense shown. (Interpoles are situated between the main poles of the machine and assist commutation. In analysis their low resistance windings are included in the term  $R_a$ ).

### 5.2. Starting procedure.

( $R_1$  is not used at present, so set it to zero).

Equation (3) shows that during starting, with the speed zero or small,  $I_a$  would be excessively high (say 20 times full-load current). Hence during starting additional resistance  $R_S$  (within the starter) must be temporarily included in the armature circuit. Also from equation (3), the armature current during starting is less if the flux  $\Phi$  is large, and so the field current is made a maximum by making the external field resistance  $R_f = 0$ . Before switching on make sure that  $R_S$  is a maximum by checking the starter handle is in the off position and  $R_f = 0$ . After switching on slowly reduce  $R_S$  to zero by moving the starter handle clockwise, and then vary the speed with  $R_f$

### 5.3. No-load test

- (a) Adjust  $I_f$  until the speed is 2000 rev/min for C10 (1000 rev/min for C22), and then keep  $I_f$  constant. Reduce  $V_a$  in the range 220 V to 60 V for C10 (80 V for C22), by increasing  $R_1$ , and note corresponding values of  $n$ . It is important not to take readings after each change in conditions until the speed has settled to its steady value. Make  $R_1 = 0$  after this.
- (b) With  $V_a$  constant at 220 V, slowly reduce  $I_f$  from its maximum value, and note corresponding values of  $n$ . Do not allow the speed to exceed 2000 rev/min for C10 (1500 rev/min for C22)

### 5.4. Load Tests

( $R_1$  is not used, so set it to zero).

Adjust  $R_f$  to give a no-load speed of 1800 rev/min for C10 (1000 rev/min for C22). Note the value of  $I_f$ , and check that it stays constant. Set the Brake control in the "minimum" position, switch it on, and then slowly increase the braking torque. Note corresponding sets of  $V_S (= V_a)$ ,  $I_S$ , and  $T_{out}$  until the full-load current (see manufacturer's specifications) is reached. Repeat this test starting with a no-load speed of 2,000 rev/min for C10 (1200 rev/min for C22).

## 6. REPORT:

Include in your report the following points:

### No-load tests

- 6.1 Plot  $n$  against  $V_a$  for constant  $I_f$ , and compare with equation (4) Theory.
- 6.2 Plot  $n$  against  $I_f$  for constant  $V_a$ , and compare with equation (4) Theory.

### Load tests

- 6.3 Plot  $I_s$  against  $T_{out}$  for constant  $V_s$  and  $I_f$ , and compare with equation (6) in Theory.
- 6.4 Plot  $n$  against  $T_{out}$  for constant  $V_s$  and  $I_f$ , and compare with equation (3) and (6) Theory.
- 6.5 Plot efficiency  $\eta = 2 \pi n T_{out} / V_s I_s$  against mechanical output ( $T_{out}$ ), and compare with theory.
- 6.6 Mention practical applications of this machine, and perhaps compare alternative sources of mechanical power.
- 6.7 What control equipment would normally be associated with this machine? What protective devices are desirable, for the safety of people and equipment.

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## PREPARATION

THE ANSWERS TO THE FOLLOWING QUESTIONS HAVE TO BE GIVEN TO THE SUPERVISOR AT BEGINNING OF THE LAB-SESSION. FAILURE TO DO SO WILL LEAD TO A PENALTY.

Sketch and explain the expected graphs of

### No-load tests

- 1 Speed  $n$  against armature voltage  $V_a$  for constant field current  $I_f$ .
- 2 Speed  $n$  against field current  $I_f$  for constant armature voltage  $V_a$

### Load tests

- 3 Supply current  $I_s$  against torque  $T_{out}$  for constant supply voltage  $V_s$  and field  $I_f$
- 4 Speed  $n$  against torque  $T_{out}$  for constant supply voltage  $V_s$  and field  $I_f$

THE UNIVERSITY OF ZAMBIA  
SCHOOL OF ENGINEERING  
ELECTRICAL ENGINEERING LABORATORIES

Console C2

EE 323 Hopkinson Test

Object

To determine the efficiency and performance on load of a d.c. shunt machine.

Machine Specifications

2 machine set on console C2, two identical Higgs machines,  
220 V d.c., 1500 rev/min, 13.2 A (motor), 8.2 A (generator)

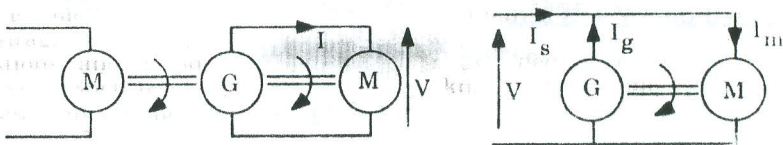
Equipment

- ✓ 1 off Voltmeter 300 V d.c. ✓
- ✓ 1 off Voltmeter -300/0/300 V d.c. ✓
- ✓ 2 off Ammeter 10 A d.c. ✓
- ✗ 2 off Ammeter 0.5 A d.c. ✗
- ✓ 1 off Ammeter 20 A d.c. ✓
- ✓ 1 off Tachometer ✓
- ✓ 1 off Motor starter (on board) ✓
- ✓ 1 off Single pole switch (on board). ✓

Background

The performance of a machine on load may be determined from actual load tests, or predicted from no-load tests. The no-load tests may be easier to perform as they involve much lower electrical and mechanical powers, but they have the disadvantage that they do not give any information on factors such as temperature rise or commutation, and various assumptions are necessary to use the data in predicting on-load performance. The category of tests known as "back-to-back" tests, where the direction of energy conversion in one machine is reversed in a second identical machine, has several advantages; the machines are genuinely working under normal load conditions, and yet only the losses need be provided from an external source of power. Such tests on transformers are known after Sumpner, and on d.c. machines after Hopkinson.

