EEE 321

EXPERIMENT #1

3-PHASE POWER MEASUREMENT

A. THE OBJECT OF THE EXPERIMENT

The primary objectives of the experiment on three-phase ac measurement include becoming familiar with the laboratory equipment as well as reviewing three-phase voltage, current, and complex power relationships studied in previous courses. This experiment also introduced the one-wattmeter and two-wattmeter methods for measuring real power.

B. THEORY

First, the basic concept will be described. The single wattmeter (Figure 1) will read (real) power flow from the "left" side to the "right". If V and I are voltage and current phasors at the left side with the reference polarities shown, then the reading of the wattmeter will be

$$P = |\mathbf{V}||\mathbf{I}| \cos \angle_{\mathbf{I}}^{\mathbf{V}} \tag{1}$$

The reactive power will be

$$Q = \pm |\mathbf{V}||\mathbf{I}| \sin \angle_{\mathbf{I}}^{\mathbf{V}} \tag{2}$$

where the sign depends on the power factor.

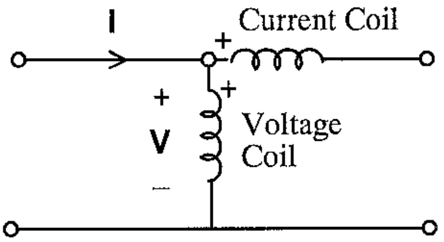


Figure 1 A Wattmeter

Now consider measuring power in a three-phase balanced system. In the three-wattmeter method, three wattmeters will be connected, each from one line to the reference (or neutral). It is easy to see that each wattmeter will read the phase power and the summation would be the total real power. Also, note that no deduction on the sign of reactive power is possible (just as in single wattmeter case).

The two-wattmeter method is an attractive alternative. The connection diagram is given in Figure 2. Any one of the three lines can be taken as the reference; in the figure line b is chosen. Suppose that the readings of the two wattmeters are P_1 and P_2, as marked. The readings P_1 and P_2 depend on the phase sequence and the power factor of the load.

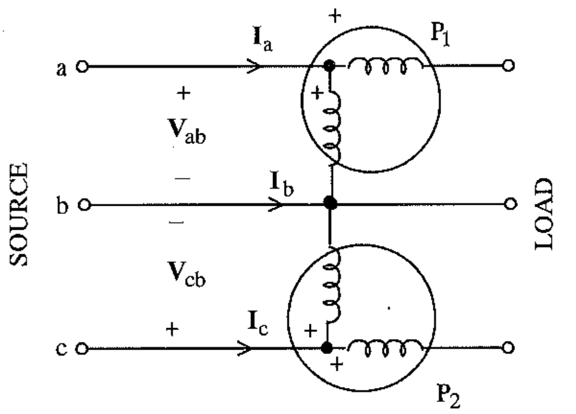


Figure 2 Three-Phase Power Measurement by Two-Wattmeter Method

Students are expected to know the meaning of "abc" and "acb" phase sequences. Figure 3a and 3b are phasor diagrams of phase voltages for abc and acb sequences, respectively. A convenient way to draw line-to-line voltages from phase voltages (or, vice versa) is indicated in Figure 4. N is the centroid (intersection of medians) of the equilateral triangle. Figure 4 is for an abc phase sequence.

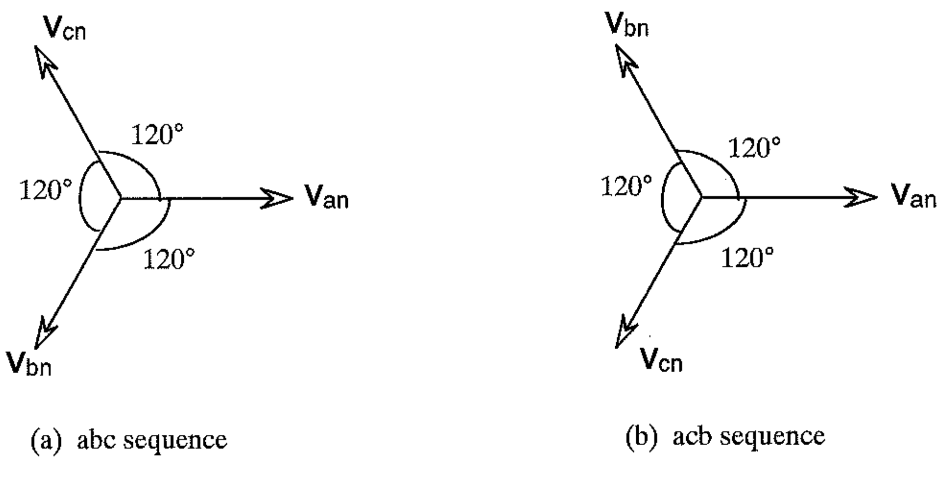


Figure 3 Definition of Phase Sequences

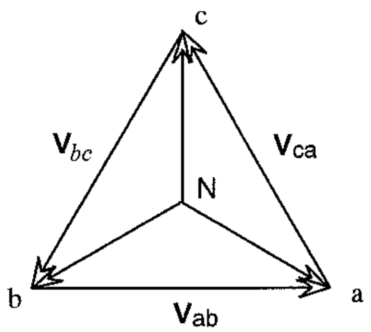


Figure 4 abc sequence

Let us analyze Figure 2 for abc sequence and lagging power factor (p.f.). Suppose that θ is the p.f. angle. The line currents will be displaced from the line-to-neutral voltages by θ. A phasor diagram involving the voltage and current phasors of interest is given in Figure 5.

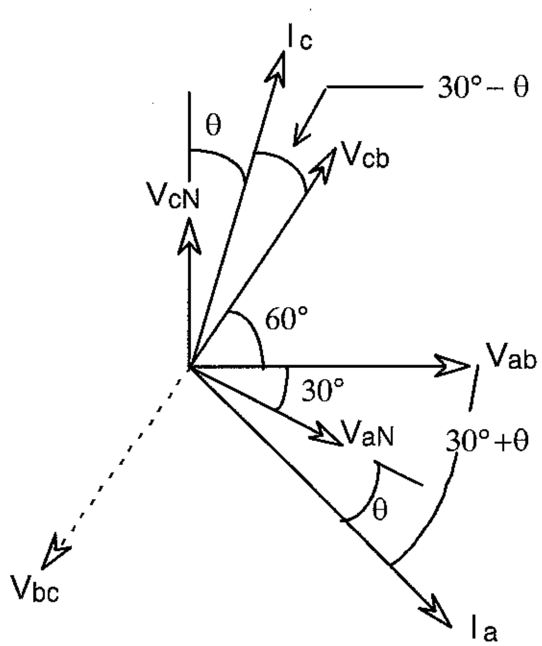


Figure 5 abc sequence and lagging p.f.

Using (1), we write

$$P_1 = |\mathbf{V}_{ab}|\,|\mathbf{V}_a| \cos \angle \frac{\mathbf{V}_{ab}}{\mathbf{V}_a} \qquad (3)$$

$$= V_{LL} I_L \cos(30° + \theta),$$

and

$$P_2 = |\mathbf{V}_{ab}|\,|\mathbf{I}_c| \cos \angle \frac{\mathbf{V}_{cb}}{\mathbf{I}_c} \qquad (4)$$

$$= V_{LL} I_L \cos(30° - \theta).$$

Note that

$$P_1 + P_2 = V_{LL} I_L \left[\cos(30° + \theta) + \cos(30° - \theta)\right] \\ = \sqrt{3}\ V_{LL} I_L \cos\theta = P \tag{5}$$

Also,

$$\sqrt{3}\ (P_2 - P_1) = \sqrt{3}\ V_{LL} I_L \left[\cos(30° - \theta) - \cos(30° + \theta)\right] \\ = \sqrt{3}\ V_{LL} I_L \sin\theta = Q \tag{6}$$

In the above analysis, the following trigonometric identity was utilized:

$$\cos(A \pm B) = \cos A\ \cos B \mp \sin A\ \sin B \tag{7}$$

For the balanced three-phase system, P and Q are the total 3-ϕ real and reactive power supplied from the source to the load. Both P and Q will be positive (since we are considering lagging power factor).

Results for other three cases are compiled below.

abc sequence, leading power factor

$$P_1 = V_{LL}\ \ I_L \cos(30° - \theta) \tag{8}$$

$$P_2 = V_{LL}\ \ I_L \cos(30° + \theta) \tag{9}$$

$$P_1 + P_2 = \sqrt{3}\ V_{LL}\ I_L \cos\theta = P \tag{10}$$

$$\sqrt{3}\,(P_2 - P_1) = -\sqrt{3}\ V_{LL}\ I_L \sin\theta = Q \tag{11}$$

acb sequence, lagging power factor

$$P_1 = V_{LL}\ \ I_L \cos(30° - \theta) \tag{12}$$

$$P_2 = V_{LL}\ \ I_L \cos(30° + \theta) \tag{13}$$

$$P_1 + P_2 = \sqrt{3}\ V_{LL}\ I_L \cos\theta = P \tag{14}$$

$$\sqrt{3}\,(P_1 - P_2) = \sqrt{3}\ V_{LL}\ I_L \sin\theta = Q \tag{15}$$

acb sequence, leading power factor

$$P_1 = V_{LL}\ \ I_L \cos(30° + \theta) \tag{16}$$

$$P_2 = V_{LL}\ \ I_L \cos(30° - \theta) \tag{17}$$

$$P_1 + P_2 = \sqrt{3}\ V_{LL}\ I_L \cos\theta = P \tag{18}$$

$$\sqrt{3}\left(P_1 - P_2\right) = -\sqrt{3}\ V_{LL}\ I_L \sin\theta = Q \tag{19}$$

In all cases, θ is considered as the magnitude of the power factor angle. You are urged to draw phasor diagrams (like Fig. 5) for the various cases and verify the expressions for P_1 and P_2. To summarize, note that for all four cases

$$P_1 + P_2 = P \tag{20}$$

and for the abc sequence

$$\sqrt{3}\left(P_2 - P_1\right) = Q \tag{21}$$

while for the acb sequence

$$\sqrt{3}\left(P_1 - P_2\right) = Q \tag{22}$$

P and Q are, respectively, total real and reactive power supplied from source to load. For leading power factor cases, Q is negative and a reactive power of $\sqrt{3}V_{LL}I_L \sin\theta$ is transferred from the load to the source.

Some more comments follow for the two-wattmeter method.

(1) Power factor is the characteristic of the load, while phase sequence that of the source. Thus, changing phase sequence does not change the power factor.

(2) For any given load, if the phase sequence is reversed, the wattmeter readings are interchanged.

(3) At unity power factor, $P_1 = P_2 = P/2$.

(4) For a power factor of 0.5, one of the two wattmeters will read zero.

(5) The phase angle, θ, and the power factor, cos θ, and be determined from the wattmeter readings alone, if the system is balanced.

$$|\,\theta\,| = \tan^{-1}\left(\frac{|\,Qtotal\,|}{|\,Ptotal\,|}\right)$$

C. PROCEDURE

A schematic diagram is given in Figure 2. Make the connections with the aid of the circuit diagram first and then verify with the wiring diagram. The assistant must check the connections.

After getting the "go-ahead" signal from the assistant, apply 380 V (line to line) to the circuit. Measure line-to-line voltage, line current and the wattmeter's readings.

De-energize the circuit by pushing STOP on the main panel and turning OFF the power supply. (Remember that no changes in the circuit should be made when it is live.). Reverse the phase sequence by interchanging any two lines at the 3-ϕ terminals. Energize the circuit and get data again.

Note: *If the time permits, your assistants may provide another load. Both Part A and Part B will then be repeated for the new load. (This second load should be of a different type in terms of being inductive or capacitive).*

D- RESULTS AND CONCLUSIONS

1. Using the data recorded for the laboratuvary works, obtain real power, *P*, complex power magnitude S, and whatever information possible on reactive power, *Q*, p.f., and the p.f. angle, θ .
2. Discuss the effects of p.f. and the phase sequence on wattmeter readings in the Two-Wattmeter Method.
3. Based on your calculations, identify the load(s). Construct the load(s) as equivalent to a star (Figure 10)). In each case, identify R and the reactance X as an inductance or capacitance.

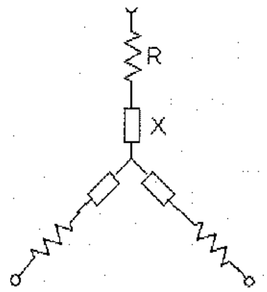
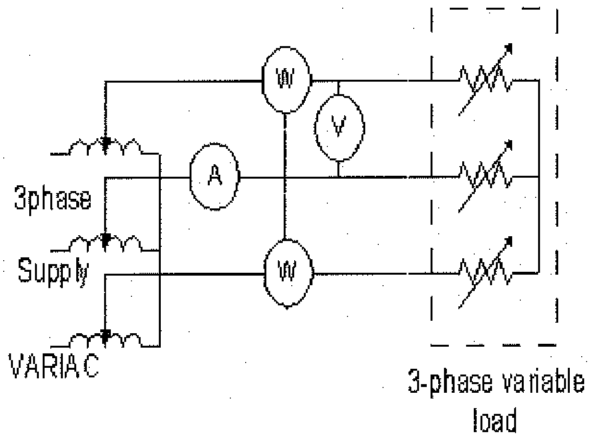


Figure 10. Representations of the 3-Phase Balanced Load

V. CONCLUSION

Summarize in one paragraph what your results were and what they signify. Discuss what you have learned and make suggestions for improving the experiment.



Equipment:

1 three-phase variac
1 ammeter, 0-12A
1 voltmeter, 0-260V
1 wattmeter 0-10A, 0-240V
1 three-phase resistive load

Figure 7- Basic connections for two-wattmeter method of power and power-factor measurement of in a three-phase system

EXPERIMENT #2

VOLTAGE AND CURRENT WAVEFORMS,HYSTERESIS LOOP AND PARAMETER DETERMINATION OF A SINGLE-PHASE POWER TRANSFORMER

A. THE OBJECT OF THE EXPERIMENT

The main object of this experiment *is* to investigate the properties of a single phase transformer. The first step is to observe the primary voltage and current waveforms at various levels of applied voltages. Also the core losses are to be determined by the use of the hysteresis loop. The second step is to calculate the parameters of the equivalent circuit of the transformer from the results of the open-circuit and short-circuit tests. The equivalent circuit is then used to calculate the primary current for a resistive load and a comparison is made between the calculated and the measured values.

B. THEORY

THE MAGNETIC STRUCTURE OF A SINGLE PHASE TRANSFORMER

The single phase transformer is a device with two coils wound on a single core

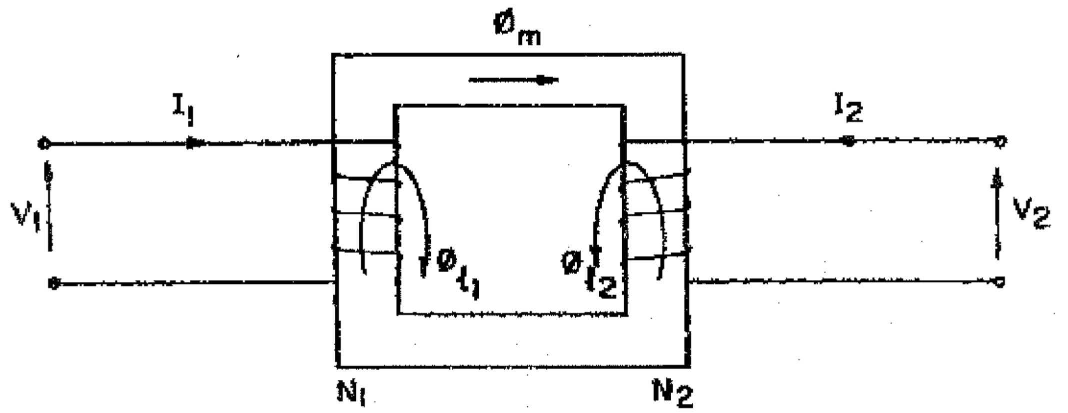


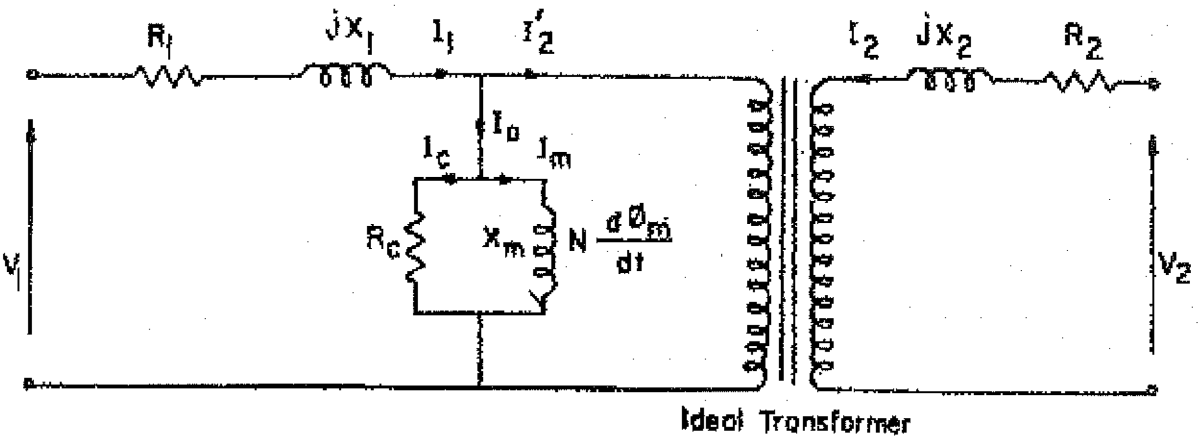
Figure 1. A Single Phase Transformer

If ϕ_m is the magnetising flux, ϕ_{l1} and ϕ_{l2} are leakage fluxes, then flux linkages λ_1 and λ_2 of the primary and secondary windings are

$$\lambda_1 = N_1\phi_{l1} + N_1\phi_m \qquad (1)$$

$$\lambda_2 = N_2\phi_{l2} + N_2\phi_m \qquad (2)$$

where N_1 and N_2 are the number of turns of the primary winding and the secondary winding respectively.