In the Hopkinson test one d.c. machine acts as a generator and the other as a motor, and they are connected together both mechanically and electrically. The main power circulates between the 2 machines, mechanical power from motor to generator and electrical power from generator to motor, and so only, the losses of the 2 machines need be provided from an external source either by an auxiliary motor or from an electrical supply.



The interpretation of results from both these methods involves some assumptions. The simplest assumption is that the efficiencies of the two machines are the same, but this is not strictly true as they are operating under slightly different conditions of load and excitation and so more refined analyses may be made.

For our test we shall supply the losses electrically and assume that each machine has an efficiency  $\eta$ , which is a function of the mechanical power  $P_m$  transmitted from the motor to the generator.

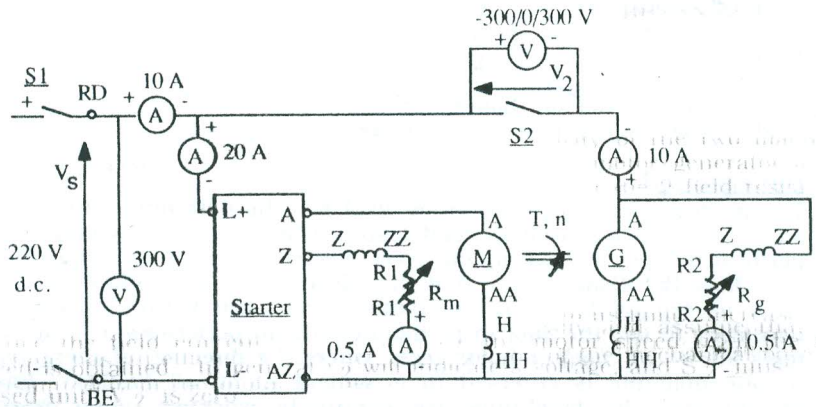
Thus for the generator  $\eta P_m = VI_g$

and for the motor  $P_m = \eta VI_m$

Thus  $\eta = \sqrt{I_g/I_m}$

and  $P_m = V \sqrt{I_g I_m}$

Note that  $I_s = I_m - I_g$



### Procedure

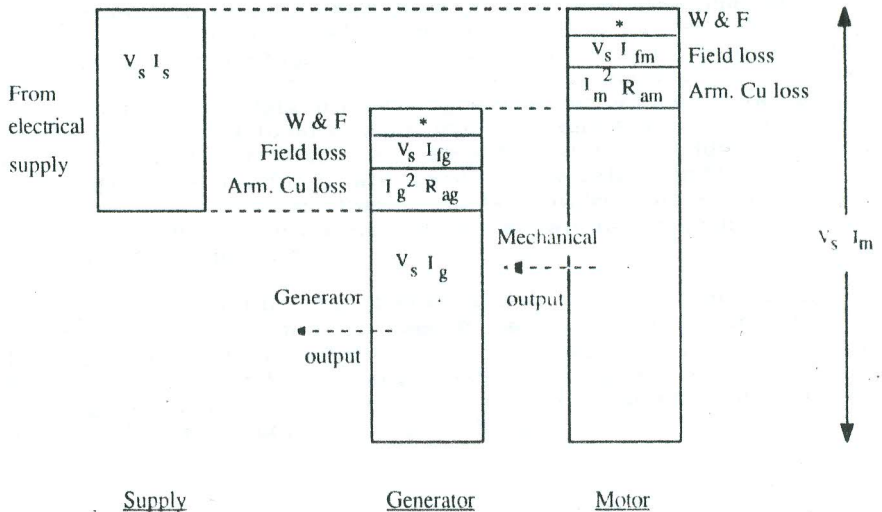
It is essential to obtain the correct relative polarity of the two machines, because a relatively small voltage acting round the motor/generator loop is sufficient to circulate full load current. Variations of the 2 field resistors is the necessary and sufficient condition for controlling the two variables of speed and circulating current.

First check that the switch  $S_2$  is open and the motor field resistor  $R_m$  is at zero. Close  $S_1$  and move the starter handle slowly to its limit. Increase  $R_m$  to reduce the field current and so increase the motor speed until the rated speed is obtained. In general  $V_2$  will indicate a voltage, and  $S_2$  must not be closed until  $V_2$  is zero.

- (a) If  $V_2 \approx V_s$  then the generator is not yet self exciting. Check that the motor speed is 1500 rev/min, and decrease  $R_g$ . The generator should now become self-exciting, as shown by  $V_2$  reducing. (Another reason for a d.c. shunt generator failing to excite is that the connections between the field and armature are the wrong way round, for the given direction of rotation. This is remedied by reversing these connections.)
- (b) If  $V_2 \approx 2V_s$  then the generator voltage is in the wrong sense with respect to the supply. This may be remedied (by the supervisor) by reversing the sense of the residual magnetism in the generator field by temporarily passing a field current from ZZ to Z
- (c) If  $V_2 \approx 0$  then the connections are correct, and the generator field resistor  $R_g$  should be varied to make  $V_2 = 0$  (exactly). Then close  $S_2$ , and from now on move  $R_m$  and  $R_g$  with caution because of the large repercussions on the currents.

Take a series of readings by varying the field resistors, keeping the speed constant and varying the generator current from zero to full load. Plot a curve of efficiency against mechanical power.

Discuss with your Supervisor how to measure the armature resistance. Then estimate the losses in the field circuit, armature copper losses, and windage and friction losses at say full load. Draw a chart to scale, as indicated below, showing power as ordinate, assuming that the windage and friction losses of the two machines (shown as \*) are identical.



2/6/83

rev. July 1990, A Lanéus