Then,

$$V_1 = I_1 r_1 + \frac{d\lambda_1}{dt} \qquad (3)$$

$$V_2 = I_2 r_2 + \frac{d\lambda_2}{dt} \qquad (4)$$

$$V_1 = I_1 r_1 + N_1\frac{d\phi_m}{dt} + N_1\frac{d\phi_{l1}}{dt} \qquad (5)$$

$$= I_1 r_1 + N_1\frac{d\phi_{\delta m}}{dt} + L_1\frac{dI_1}{dt} \qquad (6)$$

Figure 2: Half-developed Equivalent Circuit of The Transformer

similarly,

$$V_2 = I_2 r_2 + N_2\frac{d\phi_m}{dt} + L_2\frac{dI_2}{dt} \qquad (7)$$

Then the equivalent circuit is as shown in Figure 2. In this equivalent circuit, the shunt resistor represents the core losses of the transformer.

OPEN-CIRCUIT TEST

In the open circuit test, the transformer is excited from the primary while the secondary winding is open circuited. The purpose here is to measure the iron losses and the component of the no-load current which, in turn will give the relevant components of the equivalent circuit. The parameters calculated are the values referred to the side which the test voltage is applied.

$$V_1 = I_1 r_1 + N_1 \frac{d\phi_m}{dt} + L_1 \frac{dI_1}{dt} \qquad (8)$$

Since no current is drawn from the secondary,

$$V_2 = N_2 \frac{d\phi_m}{dt} \qquad (9)$$

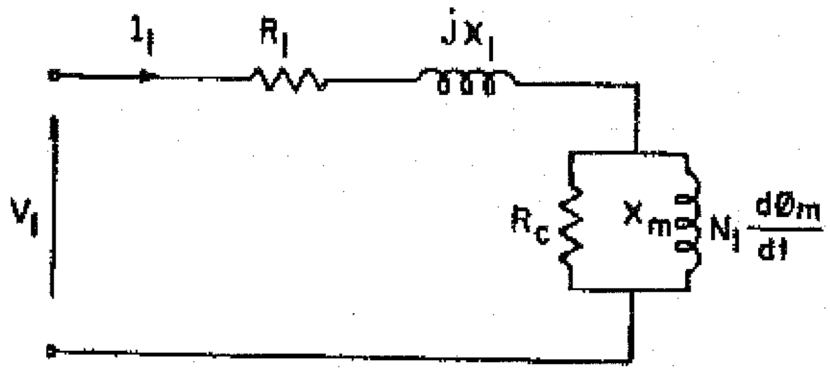


Figure 3. Equivalent Circuit of The Transformer at No-Load

Under open circuit conditions, the effect of the series resistance and inductance is very small and can be neglected. The new open circuit model is as shown in Figure 5. The terminal voltage equation is then reduced to the form,

$$V_1 = N_1 \frac{d\phi_m}{dt} \qquad (10)$$

In the open circuit test, V_1 is sinusoidal so,

$$V_{1,max}\cos\omega t = N_1 \frac{d\phi_m}{dt} \qquad (11)$$

$$\int V_{1,max}\cos\omega t = N_1 \int d\phi_m \qquad (12)$$

$$\frac{V_{1,max}\sin\omega t}{2\pi f N_1} = N_1 \phi_m \qquad (13)$$

$$\phi_m = \frac{V_{1,max}\sin\omega t}{2\pi f N_1} \qquad (14)$$

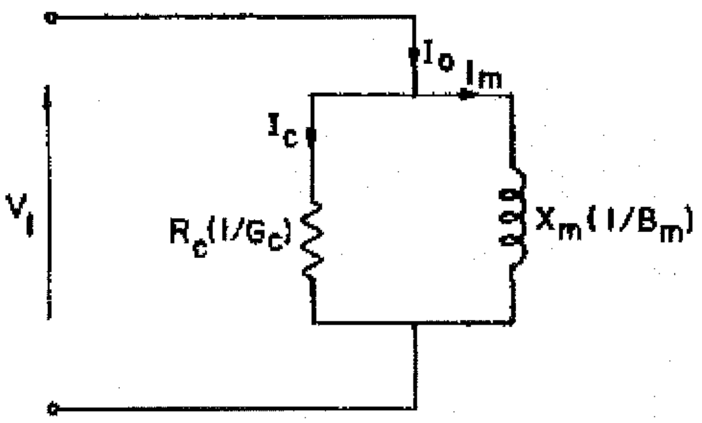


Figure 5. Approximate Open-Circuit Model of a Transformer

Here, R_c represents the iron losses and X_m represents the branch through which the magnetising current flows to establish the core flux.

In the open circuit test the open circuit voltage, current and the input power are recorded for different input voltages As $I_0(t)$ is a non-linear function of terminal voltage, the parameters of the parallel branch found are only valid for the rated voltage

$$P_{in}=\frac{V^2_{rated}}{R_c} \tag{15}$$

$$G_c=\frac{P_{in}}{V^2_{rated}} \tag{16}$$

$$B_m=\sqrt{Y_m^{\ 2}-G_c^{\ 2}} \tag{17}$$

G_c and B_m are the parallel branch components of the transformer model. If the half developed circuit model in Figure 2 is redrawn according to the above developments, the equivalent circuit model of a single phase transformer is obtained. Figure 6 shows the equivalent circuit model of a single phase transformer.

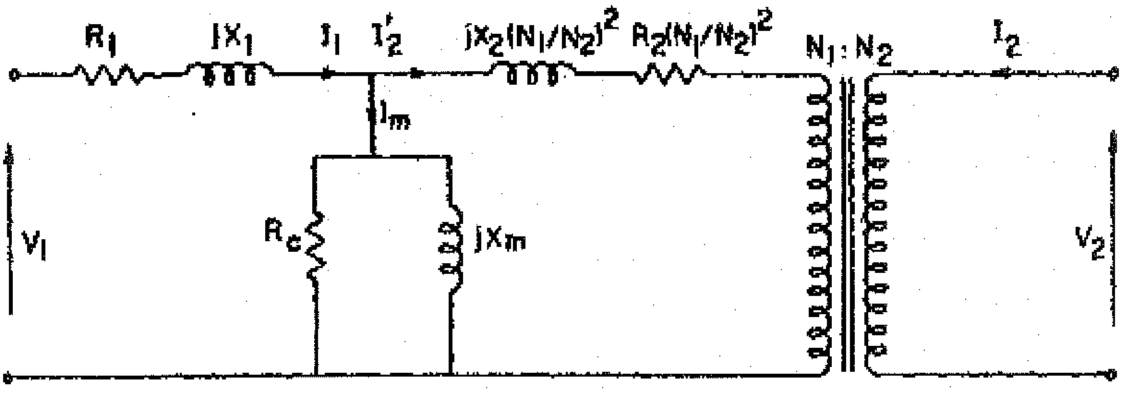


Figure 6. equivalent circuit model of the single phase transformer

HYSTERESİS LOOP:

In a magnetic circuit, magnetisation curve shows the relationship between flux density B and magnetising force H, due to the nature of the magnetic core , this is in the form of a loop which is called energy consumed to change the domain positions is not all recoverable and the domains retain their new magnetic axes which follow sudden potations until a reversing field of sufficient magnitude is applied.

When H is zero there exists a residual flux density, B_{yes} which depends on the type of material , its crystal structure and the value intensity (-Hc). This quantity regarded as the residual magnetism, force is contributed by the iron alone. As H reverses to –H and back again to +H, a complete hysteresis loop is traced on. The loop area is a function of B and can be found experimentally

THE RELATION OF CORE LOSS AND HYSTERESİS LOOP

In a time interval , dt, the energy transferred to a system , S , is defined by the equation ,

$$dE_s = e(t).i(t).dt \tag{19}$$

If the system is a transformer with open circuited secondary then,

$$dET = Vi(t).Im(t).dt \tag{20}$$

$$V_1(t) = N_1 \frac{d\phi_m(t)}{dt} \tag{21}$$

Assuming a uniform flux distribution in the core, from Ampere's Law,

$$I_m(t) = \frac{H(t) l_c}{N_1} \tag{22}$$

where H(t) is the field intensity the core and l_c is the core length.

$$dE_T = N_1 \frac{d\phi_m(t)}{dt} \frac{H(t) l_c}{N_1} dt \tag{23}$$

$$= l_c . H(t) . d\phi_m(t) \tag{24}$$

$$\phi_m(t) = B_m(t).A \tag{25}$$

Then,

$$dE_T = l_c A . H(t) . dB_m(t) \tag{26}$$

$$dE_T = v . H(t) . dB_m(t) \tag{27}$$

In the equations above,

l_c: Mean length of the transformer core.

A: Cross-sectional area of the transformer core.

v : Volume o f the transformer core.

First, consider a flux change corresponding to a variation of H from 0 to H_{max}. The energy required for this change is represented by area between the B-H curve and the B axis (Horizontally shaded area in Figure 7-a.). On decreasing H to zero again, some energy is returned to the supply, dB being negative, this again is represented by the area between the B-H curve and the B-axis (Vertically shaded area in Figure 7-b.). Therefore, the net energy transfer (between the supply and core) by increasing H, from 0 to H_{max} then decreasing H back to zero is given as half of the area of the hysteresis loop. However, a complete cycle of magnetisation will also require the net energy transfer by decreasing H from 0 to $-H_{max}$ then increasing H back to zero. Therefore, the net expenditure of energy per cycle per unit volume is represented by the area of the hysteresis loop. However, by measuring the area of the loop which is formed by flux vs ampore –turns, the net energy transfer Per cycle can directly be found. This method automatically introduces the volume term.

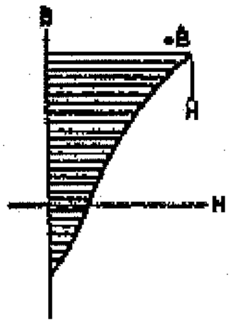


Figure 7-a.

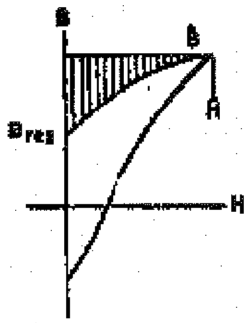


Figure 7-b.

Power loss of the system can be represented by the equations below:

$$P = \frac{1}{T}\int_{0}^{T} dE_T \tag{28}$$

$$= fv\int_{B1}^{B2} H(t).dB_m(t) \tag{29}$$

For a sinusoidal terminal voltage, $B_m(t)$ is sinusoidal.

The integral

$$\int_{B1}^{B2} H(t).dB_m(t) \tag{30}$$

over one period is the area of the hysteresis loop. For constant frequency of operation, core loss is directly proportional to the hysteresis loop area. For a cyclic frequency of f cycles/sec, the rate of energy flow in joules/sec or watts will be(loop aren) x f (Joules/cycle x Cycle/sec =Watts)

Hence

Core losses = (loop area) x f.

For a transformer

Core losses = (eddy current + Hysteresis) Losses

OBSERVATION OF THE HYSTERESIS LOOP

Using convenient signals, the hysteresis loop can be seen on a CR0 screen. Hence, the hysteresis loop is a plot of flux density against magnetising force. Signals which are directly proportional and in-phase with these quantities can be generated.

$$B(t) = \frac{\phi_m(t)}{A} \tag{31}$$

$$B(t) = \frac{1}{A}\frac{1}{N_1}\int V_1.dt \tag{32}$$

The integral of the voltage can be obtained by an RC network (see Figure.8)

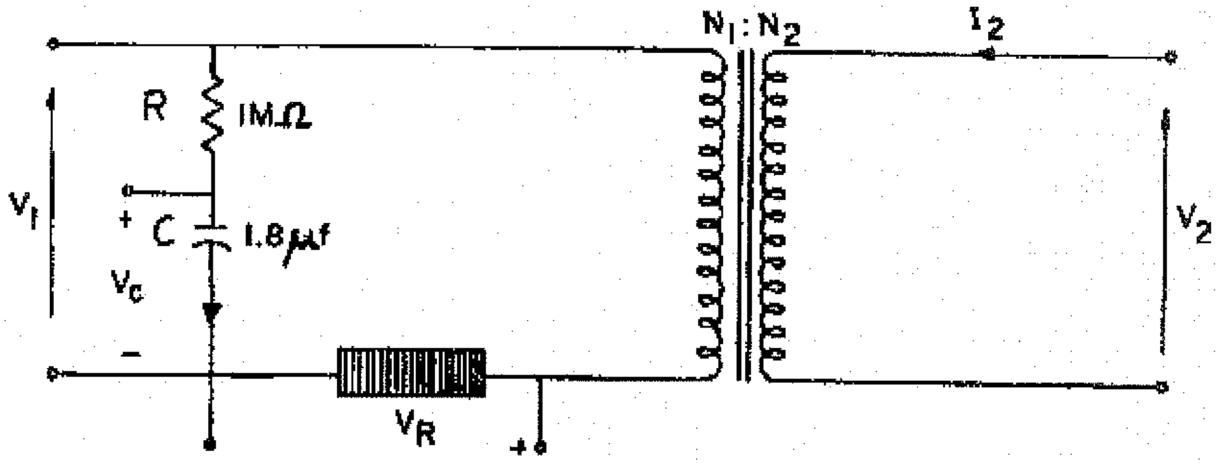


Figure 8. The circuit for obtaining the references for magnetizing force and flux density of the core

If R>>jωC then

$$I_c = \frac{V_1}{R} \tag{33}$$

$$V_c = \frac{1}{R.C}\int V_1.dt \tag{34}$$

For a sinusoidal excitation of V_1,

$$B = \frac{1}{RC}\int V_1 dt \tag{35}$$

Therefore, the capacitor voltage, V_c is directly proportional to the magnetic field density, magnetising force, H can be found as

$$H = \frac{N_1.I}{l_c} \tag{36}$$

The voltage drop on the carbon pile resistor on the current path is;

YR- I.Rc

$$V_r = I.R_c \tag{37}$$

Then, the voltage drop, V_R on the carbon pile resistor is directly proportional to the magnetic field intensity, H.

$$H= \frac{N_1}{R_c.l_c} V_R \tag{38}$$

If the capacitor voltage against carbon pile resistor voltage drop is observed the hysteresis behaviour of the magnetic core will be obtained.

SHORT-CIRCUIT TEST

In the short circuit test the transformer is excited from the primary while the secondary is short circuited. The purpose of this test is to determine the leakage reactance and the effective

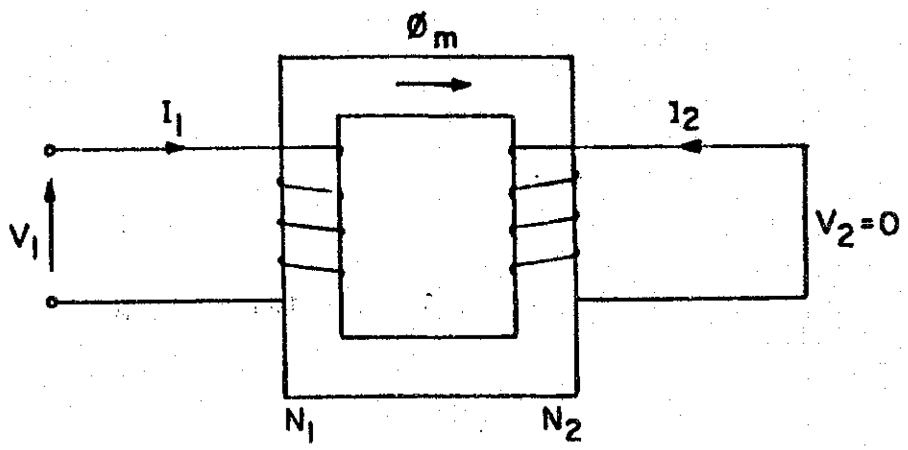


Figure 10. Short Circuited Transformer

copper loss of the transformer.

$$V_1 = I_1 r_1 + N_1 \frac{d\phi_m}{dt} + N_1 \frac{d\phi_{l1}}{dt} \tag{47}$$

$$V_2 = I_2 r_2 + N_2 \frac{d\phi_m}{dt} + N_2 \frac{d\phi_{l2}}{dt} \tag{48}$$

Note that $V_2 = 0$ as the secondary terminal is short circuited Therefore,

$$N_2 \frac{d\phi_m}{dt} = -\left(N_2 \frac{d\phi_{l2}}{dt} + I_2 r_2 \right) \tag{49}$$

$$\frac{d\phi_m}{dt} = -\frac{1}{N_2}\left(L_2 \frac{dI_2}{dt} + I_2 r_2 \right) \tag{50}$$

$$N_1.I_1 = -N_2.I_2 \tag{51}$$

Then ,

$$\frac{d\phi_m}{dt} = \frac{1}{N_2}.\left(\frac{N_1}{N_2}.L_2.\frac{dI_1}{dt} + \frac{N_1}{N_2} I_1 r_2 \right) \tag{52}$$

$$V_1 = \frac{N_1}{N_2}\left(\frac{N_1}{N_2}.L_2.\frac{dI_1}{dt} + \frac{N_1}{N_2}.I_1 r_2 \right) + L_1 \frac{dI_1}{dt} + I_1 r_1 \tag{53}$$

$$V_1 = I_1\left[r_1 + \left(\frac{N_1}{N_2} \right)^2 .r_2 \right] + \left[L_1 + \left(\frac{N_1}{N_2} \right)^2 .L_2 \right] \frac{dI_1}{dt} \tag{54}$$

Define

$$r_{eq} = r_1 + \left(\frac{N_1}{N_2} \right)^2 .r_2 \tag{55}$$

and

$$L_{eq} = L_1 + \left(\frac{N_1}{N_2} \right)^2 .L_2$$

Then, at shot circuit test, the transformer can be modelled as in Figure 11

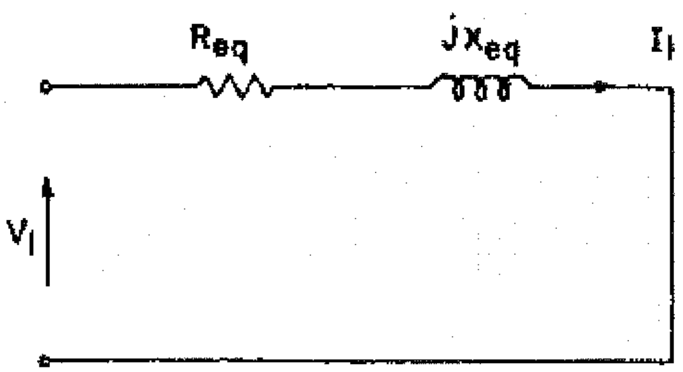


Figure 11. Equivalent Circuit of The Transformer at Short-Circuit Test

In the short circuit test, the terminal voltage, current and input power are recorded .From these measurements, the circuit parameters are calculated as shown below.

$$Z = \frac{V_1}{I_1} \quad (57)$$

$$R_{eq}=P_{in}/I_1^2 \quad (58)$$

$$X_{EQ}=\sqrt{Z^2 - r_{eq}^2} \quad (59)$$

C. PROCEDURE

Use a turns ratio $= \frac{\text{Primary turns}}{\text{Secondary turns}}$ =220/24

1. Observation of current and voltage waveforms:

Connect the transformer as shown in Fig.7 with the secondary winding open-circuited but the wattmeter initially not connected connect y points E, A, and C to the earth, Y_1 and Y_2 respectively of a C.R.O.

Switch on the supply and adjust the single phase terminal voltage to 220V by means of the auto-transformer. Note the meter readings, and sketch the voltage and current a waveforms. (Adjust the variable resistor R to give sufficient signal for the current to the C.R.O. Keep R at minimum if possible and use the C.R.O. amplifier.). Repeat the test for voltages of 250, 200, 150, 100 and 50V. and make sketches of the waveforms.

2. Hysteresis loop and Open Circuit Test:

Switch of the supply and connect the wattmeter into the circuit using current and/or voltage transformers in conjunction with it so that a reasonable deflection can be obtained on the instrument if necessary.

Reconnect point C to the X terminal, and connect B to Y calibrate the X and Y inputs of CRO so that largest loop is obtained on the screen for 250V.

Keep the CRO X and Y constant throughout this test, and commence with the highest voltage value for the largest loop on the screen.

For the voltages in the first part of the experiment observe and sketch the hysteresis loop. Record at each step the value of primary voltage, current, an power.

Measure the dc-resistances of the primary and secondary windings with a Voltmeter-Ammeter-Battery set.

3. Short Circuit Test:

Connect the circuit as shown in Fig.8 with the secondary-winding short-circuit and with the wattmeter again initially NOT connected.

Increase the primary voltage VERY SLOWLY until the primary current exceeds the rated value by 10% and not the value of the voltage and current under these conditions. Switch of the supply and connect the wattmeter into the circuit using current and/or voltage transformers in conjunctions with it such that a reasonable deflection can be obtained on the instrument, if necessary. Non increase the primary voltage in steps until the primary current exceeds rated value by 10% recording at each step the value of primary voltage, current an power.

4. Load Test

Connect a resistance to the secondary winding of the transformer as shown in Fig.9. Increase the primary voltage and adjust the resistance until the rated secondary current is obtained with the primary voltage at its rated value; record the values of primary voltage, current and power and the value of the secondary current.

Measure the value of the resistance of the secondary load. Repeat the experiment with a combination of resistance and inductance which gives a secondary load with a power-factor of approximately 0.8 lagging.

Measure the value of the resistance and reactance of the secondary load.(See GEE 321-1).

D- RESULTS AND CONCLUSIONS

1) Calculate the core losses for each of the voltages ($P_{core} = P_T = P_{cu}$). Plot the core losses against the square of the voltages.
2) Estimate the area of the hysteresis loop for each test point and plot on the same graph.(The results will be very approximate).
3) Using the results of the open-circuit test, plot curves of primary voltage against current and core-loss against voltage and hence determine the value of the magnetising reactance and resistance of the equivalent circuit of the transformer at rated voltage.
4) Using the results of the short-circuit test plot curves of primary voltage and copper-loss against current and hence determine the value of resistance and leakage reactance of the equivalent of the transformer. Compare the value of ($r_{1\,d.c} + r_{2\,d.c}$) with R_T and comment on the results.
5) Draw the equivalent circuit of the transformer for each of the secondary loads used in the load test and calculate the primary current in each case; compare the calculated and measured voltages. Draw to scale the phasor diagram of voltages and currents for each load test.
6) Explain the changes in the current and hysteresis loop with increasing Voltage. To what extend do you think the measured hysteresis loop represent the actual hysteresis loop?
7) Indicate how close the performance of the transformer approaches that of an Ideal Transformer.
8) Why is the hysteresis loss calculated from the area of the hysteresis loop different from the core loss obtained from wattmeter readings.
9) What does eddy current loss mean? Why are the transformer cores laminated?

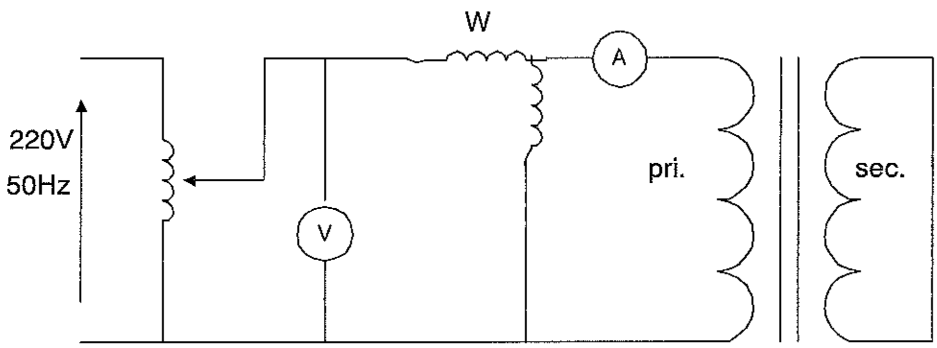


Fig 8. Short-circuit test

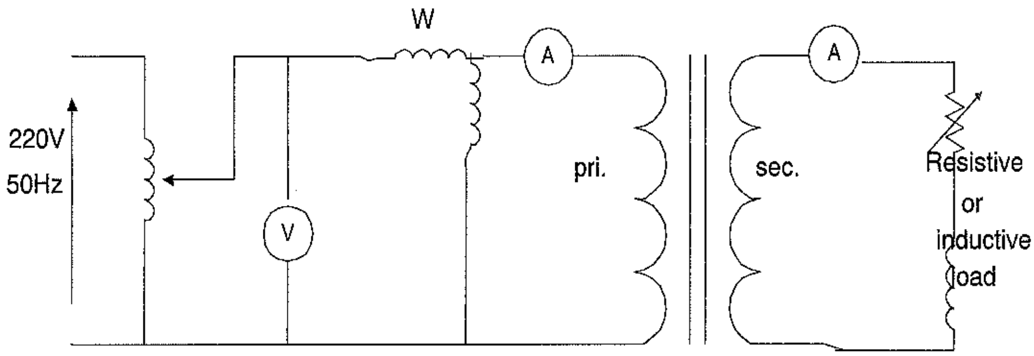


Fig 9. Load test

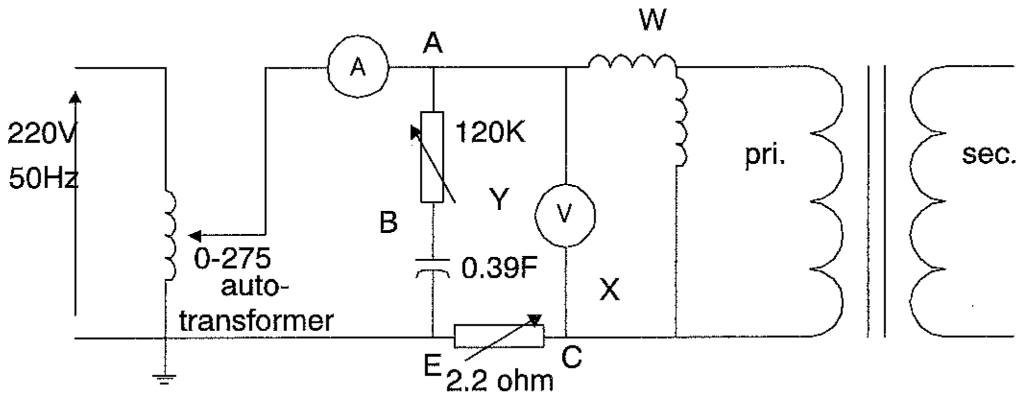


Fig.7.Hysteresis loop and open circuit test

EQUIPMENT

Single-phase variac

Voltmeter, 0-130V

Ammeter, 0-6A

Wattmeter, 0-5A, 0-60V

EQUIPMENT:

Single-phase variac

Ammeter 0-1,2A

Voltmeter 0-250V

Wattmeter 0-5A,0-240V

Single-phase transformer 220:24,500W

	V	A
Primary wind.		
Second wind.		

V	I	P

E.2. Data table for part C.2.

V	I1	I2	P

E.3.Data tables for resistive

V	I (A)	P (W)
220		
250		
200		
150		
100		
50		

Y_{max} (cm)	X_{max} (cm)

EXPERIMENT#3

REGULATION AND EFFICIENCY OF A THREE-PHASE TRANSFORMER

A. THE OBJECT OF EXPERIMENT

The object of the experiment is to investigate the variation of the regulation and efficiency of a three phase transformer with load. Some critical points such as the maximum efficiency conditions and approximate equivalent expression of the regulation will be considered.

B. THEORY

Voltage regulation and efficiency are the two important performance indices of a practical transformer. In practice, the transformers having the voltage regulation as low as possible and efficiency as high as possible are preferred.

a. EFFICIENCY:

The efficiency of a transformer is defined as:

$$\eta = \frac{outpower}{inputpower} = \frac{outpower}{outpower + losses}$$

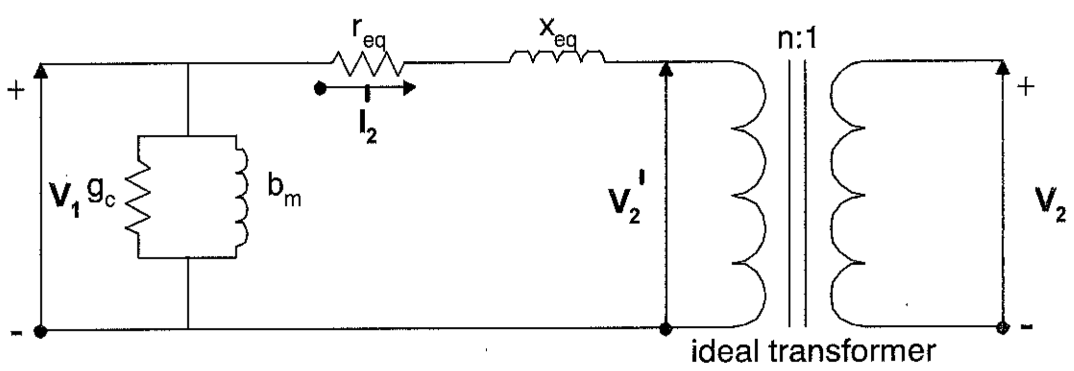


Figure 1. Approximate equivalent circuit

The approximate equivalent circuit of a transformer is shown in Figure 1.

The transformer equivalent circuit parameters are defined as:

$r_{eq} = r_1 + r_2'$

$x_{eq} = x_1 + x_2$

$V_2' = n.V_2$ where;

n :turns ratio

r_1 :the internal resistance of primary winding

r_2' :the referred internal resistance of secondary winding

x_1 :the leakage reactance of primary winding

x_2 :the referred leakage reactance of secondary winding

g_c :admittance corresponding to core losses

b_m :susceptance corresponding to magnetising current

Assume that a load with a certain p.f. is connected at the secondary and the input voltage V_1 is kept at its rated value while a current I_2' is delivered to the load. The losses under such an operating condition will be as follows;

1)Core losses P_C:

The losses which occur in magnetic material are called *iron losses or core losses.*

Core losses depend on both the frequency and voltage, V_1.Since V_1 may be assumed to be approximately constant as I_2'changes, P_C will be constant.

$P_C = 3V_1^2 g_c$ (V_1:Phase Voltage)

2)Copper losses P_{CU} :

Copper losses which occur in windings are function of I_2'.

$P_{CU} = 3(I_2')^2\ r_{eq}$ (I_2':Referred Phase Current)

By substituting the Eq^n(5)and Eq^n(6) into Eq^n(1) having the out power;

P_{OUT}=3 $V_2' I_2' \cos\theta$ (V and I are phase voltages & currents)

We obtain,

$$\eta = \frac{V_2' I_2' \cos\theta}{(V_2' I_2' \cos\theta + V_1^2 g_c + (I_2')^2 r_{eq})}$$

where cosθ is the power factor of the load.

Maximum efficiency:

To find the maximum efficiency of the transformer at a specified power factor;

$$\frac{\delta\eta}{\delta I_2'} = 0$$

which yields;

$P_C=3(I_2')^2 r_{eq}$

That is **the maximum efficiency occurs when the copper losses are equal to the core losses.**

REGULATION

Voltage regulation is the criteria to describe the ability of a transformer in order to maintain its output voltage on load. It is defined as the percent change, in the secondary voltage from no load to certain load while the primary voltage is kept constant.

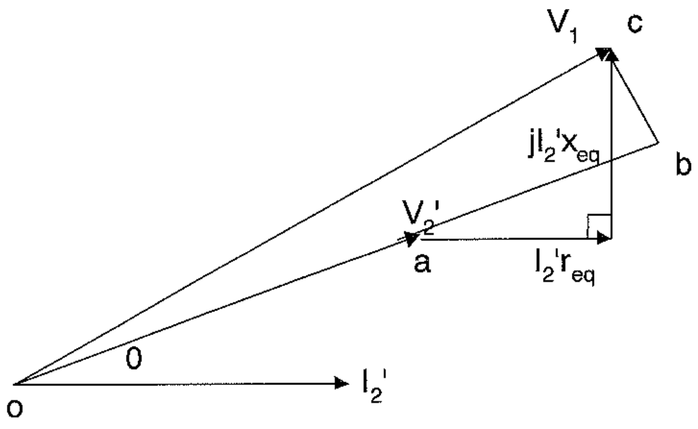
$$\text{Reg.}= \frac{|V_2'_{no-land}| - |V_2'_{load}|}{|V_2'_{rated}|} \times 100$$

All quantities are referred to the primary with reference to Figure1.

$V_2'_{\text{no-load}}=V_1$

$$\text{Reg}= \frac{|V_1| - |V_2'_{load}|}{|V_2'_{rated}|} \times 100$$

If V_1 is set to its rated value and V_{base} is chosen to be equal to V_{2rated}, then;



Reg=100(1-$|V_2{'}_{load}|$ pu)

An approximate expression for regulation:

Consider the phasor diagram given in Figure2. Corresponding to the circuit given in Figure1.

Figure 2. The phasor diagram of the transformer shown in Fig.1.

This phasor diagram is drawn considering an inductive load being connected to the transformer terminals, where;

$$|ab| \cong I_2{'}r_{eq}\cos\theta + I_2{'}x_{eq}\sin\theta$$

$$|ob| \cong |oc|$$

Hence;

$$|V_1| = |V_2{'}| + |I_2{'}|(r_{eq}\cos\theta + r_{eq}\sin\theta)$$

$$\mathrm{Re}\,g = \frac{|V_1| - |V_2{'}|}{|V_2{'}_{rated}|} \times 100$$

$$\mathrm{Re}\,g = \frac{|I_2{'}|(r_{eq}\cos\theta + x_{eq}\sin\theta)}{|V_2{'}_{rated}|} \times 100$$

If the load current I_2' is also equal to its rated value, then;

$$\text{Re}\,g = r_{eq-pu}\cos\theta + x_{eq-pu}\sin\theta$$

also at unity power factor;

$$\text{Re}\,g = r_{eq-pu}$$

Zero Regulation:

The expression for the power factor of *zero regulation* is obtained by equating the Eq^n(20) to zero;

$$-r_{eq}\cos\theta = x_{eq}\sin\theta$$

$$\frac{-r_{eq}}{x_{eq}} = \frac{\sin\theta}{\cos\theta}$$

then;

$$\tan\theta = \frac{-r_{eq}}{x_{eq}} \quad \text{or} \quad \theta = \tan^{-1}\left(\frac{-r_{eq}}{x_{eq}}\right)$$

For zero regulation, the phase angle, θ, of the load should be equal to $\tan^{-1}(-r_{eq}/x_{eq})$ which means that the phase angle θ has a negative value and therefore should be capacitive.

Maximum Regulation :

Similarly, the expression for the power factor of the load for *maximum regulation* is obtained by differentiating the Eq^n(20) with respect to θ and equating the resulting expression to zero ;

$$-r_{eq}\sin\theta + x_{eq}\cos\theta = 0$$

hence;

$$\theta = \tan^{-1}\left(\frac{x_{eq}}{r_{eq}}\right)$$

C. PROCEDURE

Use a transformation ratio of approximately 1:2 and connect the primary and secondary windings star/star as shown in figure3

The ratings of the primary and secondary windings per phase is than:

Primary: 380 V line to line

Secondary:190 V line to line

(I rated)=7.6 Ampere (H.V side for 5 KVA transformer)

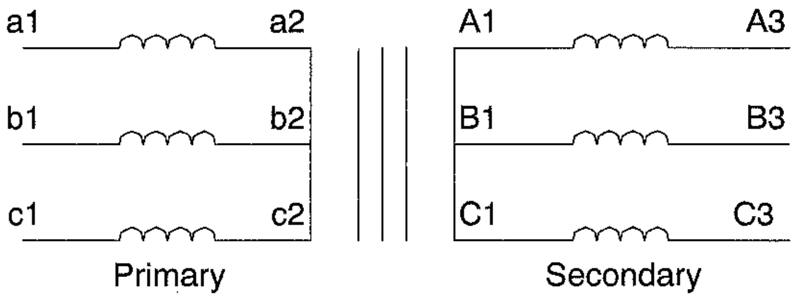


Fig.3. Star/Star connection of the transformer

Note: 100 single wattmeter (voltage setting of wattmeter is up to 240 V, connect it between phase and neutral point)

Assuming that the rated primary voltage is 380 V line, measure the rated secondary voltage by a voltmeter and check the turns ratio of the transformer.

1. Carry out and open-circuit test on the transformer for primary voltage up to rated value.
2. Carry out a short-circuit test on the transformer for primary currents up to rated value.
3. Connect the circuit as shown fig. 4 with a resistive load. Bring the primary voltage up to the rated value and hold it constant at that value throughout the test.

Increase the load current in steps, up to the rated value (if possible) at each step record the values of the primary power ,secondary power, secondary voltage and load current.

RESULTS AND CONCLUSION

1. Draw the curve of total iron-loss and copper-loss against load current on the same graph. Using Eqn. (4) calculate the efficiency of the transformer for load currents up to 10 % over the rated value; Plot the curve of efficiency against load current on the same graph
   From the measured values of primary power and secondary power calculate the efficiency of the transformer at each load current and plot the curve of the variation on the same graph as above.

2. At each value of load current calculate the regulation of the transformer and plot the curve of regulation and the value of secondary voltage against load current on the same graph
3. From the measurements of the short-circuit test calculate the per-unit value of the equivalent resistance of the transformer and the check the validity of equation(12) at full-load current.
4. Comment on the shape of all curves and discuss any discrepancies between calculated and measured values. Comment on the conditions at which the transformer has maximum efficiency.

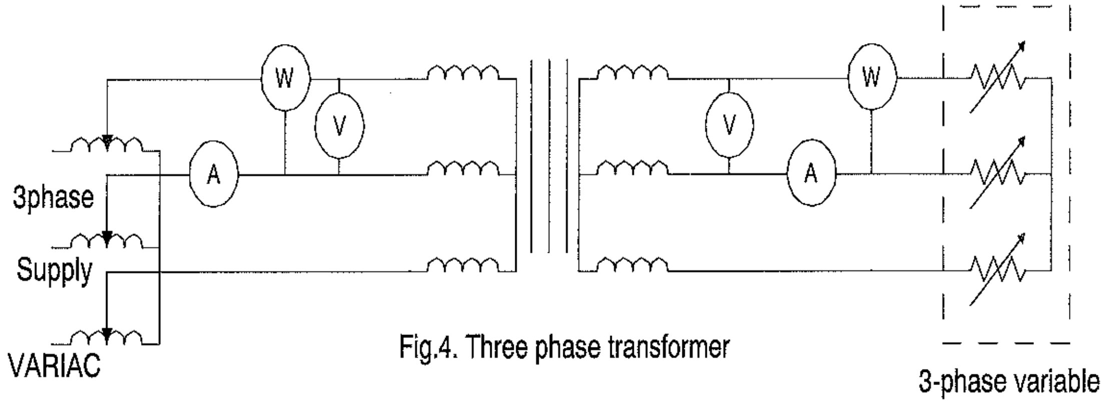


Fig.4. Three phase transformer

EQUIPMENT:

There-phase transformer, 380V:190V

There-phase variac

Ammeters, 0-12A (A , A)

Voltmeter, 0-520V (V)

Voltmeter, 0-260V (V)

Wattmeter, 0-10A, 0-240V

There-phase variable resistive load

V	A	W1	W2

E.1. Data table for open-circuit test:

V	A	W1	W2

E.2. Data table for short-circuit test

V	A	W1	V	A	W2

E.3. Data table for loading test

EXPERIMENT #4

THE MAGNETIZATION CURVE OF SEPARATELY AND SELF EXCITED D.C. GENERATORS

A. THE OBJECTS OF THE EXPERIMENT

1) To investigate the relationship between the induced voltage and the field current of a separately excited generator driven at constant speed.

2) To study the conditions under which a D.C. generator will self excite and to observe the relationship between induced voltage and the total resistance of the field circuit.

B. THEORY

THE MAGNETIZATON CURVE OF A D.C. MACHINE

The *magnetization curve* of a D.C. machine shows the relationship between the induced armature emf, E_a and the field excitation, I_f .Due to the magnetic properties of the core, the magnetization characteristics is in the form of a loop (hysteresis loop). Such a loop is shown in Figure 1. To obtain a regular magnetization curve, a systematic procedure such as the one described in the "Procedure" section must be applied. However, the magnetization curve of a D.C. machine is often shown as a single curve taken upwards from the residual value, $E_{a\ res}$ *or* from a demagnetized state (i.e. origin). Note that, the magnetization characteristics should be drawn for constant speeds. Figure 2 shows two different magnetization characteristics for two different speeds.

The induced Emf across the armature winding of a D.C. machine is a function of rotor speed, w_m and field current, I_f (see Figure 2) Hence, the emf equation can be written in the following manner

$E_a = K_a \phi_p \ w_m = M \ w_m \ I_f$

where

E_a	Induced back-emf across the armature winding (volts)
K_a	Winding constant
ϕ_p	Flux per pole (Webers)
w_m	Rotor speed (radians/sec)
M	Mutual inductance (henry)
I_f	Field current (Amperes)

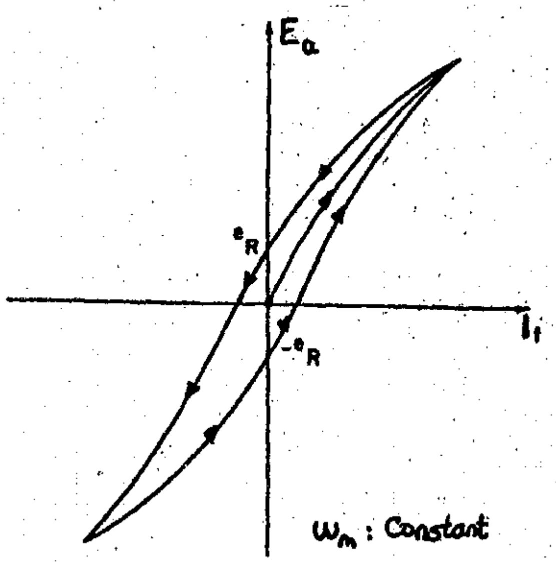


Figure 1. The complete magnetization curve of a D.C. machine

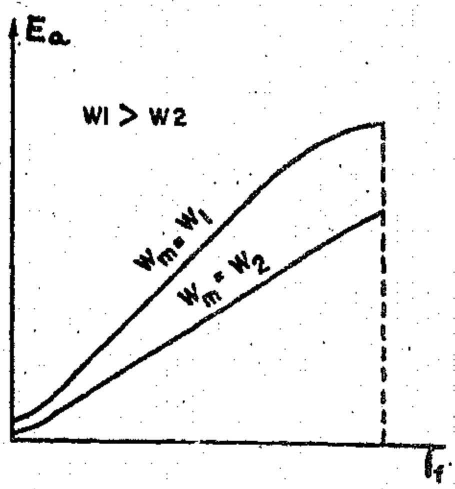


Figure 2. The magnetization curves for two different speeds

SELF EXCITED D.C. GENERATORS

The separately excited generator has one major drawback; it requires a separate D.C. source for the field circuit. Self excited generators avoid this by exploiting some properties of ferromagnetic materials. These properties are *residual magnetism* and *saturation.* Consider for example, a self excited D.C. generator whose field circuit is connected in parallel with the *brush terminals* as shown in Figure 3 (shunt connection).

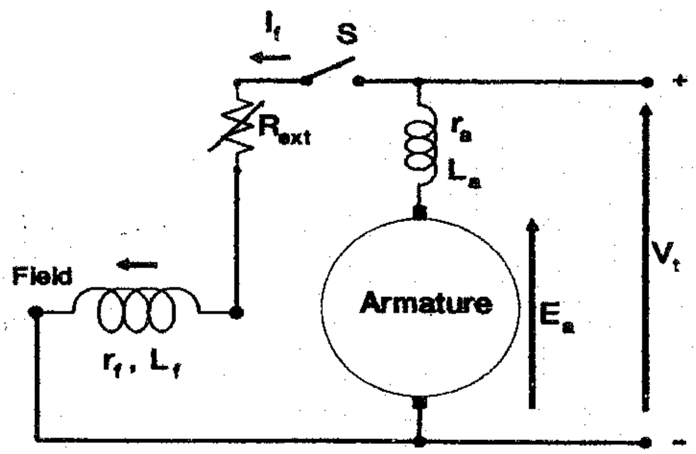


Figure 3. Self-excited D.C. shunt generator

Initially, the switch S. is kept open and the machine is run at constant speed. This means that we rotate the rotor (armature) of the D C generator by a motor (A C or D.C.). Next, suppose that the no-load magnetization curve of the machine is available, as well as the relation

$$E_a = R_f I_f \tag{2}$$

Where

$$R_f = r_f + r_a + R_{ext} \tag{3}$$

drawn on the coordinate axes, as in Figure 4. Suppose now the switch in the field circuit *is* closed. We ask the following question: "What is the voltage across the terminals of the machine?" Note that the machine terminals are open (i.e. the machine is on no-load) so that the armature current is equal to the field current ($I_a = I_f$).

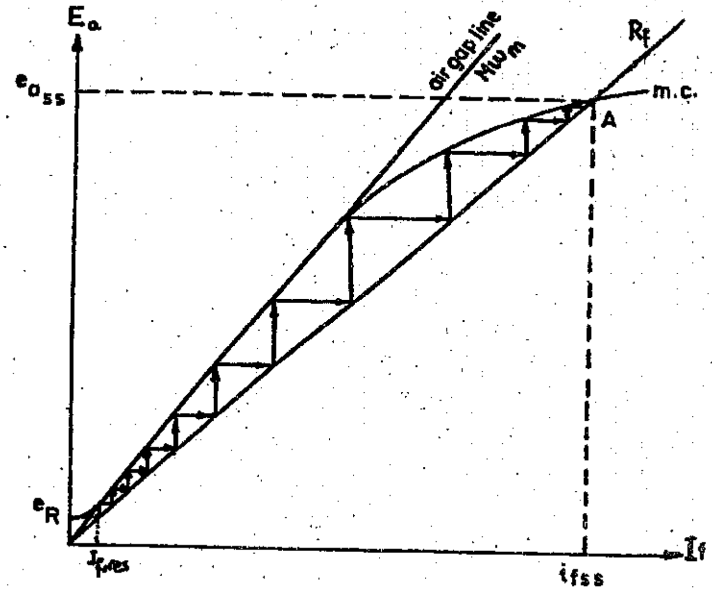


Figure 4. The build-up process of induced voltage and field current

It is now evident that the steady state solution of these equations is the point of intersection of these two curves (i.e. point A). It should be emphasized that the ordinate of this point is the induced armature voltage of the generator at steady state, ~ and the terminal voltage is

$$V_t = E_a - I_f \; r_a \qquad (I_a = I_f) \qquad (4)$$

The process in which such a machine reaches the operating point can be crudely described in the following manner When the field current is zero, there is a voltage $E_{a\ res}$ (Residual *voltage)* across the brushes, due to the *residual magnetism.* When the field circuit is closed, the induced voltage (residual voltage) forces some current through the field circuit, $I_{f\ res}$ (= $E_{a\ res}$ /Rf). Consequently, this new value of field current increases the value of the induced voltage, as in Eqn (1). This interdependent build-up process of induced voltage and field current continues (by positive feedback) and comes to a stop if a point of intersection between the two curves exists (i.e. when the machine saturates). Note that, the no-load voltage of a self excited D.C. generator, $E_{a\ ss}$ can be adjusted by varying the external resistance connected in series with the field winding, R_{ext}. Changing R_{ext} will also change the value of Rf which will affect the Slope of the line in Figure 4. Hence, the intersection point of the line with the machine characteristics will change

Mathematical Approach To Self Excitation

The generator is on no-load, hence

$$Ia = If \qquad (5)$$

Let

$$I = Ia = If \qquad (6)$$

The loop equation is

$$(L_a + L_f)\frac{di}{dt} + (r_a + r_f + R_{ext})i - E_a = 0 \qquad (7)$$

or, from Eqn (3)

$$(L_a + L_f)\frac{di}{dt} + (R_f)i - E_a = 0 \qquad (8)$$

and

$$E_a = M\omega_m I \tag{9}$$

Let the current at time zero be I_o (=$I_{f\ res}$). Then, the Laplace transform of the above equation gives;

$$[(L_a + L_f).s + R_f - M\omega_m]I(s) - (L_a + L_f).I_0 = 0 \tag{10}$$

Hence,

$$I(s) = \frac{I_0}{s + \left(\dfrac{R_f - M\omega_m}{L_a + L_f}\right)} \tag{11}$$

Remember that we have

$$\leq\{e^{-at}\} = \frac{1}{s+a} \tag{12}$$

Combining Eqn (11) and Eqn (12), the inverse Laplace transform of I(s) is,

$$i(t) = \leq^{-1}\{I(s)\} = I_0.e^{-\left(\frac{R_f - M\omega_m}{L_a + L_f}\right)t}$$

From the above result, three modes of operation arise:

* if ($r_a + r_f + R_{ext}$) >$M.w_m$ the current decays to zero.

* if ($r_a + r_f + R_{ext}$) = the current remains constant.

* if ($r_a + r_f + R_{ext}$)< $M.w_m$ the current increases without limit.

In the actual machine, I_o is caused by the *residual magnetism* and if R_f < M wm in the unsaturated region, the machine builds-up the armature voltage and the current increases. When the machine starts to saturate, the value of M decreases. When M has decreased down to the point (the operating point) where $R_f = M\ w_m$, there is no further increase in the armature voltage or current (Hence, practically, the current can never increase without limit due to saturation). On the other hand, if Rf > M w_m, the total resistance is larger than *the critical resistance* so the machine does not self excite. The critical resistance is defined as the maximum *value of the total resistance* at *which self-excitation starts (i.e. the slope of the air gap line).* The above three modes of operation are shown graphically in Figure 5.

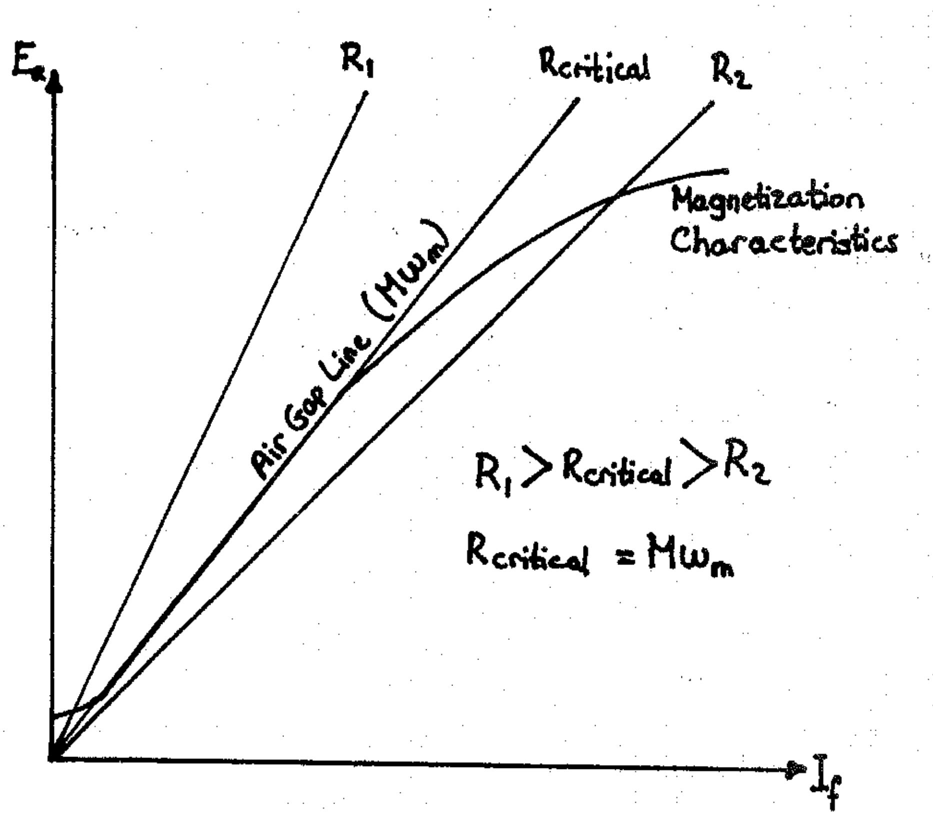


Figure 5. The three possible modes of operation

C. PROCEDURE

1. Connect the d.c. generator for separate excitation as shown in Fig.6.
2. Start the machine, switch on the field supply on observe that the generator will develope a voltage for either polarity of the field and either direction of rotation of the armature.
3. For a fixed direction of rotation observe what happens when field current is increased from zero to some value for either polarity of field excitation.

4. Start the machine and adjust the speed to the rated value and hold it constant at this value throughout the test, increase the field current until the induced voltage in the armature exceeds the rated value by 10%.
5. Decrease the field current from this value to zero in steps, recording at each step the value of field current and armature voltage. Record the value of residual voltage.

Important Note

Once the field current has been reduced to a new value it must not then be increased again, otherwise the magnetisation curve.

6. Switch off single-phase variac. Interchange the terminals of external d.c. supply (i, e, L →L) manually. Also in doing so the polarities of the AVO's i, e.(AVO8) and (AVO8) , must be reserved using the button (REV M.C.) on the meters.

The procedure mentioned in the above paragraph must be done. If required, where following part of the procedure. Increase the field current in steps in the reverse direction until the induced armature voltage exceeds the rated value 10% at each step record the value of field current and armature voltage. The procedure of (5) and (6) gives the descending branch of the magnetisation curve.

7. Obtain the ascending branch of the magnetisation curve thus completing the loop by starting with the field current at the last value used in (6) and without switching off the field supply, recording at each step the same data as for the ascending branch of the magnetisation curve and using values of field current as close as possible to the values used for the descending branch. Record the value of residual voltage in this case. Perform the procedure given in 5 and 6 for ascending branch as shown in Fig.1.
8. Connect the d.c. generator for self-excitation as shown in Fig.7. and with the maximum value of field resistance in circuit, start the machine and adjust the speed to the rated value. Gradually reduce the field resistance in steps recording at each step the values of field current and armature voltage until the machine self-excites; note the values at which self-excitation occurs. Measure the values of external field resistor at which self-excitation occurs. After self-excitation occurs, continue to decrease the field resistance and record the values until the armature voltage exceeds the rated value by 10%. If the machine does

not excite under these conditions reverse the polarity of the field and repeat the above procedure.

9. Measure the armature and field winding resistance.

D. RESULTS AND CONCLUSION

1. Plot on the same graph the ascending and descending branches of the magnetisation curve for rated armature speed and draw in the air-gap lines.
2. Explain the significance of the air-gap line and what determines the displacements between the ascending and descending branches of the magnetisation curve.
3. Repeat the descending branches of the magnetisation curves for rated speed on a new graph those curves are identical for all practical purposes with the curves of induced armature voltage under self-excited conditions since the voltage drop in the armature voltage due to the flow of the field current is extremely small. Draw a series of lines through the origin of the graph cutting the magnetisation curves at different points. For each intersection calculate the equivalent field resistance and the corresponding induced voltage as measured from the magnetisation curve. Plot a curve of induced voltage against field resistance.
4. From the measured values of field current and induced voltage. Calculate the total field resistance at each point and plot these on the same graph as conclusion (3) above.
5. Compare the two curves of induced voltage against field resistance and explain why the generator will self excite for only one polarity of field.
6. Explain the change in the armature voltage vs. total field resistance graphs with changing speed.

E.1Data table for separately excited DC generator

Va	If (ma)	Va	If (ma)	Va	If (ma)	Va	If (ma)

E.2 Data table for self-excited DC generator

Va (V)	If (mA)

E.3 Data table for C(9)

Ra Rf

V	A	V	A

EXPERIMENT #5
THE LOAD CHARACTERISTICS OF SERIES, SHUNT AND COMPOUND D.C. GENERATORS

A. THE OBJECT OF THE EXPERIMENT

The object of the experiment is to obtain the variation of terminal voltage with load current for series and shunt connected D.C. generators driven at constant speed. Both series and shunt fields are then used simultaneously in a compound connection for the additive and subtractive cases and the new load characteristics obtained under these conditions are investigated.

B. THEORY

Direct current machines may be magnetised in two different ways:

1) They may be magnetised by supplying current to the field winding from a separate D.C. source, such as a battery or an auxiliary dynamo called *exciter.* This type of excitation is called *separate excitation* (Fig. 1).

2) They may generate their own magnetising currents. This type of excitation is called *self excitation.* Such machines may have their field windings connected in parallel with the armature circuit *(shunt connection,* Fig.2), in series with the main (armature) circuit *(series connection,* Fig.3) or both shunt and series field windings may be used *(compound connection,* Fig.4).

Generally, separate excitation is used in testing the D.C. machines for determining the open circuit (magnetisation) characteristics, as in Experiment #4.

Separate excitation has the advantage that the value of the exciting current entirely independent of the load current in the armature, and that it permits a machine to work satisfactorily over a range of voltages extending from zero to the maximum which the machine can generate. However, the practical voltage range during operation is limited.

For shunt machines, the number of turns in the field winding is large, the field winding resistance is higher, and the rated field current is lower than that of the other types. For series machines, the field winding has only a few turns and a low resistance. Since the series field winding is connected in series with the armature, the rated series field current is equal to the rated armature current value. The series windings of compound machines have even smaller number of turns.

For a D.C. generator, the terminal equation is:

$$Vt = E_a - I_a r_m \tag{1}$$

where r_m is the total resistance in the armature circuit. This is composed of the armature resistance, the *interpole winding* resistance (see one of the reference books), the series field winding resistance (if it exists) and the brush contact resistance. In addition to the positive voltage drop, the *armature reaction* further reduces the voltage that appears across the terminals .

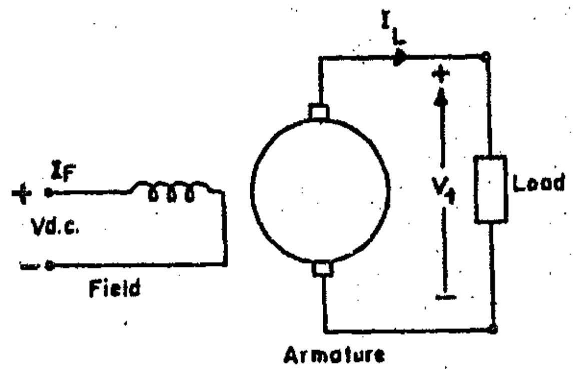


Figure 1. Wiring Diagram of a Separately Excited Generator

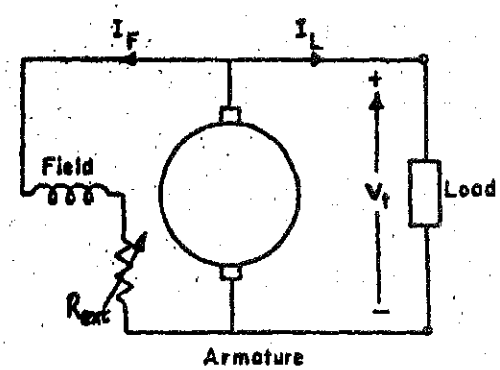


Figure 2. Wiring Diagram of a Self-Excited Shunt Generator

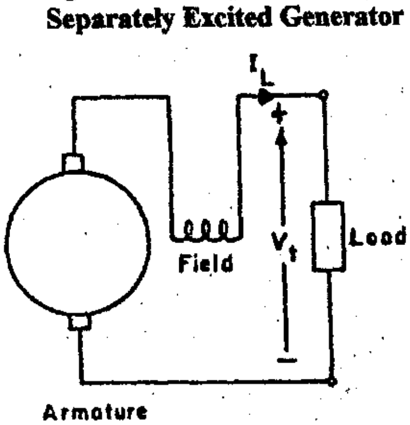


Figure 3. Wiring Diagram of a Self-Excited Series Generator

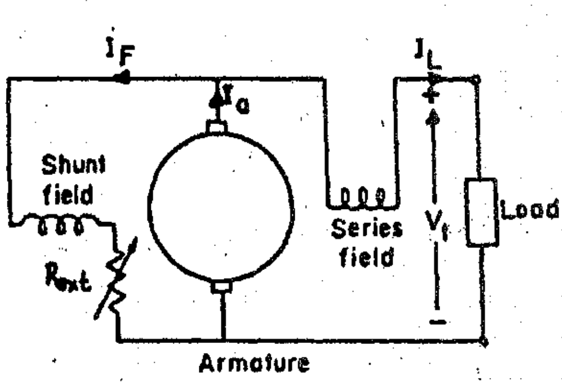


Figure 4. Wiring Diagram of a Self-Excited Additive Compound Generator (Short-Shunt Connection)

TERMINAL (LOAD) CHARACTERISTICS OF D.C. MACHINES

<u>Separately Excited Generator (Figure 5)</u>

The separately excited generator *terminal characteristics (terminal* voltage vs. load current) departs from the ideal flat shape due to the *resistance voltage drop,* caused by the load current and *armature reaction,* as shown in Figure .5.

<u>Self Excited Shunt Generator (Figure 6)</u>

The shunt generator has a more drooping characteristics than the separately excited generator. This is because as the machine is loaded, the terminal voltage decreases (as in the case of a separately excited generator) This, in turn, also decreases the field current which reduces the generated emf , causing a larger voltage drop in the terminal voltage than that would he observed in the case of a separately excited generator Fig.6).

<u>Self Excited Series Generator (Figure 7)</u>

The series generator characteristics are quite different from the two types of generators considered above. This is because the field flux increases with increasing load current; hence the terminal voltage increases as well. This goes on until a certain (critical) load current value is reached. Further increase of load current causes terminal voltage to fall rapidly due to armature *reaction* (Fig.7).

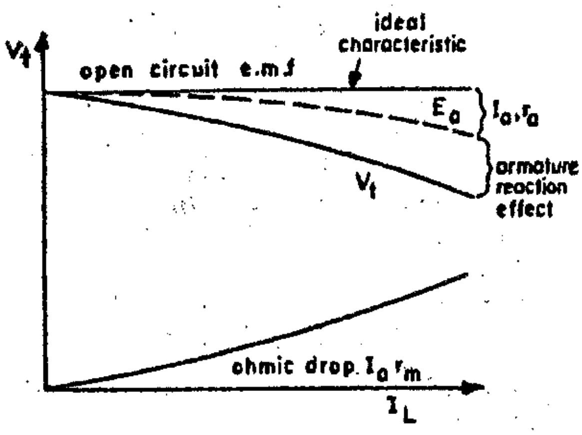


Figure 5. External Characteristics of a Separately Excited Generator

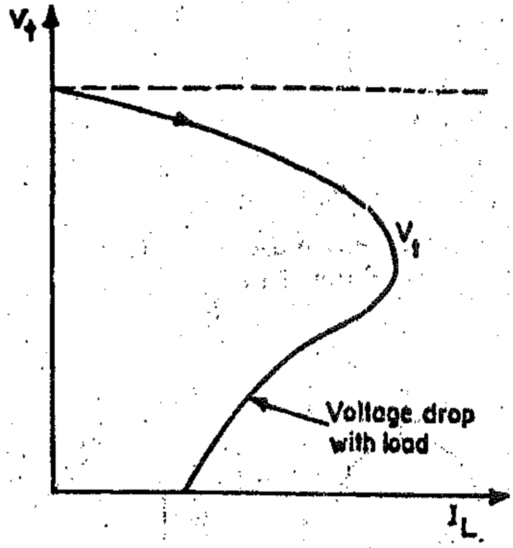


Figure 6. External Characteristics of a Self-Excited Shunt Generator

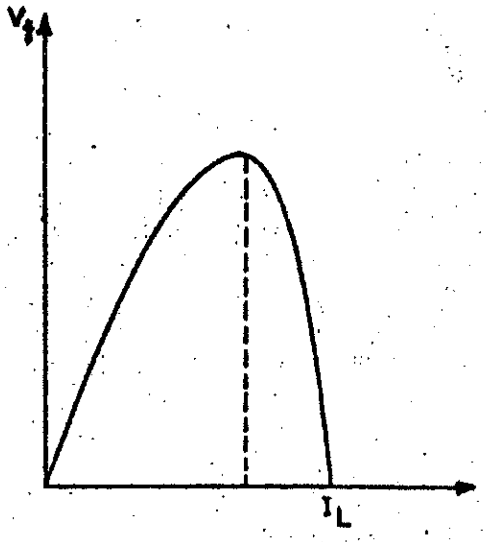


Figure 7. External Characteristics of a Self-Excited Series Generator

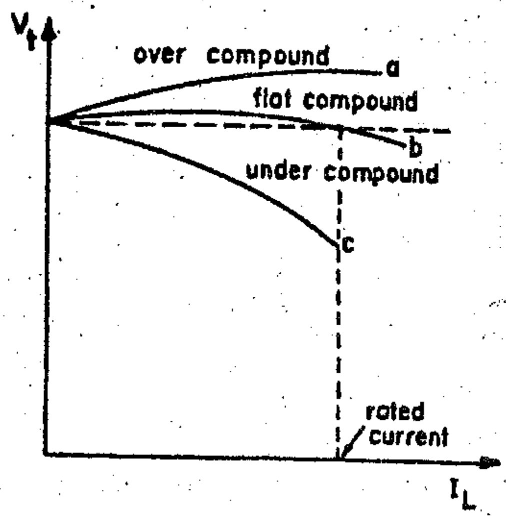


Figure 8. External Characteristics of a Self-Excited Additive Compound Generator

<u>Self Excited Compound Generator (Figure 8)</u>

A compound generator has both series and shunt field windings The *short-shunt* connection, where the shunt field is connected in **parallel to the armature,** is shown in Figure 4. If the shunt field winding is connected in **parallel to the** load, it is called the *long-shunt* connection. The polarity (direction) of the series field is also important. The series winding may be connected such that it may strengthen the shunt field *(additive compounding)* or that it may weaken the shunt field *(subtractive compounding).* In practice, subtractive compounding is used very exceptionally.

Additive compound generator characteristics may be obtained theoretically by adding the shunt generator characteristics with the series generator characteristics (Fig.8). Similarly, subtractive compound characteristics may be obtained by subtracting the series generator characteristics from the shunt generator characteristics.

Additive compound machine characteristics may further be classified according to the strength (i.e. the number of turns) of the series field winding. With sufficient number of turns, an increase in the terminal voltage may be achieved *(over-compounding,* Figure 8, case-a). On the other hand, if the series field is made just strong enough to compensate for the voltage drop due to the armature circuit resistance and armature reaction, a flat characteristics may be obtained *(flat-compounding,* Figure 8, case-b). However, if the series field is weaker, the terminal voltage falls with increasing load *(under compounding,* Figure 8, case-c).

C. PROCEDURE

IMPORTANT NOTE: At each step adjust the speed of the driving motor to the rated value.

The armature current of the driving motor should not exceed the rated value more than 10%.

1. Connect the machine as shown in Fig.9. in which the series winding (conclusion1-2) is supplied separately but with values of current up to 10% above the rated load current machine: be sure therefore to choose instruments and resistors to suit this condition. Start the driving motor and adjust the speed to the rated value; record the value of residual voltage. With the field resistor at its maximum value (i.e. minimum current) close switch S. Reduce the field resistance in steps until the field current exceeds the rated load current of the machine by 10% and record at each step the value of field current and armature voltage. The characteristic obtained from this test is the series compounding characteristic of machine.
2. Connect the machine as a separately-excited shunt generator as shown in Fig.10. using only the shunt field winding E1-E2, start the driving motor and adjust the speed to the rated value. With switch S open adjust the field current until the generator develops rated voltage and then hold the field current constant at this value throughout the rest of the test. With the load resistor at its maximum value close switch S and then reduce the load resistance in steps until the armature current exceeds the rated value by 10%, at each step record the value of armature voltage and armature current.
3. Obtain the open circuit characteristic of the d.c. generator (its shunt field winding is separately-excited) . Ea/i , in steps until the armature voltage exceeds the rated value 10%.

4. Connect the machine as a self-excited compound generator as shown in Fig.11. using both series and shunt fields, start the driving motor and adjust the speed to the rated value. With switch S open Adjust the field resistor until the armature develops its rated voltage and leave it in this position for the rest of the test. With the load resistance at its maximum value close switch S and then reduce the load resistance in steps until the armature current reaches the rated value; each step record the value of field current, armature current and armature voltage.
5. Measure the resistance of the armature circuit for several positions of the armature at a current of approximately half of the rated armature current, using a battery-ammeter-voltmeter set.
6. Measure the resistance of the series field winding at half of the rated armature current.

D. RESULT AND CONCLUSION

1. Subtract the residual voltage from the values of armature voltage obtained from part (1) of the procedure. The resulting values give the true series characteristic.
2. Calculate armature voltage drop for each load current neglecting the field current. Plot on the same graph the true series characteristic, and the armature voltage drop against load current.
3. Using the results of part (3) of the procedure draw magnetisation curve of the separately excited d.c. generator.
4. Using the results of part (4) of the procedure draw shunted field current versus load current, for additive compounding cases.
5. Using the curves drawn in parts (3) and (4) of the results and conclusion section draw generated e. m. f. due to shunt field versus load current for additive compounding case.
6. Using the appropriate values from the curves drawn in parts (2) and (5) of the results and conclusions section construct theoretical load characteristic (terminal voltage versus load current) for the additive compounding case.
7. Plot the theoretical load characteristic and actual measured characteristics for the shunt and compound generators on the same graph.
8. Which type of generator used in the experiment has the worst regulation? Explain.
9. Compare the theoretical and experimental load characteristics of compound DC generators and comment.

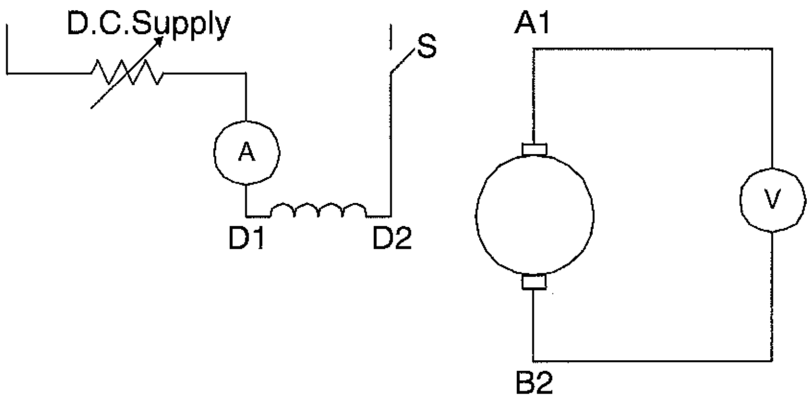


Fig.9 Seprerately excited dc genarotor
(Using the series field winding)

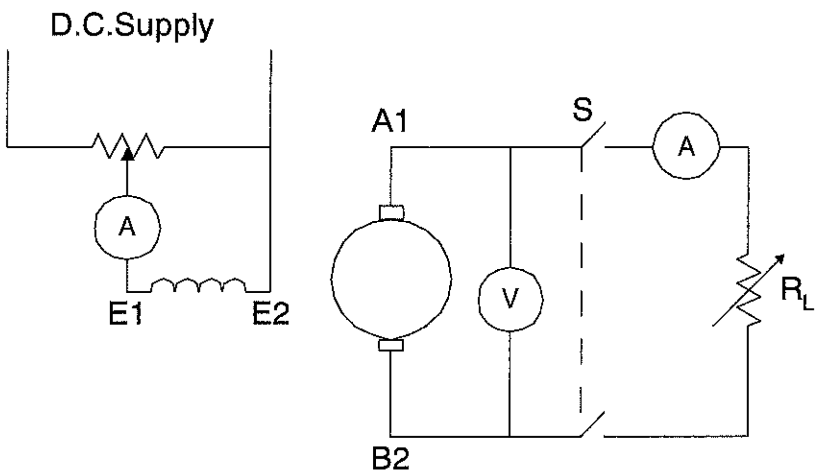


Fig.10 Seperately excited d.c.genarator(Using the shunt field winding)

EQUIPMENT:

1 Ammeter 0-1.2 A.

1 Ammeter 0-30 A.

1 Voltmeter 0-260 V.

1 Field rheostat 1320 ohm, 0-6A.

1 Ammeter 0-1.2 A.

1 Ammeter 0-30 A.

1 Voltmeter 0-260 V

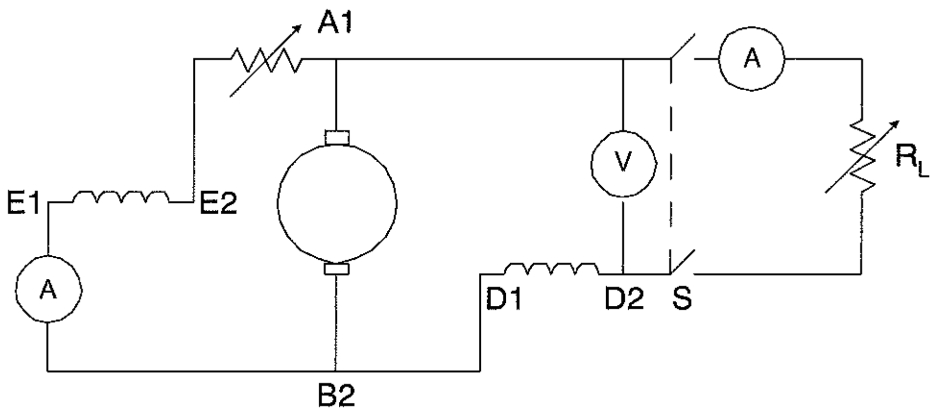


Fig.11 Self-excited compound generator

E.1 Data tables separately excited generator.

a) Using the shunt field winding (Part C.1)

I_f (A)	E_a (V)

b) Using the shunt field winding (Part C.2 and C.3)

No Load

I_f (A)	E_a (V)

With Load

I_f (A)	E_a (V)	I_l (A)

EXPERIMENT #6

THE D.C. SHUNT MOTOR STARTER

A. THE OBJECTS OF THE EXPERIMENT

1) To investigate the internal connections of a D.C. shunt motor starter using an Avometer, to draw the schematic diagram of the starter and to explain the action of the starter.

2) To calculate the values of the resistance's required in each step of the starter for a particular motor and to compare these values with those of an actual starter.

3) To observe the variation of the armature current when the motor is started on-load using the starter.

B. THEORY

The representation of a D.C. shunt motor during steady-state operation is shown below:

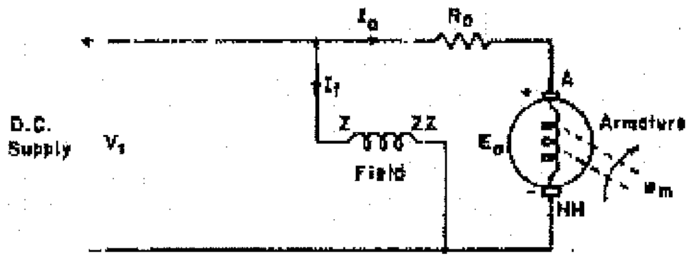


Figure 1. Electrical representation of a D.C. machine for motor operation

V_t: Terminal voltage
E_a: Generated back emf
I_a: Armature current
I_f: Field current
r_a: Armature resistance
ω_m: Angular speed (rad/s)
n: Speed in rpm (rev/min)

The steady-state equation of this motor is given by:

$$V_t = E_a + I_a r_a \tag{1}$$

giving

$$I_a = \frac{V_t - E_a}{r_a} \tag{2}$$

The back emf, Ea is directly proportional to the speed, ω_m for the shunt motor. Therefore,

$$E_a = C\omega_m \tag{3}$$

Thus, at starting, where n = 0, Ea = 0 as well (i.e. there is no generated back emf since the motor speed is zero). Therefore, the starting current is given by

$$I_{a,starting} = \frac{V_t}{r_a} \tag{4}$$

It can be seen that the starting current *is* only limited by the armature resistance, r_a.

For a 240V rated, 5 h.p. D.C. motor with an efficiency of 0.97, we can calculate the full load current at steady-state by,

$$I_{a,full-load} = \frac{inputpower}{ter\min alvoltage} = \frac{outputpower/efficiency}{ter\min alvoltage} \tag{5}$$

so the full-load armature current for this motor is

$$I_{a,full-load} = \frac{5\times 746}{240\times 0.97} = 16A \qquad (1h.p. = 746Watts) \tag{6}$$

If the armature resistance is about 1Ω for this particular motor (which is typically the case), then the starting current is,

$$I_{a,starting} = \frac{240V}{1\Omega} = 240A \tag{7}$$

It is seen that the starting current (240A) is 15 times higher than the rated current (16A). This high value of armature current would certainly damage the armature winding if it were not limited by an external resistance. A *starter* is used to provide current limitation to protect the machine against high starting currents. In practice, the machine must also be protected against over-load currents, and zero field voltage, both of which would cause damages to the machine.

Effectively, a starter is simply a set of resistances connected in series with the armature winding of the machine to limit the starting currents. Practically, there are two types of starters: Three-terminal types and four-terminal types. The Three-terminal type is shown in Figures 2.

A starter performs the following functions:

1) It allows the motor to be started from an ordinary supply of rated voltage without drawing an excessively large starting current. Note that such high currents flow when the back emf is zero or very small *(i.e.* motor stationary or rotating very slowly).

2) It protects the motor against heavy over-currents which may result from mechanicalover4oads during operation, by disconnecting the motor from the supply in such cases.

3) It disconnects the motor from the supply if the supply voltage is lost, alter which the

motor can safely be restarted using the starter.

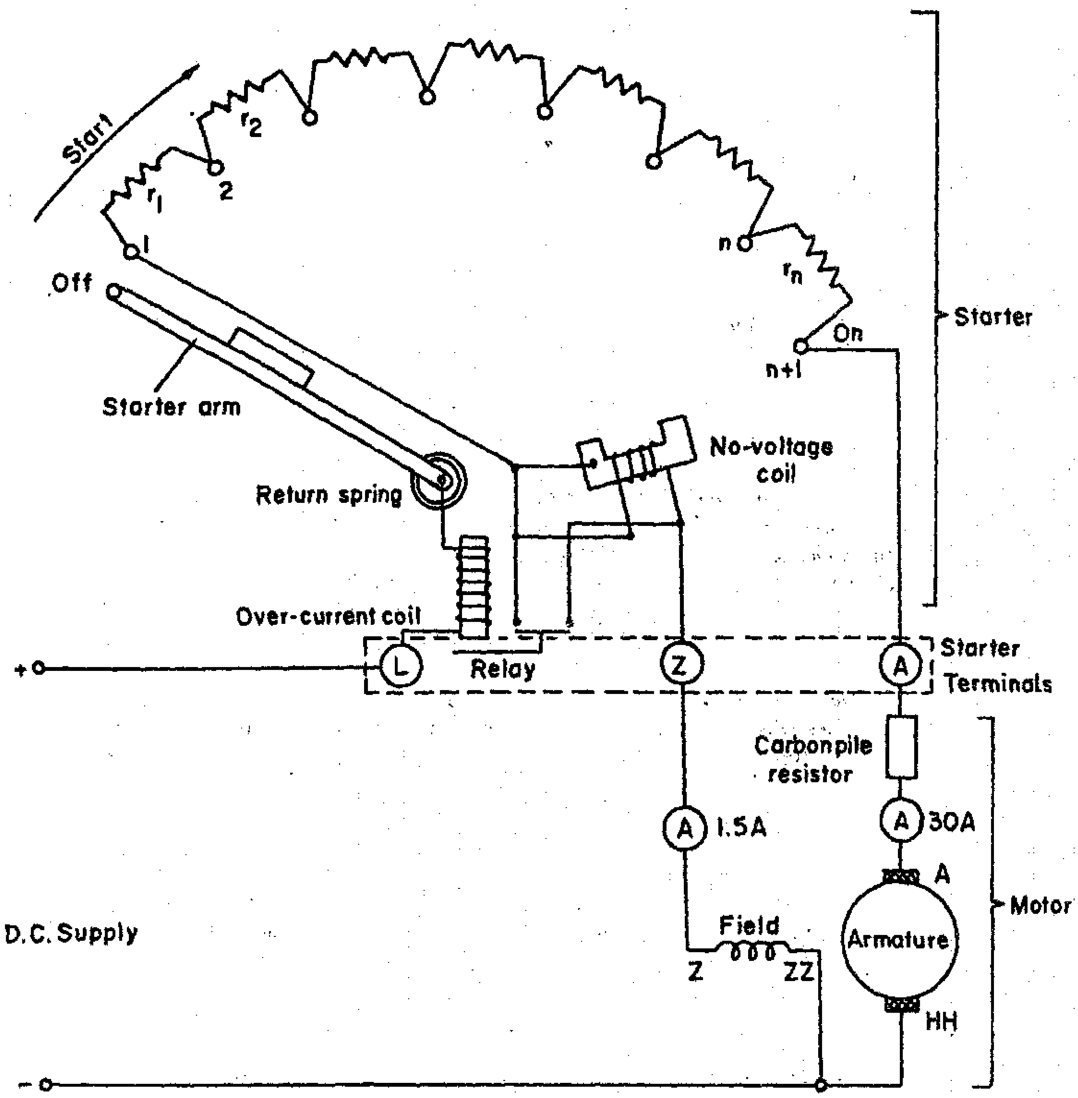


Figure 2. The Three Terminal Starter

4) (For the three-terminal type only) If the field circuit becomes open circuited, it disconnects the motor from the supply to protect the motor against over-speeding.

The conventional starter as shown in the simplified diagram of Figure 3, uses resistances in series with the armature circuit *which are gradually shorted out as the machine speeds up (i.e.* the generated back emf, E_a, increases and begins limiting the current) When the machine reaches its full speed (i.e. rated speed), these resistances are completely shorted out so they are ineffective.

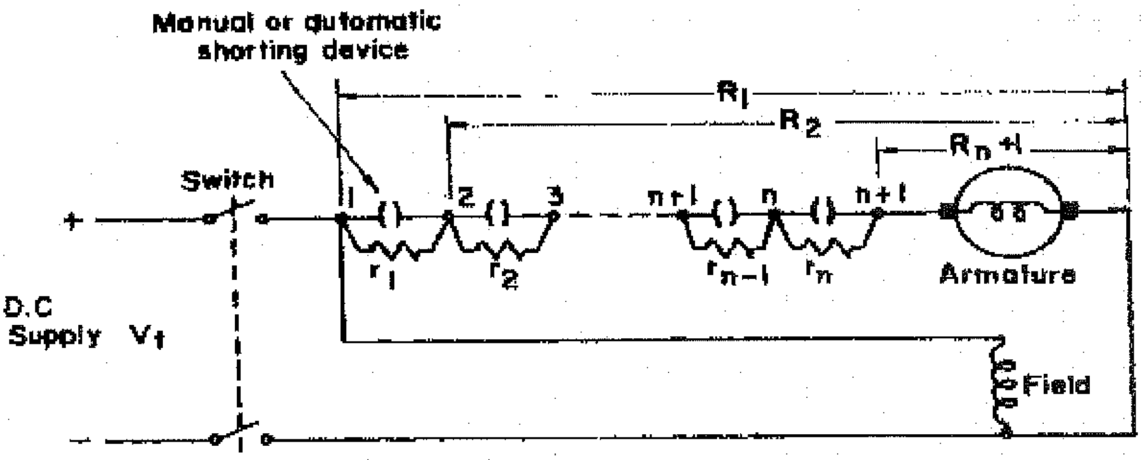


Figure 3. The Conventional D.C. Shunt Motor Starter

For the starter circuit, the *following* equations hold:

$$R_1 = (r_1 + r_2 + r_3 + \ldots + r_n) + r_a \tag{8}$$

$$R_2 = (r_2 + r_3 + \ldots + r_n) + r_a \tag{9}$$

.

.

$$R_n = r_n + r_a \tag{10}$$

$$R_{n+1} = r_a \tag{11}$$

When the starter arm is at the mth stud (i.e. armature resistance is R_m, and the generated back emf is $E_{a,m}$ .At this instant, the armature current, $I_{a,m}$,is given by

$$I_{a,m} = \frac{V_t - E_{a,m}}{R_m} \tag{12}$$

When notching up to the (m + 1)th stud occurs (i.e. the starter arm is manually moved to the next stud), the machine speed is momentarily unchanged so $E_{a,m}$ is still the same, *but* the new *circuit resistance is now* R_{m+1}, Hence, at this instant, the new current is $I_{a,m+1}$ and is given by

$$I_{a,m+1} = \frac{V_t - E_{a,m}}{R_{m+1}} \tag{13}$$

Combining the previous two equations, we get

$$\frac{I_{a,m+1}}{I_{a,m}} = \frac{R_m}{R_{m+1}} \tag{14}$$

Observe that in the above case, $I_{a,m+1}$ is the maximum value of current permitted by the starter to flow in the armature winding Also, for maximum motor acceleration $I_{a,m}$ is chosen to be equal to the rated current. Usually, the maximum current permitted to flow without damaging the winding is around 1.5 times the rated current. Therefore, a current vs. time diagram can be drawn for the motor start-up. Such a diagram is shown in Figure 5, for a constant ratio of Imaxr/Irated.

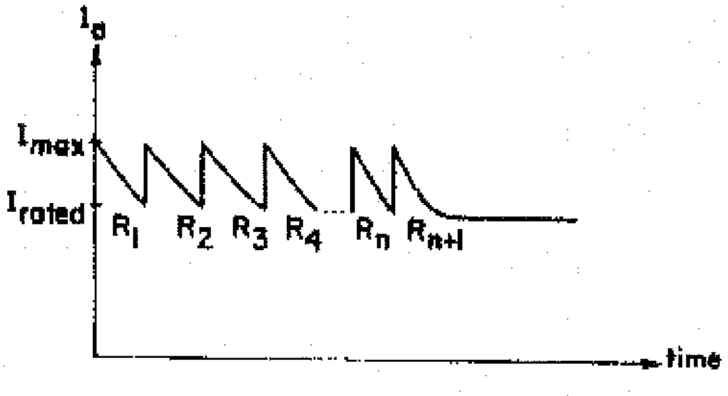


Figure 5. The current vs. time diagram for the start-up of a D.C. motor under full-load conditions

An arithmetical method for the calculation of starter resistances is as follows:

$$\frac{I_{max}}{I_{rated}} = \frac{I_{a,m+1}}{I_{a,m}} = \frac{R_1}{R_2} = \frac{R_2}{R_3} = \ldots = \frac{R_{n-1}}{R_n} = \frac{R_n}{r_a} \qquad (15)$$

The resistances , R_i , thus follow a geometric sequence, the common ratio being the ratio of currents

If

$$k = \frac{R_1}{R_2} \qquad (16)$$

then

$$k^n = \frac{R_1}{R_2}\frac{R_2}{R_3}\ldots\ldots\frac{R_{n-1}}{R_n}\frac{R_n}{r_a} = \frac{R_1}{r_a} \qquad (17)$$

or

$$k = \sqrt[n]{\frac{R_1}{r_a}} \qquad (18)$$

Usually, r_a (armature resistance) and k (ratio of maximum permissible current to rated current) are known. R_1 can be calculated from the starting conditions (Ea = 0) as follows:

$$R_1 = \frac{V_{rated}}{I_{\max}} = \frac{V_{rated}}{kI_{rated}} \tag{19}$$

Then n (the number of starter resistances) can be calculated using Eqn (18) after which each starter resistance is easily found. Note that if n turns out to be a fractional number, it must be rounded to an integer such that $R_{n+1} \leq r_a$.

If, on the other hand, a current time diagram for a certain starter-motor pair is available, the values of the resistances may be calculated graphically as follows:

$$\frac{R_n}{R_{n+1}} = \frac{I_{n+1}}{I_n} \tag{20}$$

where n denotes the n^{th} step and the values of I_n and I_{n+1} are determined from the diagram for each step. Note that in the above equation, R_{n+1} corresponds to the armature resistance, ra. Therefore, the resistance R_n can be calculated from

$$R_n = r_a \frac{I_{n+1}}{I_n} \tag{21}$$

Similarly, R_{n-1} can be calculated from R_n and so on. Hence, the correct determination of the starter resistances depends upon the correct measurement of r_a.

C. PROCEDURE

1. Identify all the component parts of the starter and, using an Avometer on the "ohm" range, determine how the component parts are connected together: hence deduce how the starter performs the functions described in section B above.
2. Connect the starter to the motor as shown in Fig.6.
3. With the maximum field current, start the motor and adjust the speed to the rated value using the field rheostat and keep constant for the rest of the test. Switch off the supply using starter.
4. Slowly turn-on the d.c. motor starter and observe a deflection on the armature ammeter very quickly observe and record the maximum and minimum values of armature current until starter arm is brought to point A of the armature. Also record the value of armature current at steady state for various positions of the starter arm.

   Switch off the supply using main switch without changing the position of the d.c. motor starter; allow the m / c to come to rest. Disconnect the connections of L, Z and A terminals. Measure and record the value of each step resistor 'r' of the starter (between Z and A terminals).

Reconnect the starter to the motor. Repeat the procedure mentioned in the first paragraph until the d.c. motor starter is fully turn on to the right.

5. Connect eddy current brake as shown in Fig.7. start the motor and apply 25% of the full-load to the d.c. motor (allow approximately 25% of the rated armature current to pass). Stop the d.c. motor using starter and wait for the motor to come to rest. Carefully restart d.c. motor step by step by using the starter. Record the value of armature ammeter at deflection and steady-state.
6. Measure the resistance of the armature of the motor using an ammeter-voltmeter set.

RESULT AND CONCLUSION

1- Write down the main function of a starter during DC motor start-up. Explain also the use of the starter resistances.

2- Using the nameplate data of the motor and a factor of 1.5 for the ratio of maximum current to no-load current, calculate the number of resistance steps required and the value of the resistance at each step. Use the arithmetic method for this calculation.

3- Calculate the values of starter resistances again, but now using I_a vs to graph recorded during procedure (Assume that you know the value of armature resistance).

4- Compare the calculated and measured values of the step number and the resistance of each step and discuss any differences between the two.

5- For the same motor as used in the experiment, assume that you want to decrease the current tolerance from 40% to 20%, what should you change in the starter? (i e. to decrease k from 1.4 to 1.2).

NOTE: Actually, this experiment will be done at full-load condition, later on.

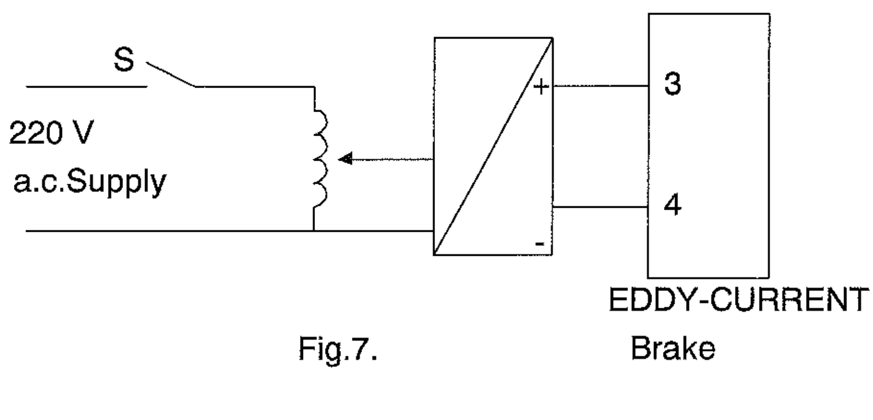


Fig.7.

EQUIPMENT:

Single phase variac
Single phase rectifier
Eddy-current brake

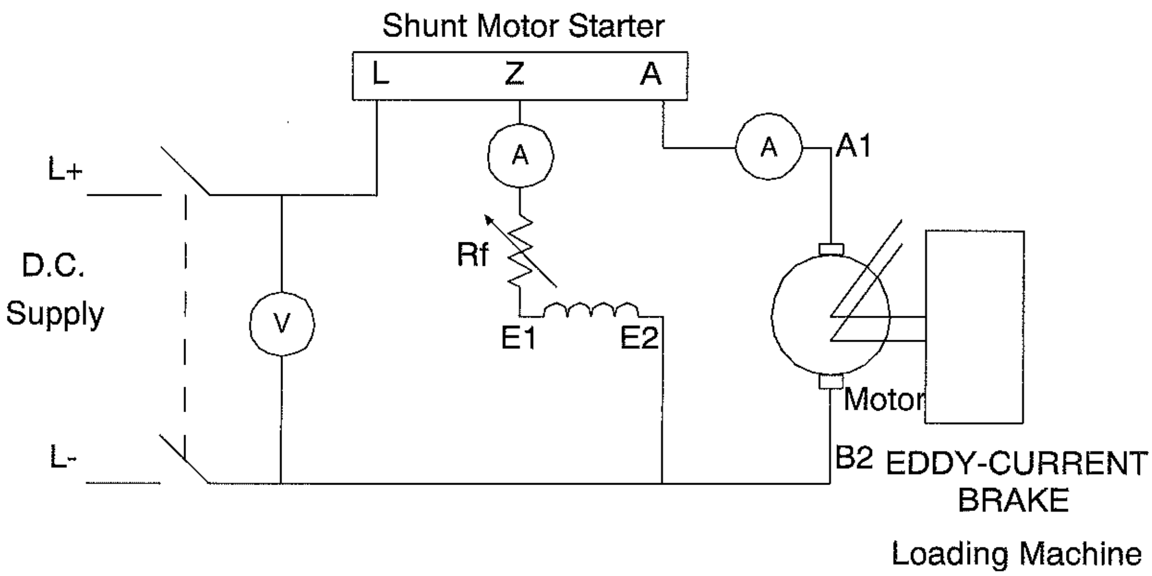


Fig.8.

EQUIPMENT:

D.C. motor starter
Field rheostat 1320 ohm. 0.6 A
Voltmeter 0-260 V
Ammeter 0-1.2 A (A1)
Ammeter 0-30 A (A2)

Data table for part C.4

Step	**r**

Ia_{max}	**Ia_{min}**

Data table for part C.5

Ia_{max}	**Ia_{min}**

Data table for part C.7
Resistance of Armature

V	**I**

EXPERIMENT #7

THE LOAD CHARACTERISTICS OF SERIES, SHUNT AND COMPOUND D.C. MOTORS

A. THE OBJECT OF THE EXPERIMENT

The object of the experiment is to obtain the load characteristics of a series, shunt and compound D.C. motor by loading it with a generator coupled directly to the same shaft.

B. THEORY

The most versatile type of the electric motors is the direct current motor. When D.C. motors are operated from a constant voltage source, a wide range of torque-speed characteristics can be obtained, depending on the motor type. The *series motor* is a variable speed motor, whose speed varies with load. Its ability to slow down while large load torques are applied, reduces its power demand from the line. On the other hand, the *shunt motor* is essentially a constant speed motor. The *compound motor* characteristics is composed of its shunt and series wining characteristics. One could call it an "adjustable speed motor". The exact characteristics depend on the strengths of the shunt and series windings fields at full load.

The D.C. motor equations can be summarised as follows: (The generator equations are basically the same except that the direction of the armature current reverses.)

The back emf : $Ea=K_g\,\Phi_f\,\omega$ (1)

Torque : $T=K_g\,\Phi_f\,Ia$ (2)

Terminal voltage: $V_t = E_a + r_a\,I_a$ (3)

where;

V_t : Terminal (supply) voltage (Volts)

Φ_f : Field flux per pole (Webers)

K_g : Winding constant $(=\dfrac{p.Z_a}{2.a})$

ω : Angular velocity (radians/sec)

p : Number of poles

Z_a : Number of conductors in the armature a : Number of parallel paths in the armature

I_a : Armature current (Amperes)

r_a : Armature resistance (Ohms)

SERIES MOTOR CHARACTERISTICS

The field winding is connected in series with the armature. Then,

$$I_a = I_f \tag{4}$$

If we assume that

$$\Phi_f = K_f I_f \tag{5}$$

substituting (5) and (4) into (2); we obtain

$$T = K.I_a^2 \tag{6}$$

where

$$K = K_g K_f \tag{7}$$

is a constant. From (2);

$$K_g \Phi_f = \frac{T}{I_a} = K I_a \tag{8}$$

If we solve (1) and (3) for ω

$$\omega = \frac{V_t - I_a r_a}{K_g \Phi_f} \tag{9}$$

Then;

$$\omega = \frac{V_t - I_a r_a}{K\ I_a} \tag{10}$$

This is the relation between the armature current and speed. If r_a is neglected;

$$\omega = \frac{V_t}{K\ I_a} \tag{11}$$

If we solve (1) and (3) for I_a;

$$I_a = \frac{V_t}{r_a + K\omega} \tag{12}$$

Substituting (12) for (6);

$$T = \frac{K V_t^2}{(r_a + K\omega)^2} \tag{13}$$

This equation describes the torque-speed characteristics of a series motor.

For the series motor, the torque vs. armature current characteristics and the torque vs. speed characteristics are a parabola (Fig. 1) and a hyperbola (Fig.2), respectively. Also, it is seen that decreasing the torque or the armature current increases the speed.

IMPORTANT NOTE

A series motor should never he allowed to run under no-load conditions. If the torque tends to zero, then the armature current goes to zero so the speed tends to **infinity!**

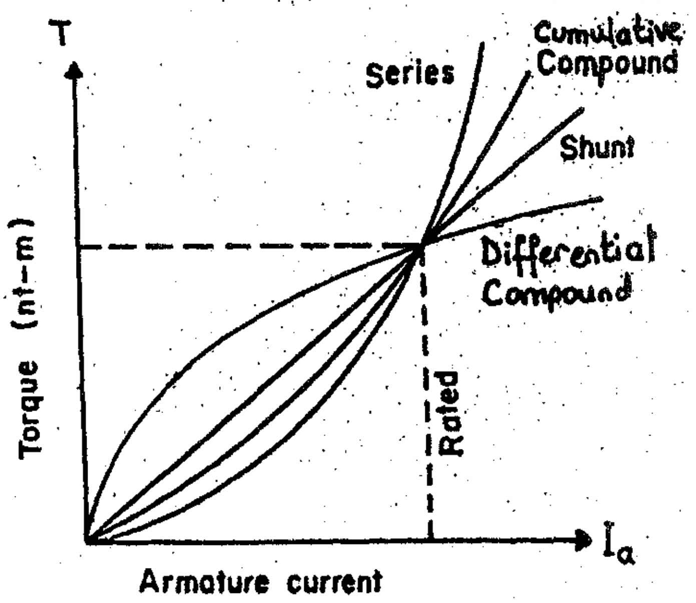


Figure 1. Torque vs. Current Characteristics of D.C. Motors

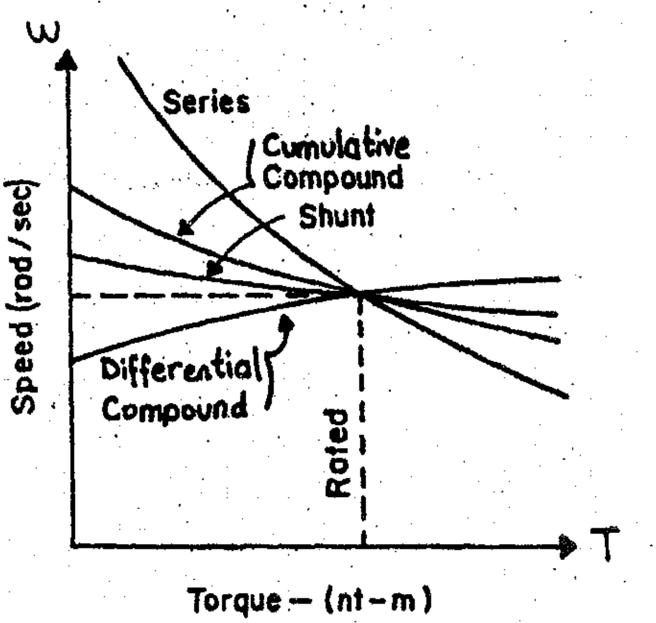


Figure 2. Speed vs. Torque Characteristics of D.C. Motors

SHUNT MOTOR CHARACTERISTICS

In the shunt motor, the field winding is connected directly across the supply voltage and the field current is therefore approximately constant. The equations for speed and torque are as follows;

$$K_g \Phi_f = \frac{1}{K'} \quad \text{(Where K' is a constant)} \tag{14}$$

From equations (2) and (14);

$$T = \frac{I_a}{K'} \tag{15}$$

From equations (1), (3) and (14),

$$\omega = (V_t - I_a r_a)K' \tag{16}$$

$$\omega = \omega_0 - K' I_a r_a \quad \text{where} \quad \omega_0 = V_t K' \tag{17}$$

From equations (15) and (17),

$$\omega = \omega_0 - K'K' r_a T \tag{18}$$

$$\omega = \omega_0 - K''T \quad \text{where } K'' = K'K' r_a \tag{19}$$

For the shunt motor, therefore, torque is directly proportional to the armature current and speed is virtually independent of the armature current (if $I_a r_a$ is neglected) In practice, however, the speed fills slightly as the armature current increases It may be deduced from equation (19) that, for a shunt motor, the speed falls slightly as the torque increases. Such a *drooping* characteristic is ideally suited for constant speed applications and the machine is widely used for nearly constant speed applications.

COMPOUND MOTOR CHARACTERISTICS

Consideration of equation (9) shows that if, as the armature current increases, the field flux is also forced to increase, then the motor will have a drooping characteristics of speed against the current. if on the other hand, as the armature current increases, the field current is decreased, then the motor may have a ri*sing* characteristics. These form the basic principles for understanding compound generator operation.

The field flux may be changed with armature current by winding an additional field winding on the poles, connected in series with the armature. The series winding may be connected such that, the flux produced by it either aids or opposes the main field flux of the shunt winding. if the series field is connected such that the flux produced by it aids the shunt winding, then assuming a linear magnetic characteristics;

$$T = K_g\left(\Phi_{f,shunt} + \Phi_{f,series}\right)I_a \tag{20}$$

Combining equations(4),(7)and(20)

$$T = K_g\Phi_{f,shunt}I_a + KI_a^2 \tag{21}$$

Motors with such an arrangement are called *cumulatively compounded motors* and have a *drooping* characteristic (Fig.2).

Similarly, if the series field is connected in the opposite direction (i.e. its flux opposes the shunt field's flux), then;

$$T = K_g\left(\Phi_{f,shunt} - \Phi_{f,series}\right)I_a \tag{22}$$

$$T = K_g\Phi_{f,shunt}I_a - KI_a^2 \tag{23}$$

Those with such an arrangement are called *differentially compounded motors* and have either a *constant* or *rising* characteristic (Fig.2). The result is therefore a combination of shunt and series motor characteristics.

IMPORTANT NOTE

In differentially-compounded motor during starting, the field *weakening effect* of the series winding may be sufficiently great to cause instability or run-away. This winding should therefore be shorted out while the motor is started.

A Brief Comparison

A comparison of the several types of D.C. motors can best be made when their characteristics are presented on the same graph (Fig. 1 and Fig. 2). All sets of curves are **for motors having** identical rating. In general, the series motor produces a greater torque per ampere at high current values while the shunt motor yields more torque per ampere at small values of armature current The cumulative compound motor characteristics lies between the shunt and series motor characteristics. At starting, all motors carry currents greater than rated; hence they can develop sufficient excess torque for acceleration If larger starting torques are necessary and the load will tolerate large speed regulations, then the series or heavily compounded motors are best. If the load requires a small regulation, the shunt motor is more suitable.

Efficiency Calculations

Let the efficiencies of the motor and generator shown in Figure 3 be η_m and η_g respectively. Then

$$P_{m\,out} = P_{min}.\eta_m \qquad (24)$$

$$P_{g\,out} = P_{g\,in}\,\eta_g \qquad (25)$$

Since the machines are directly coupled together

$$P_{g\,in} = P_{m\,out} \qquad (26)$$

Therefore,

$$P_{g\,out} = P_{m\,in}\,\eta_m\eta_g \qquad (27)$$

giving

$$\eta_m\eta_g = \frac{P_{gout}}{P_{min}} \qquad (28)$$

Since the machines are similar and working approximately under the same conditions of saturation, it may be assumed that;

$$\eta_m = \eta_g = \sqrt{\frac{P_{gout}}{P_{min}}} \qquad (29)$$

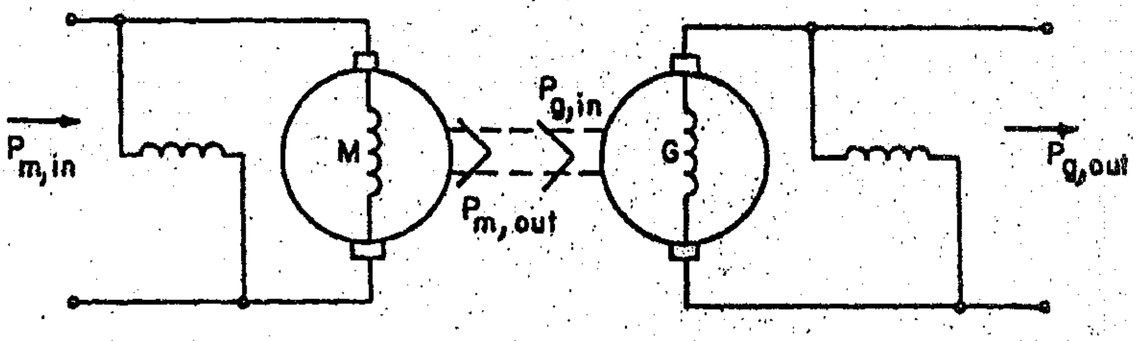


Figure 3. Power Flow In A Motor-Generator Set

Calculation of Shaft Torque

The shaft torque, T_s at the speed of ω (rad/sec) is given by

$$T_s = \frac{P_{mout}}{\omega} \quad \text{where} \quad \omega = \frac{2.\pi.n}{60} \quad \text{(n:Speed in rpm)} \qquad (30)$$

Measurement of Shaft Torque

For dynamometer motors with spring balances, the round handle above the balance(s) should be turned until there is a steady reading on the balance. At .this position, the stator of the motor must be free to move on its brings and not be bottomed on the side. Check this by moving the stator frame slightly. The balance should be set to read zero when the motor is stationary.

For machines with two balances, one on either side, the handles should be turned so that one is set at zero with the motor stationary to give positive torque readings when the motor is loaded. If a zero reading on the balances is not possible, note the actual reading when the motor is not running, and then note the difference between this reading and the actual reading under load conditions. For the true value of the torque .Two balances are sometimes used so that the force (hence the torque) reading can be obtained for either speed direction. To be small amount of rotation of the stator frame before it bottoms on the bed plate must be observed carefully. The handles should be adjusted accordingly so that the frame is always free to rotate at the particular load condition. This permits greater accuracy of the torque readings. Any such change the balance readings. It is better practice to leave one of the balances off; and to make all the adjustments on one side. The torque arm should always be horizontal to the floor and the balance in the vertical position.

When taking torque readings note the length of the torque arm from the center axis of the shaft in meters.

Some Useful Conversion Factors:

1kg	= 9.81 N (Newton)
1 lb (pound)	= 4.448 N (Newton)
1foot	= O.3048 m.
1 lb-foot	= 1.3565 N-rn. (Newton-meter)
1N-rn	= 1 joule
1watt	= 1 N-m/sec
1 h.p.	= 746 watts

The output of the power in terms of shaft torque is defined as;

$$P_{m\ out} = T_m\ \omega \tag{32}$$

If the test machine has no dynamometer system but is equjpped with a loading machine that has, torque readings from the load machine give approximately the shaft torque of the test machine less a small torque due to windage that does not react with the load machine stator frame and the friction of the load machine bearings. For a machine with its own dynamometer system, the torque readings will give the shaft torque plus a small torque due to the windage that does not react with the machine stator frame and the bearing friction. Usually the bearing friction is small and the non-reacting windage is negligible except for special machines where heavy cooling is required. So the balance will give approximately the shaft torque for either machine.

C. PROCEDURE

a. Series Motor:

1. Connect the circuit as shown in Fig.4. adjust the load so that it is maximum and start the motor.
2. Gradually reduce the load in steps until the motor speed exceeds the rated value by 50% recording at each step the values of the applied voltage and total input current to the motor, the armature speed, and the torque.

b. Shunt Motor:

1. Connect the circuit as shown in Fig.5. adjust the field resistance to maximum field current start the motor. Readjust the field resistance until the motor runs at rated speed and then keep the field current constant at this value for the react of the test.
2. Load the motor by eddy-current brake until the motor current exceeds the rated value by 10% . At each step record the values of the applied voltage and the total input current to the motor armature speed and the torque.

c. Compound Motor

1. Connect the circuit as shown in Fig.6. and proceed as in Procedure.b1 above with the series winding (Conclusion1-2) short-circuited during starting.
2. Proceed as in Procedure.b2 above.
3. Reverse the polarity of the series winding and repeat the procedure Procedure.c1 and Procedure.c2.

D. RESULT AND CONCLUSION

1. Calculate the efficiency ant the theoretical torque developed by the machine for series, shunt and compound motor.
2. Plots the output power versus ;
   a. The efficiency of the motor for each type of motor on the same graph.
   b. Shaft torque (theoretical) of the motor for each type on the same graph.
   c. Shaft torque (experimental) of the motor for each type on the same graph.
   d. Armature current of the motor for each type on the same graph.
   e. Angular speed of the motor of the rotor for each type on the same graph.
3. Plot shaft torque (experimental) versus angular speed of the rotor for each type on the same graph.

4. If you need to drive a light load at high speeds (e.g. at 3000-4000 rpm) which type of dc motor do you select? Explain briefly. Do the experimental results support your answer? If your answer is no, explain the reason.

5. Which type of motor's speed is less sensitive to load changes? Explain briefly. Do the experimental results support your answer? If your answer is no, explain the reason.

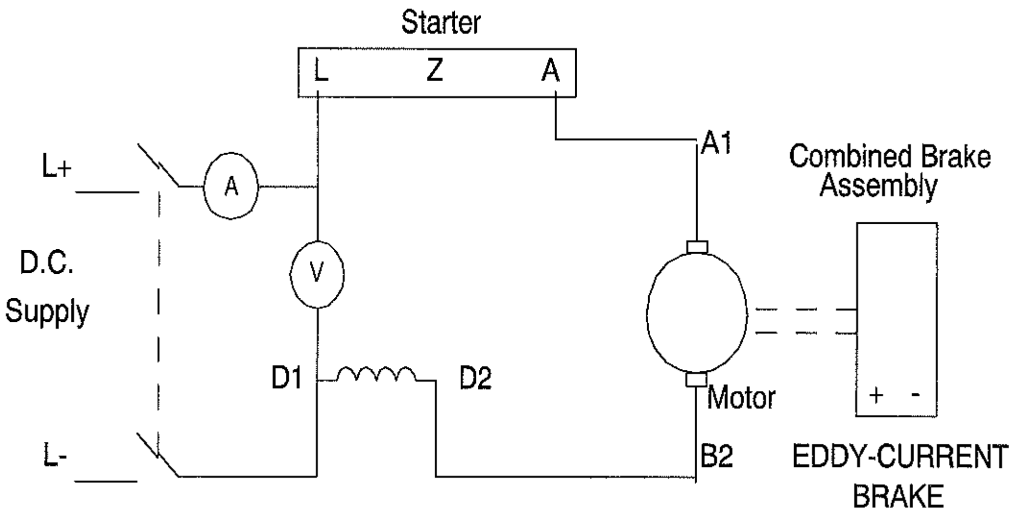


Fig.4 Series Motor Connecting Diagram

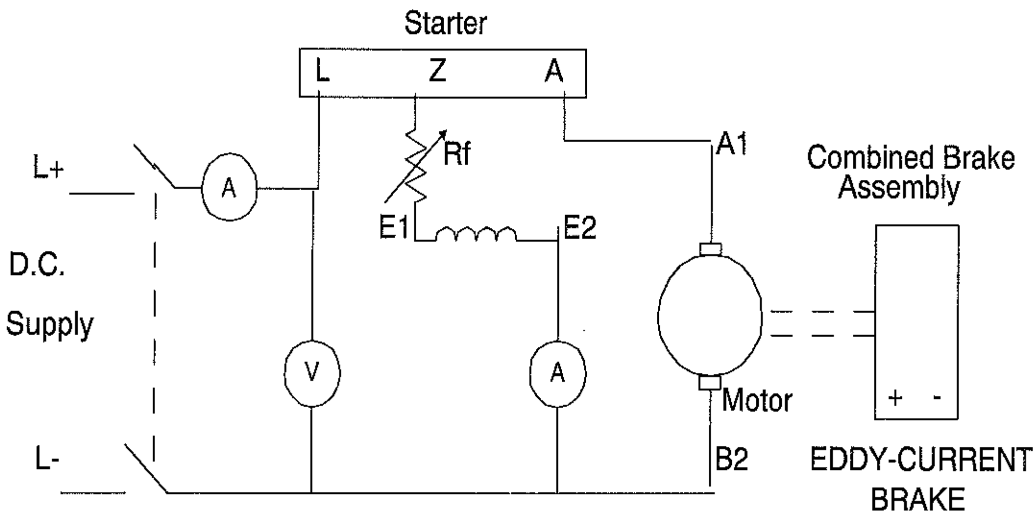


Fig.5 Shunt Motor Connecting Diagram

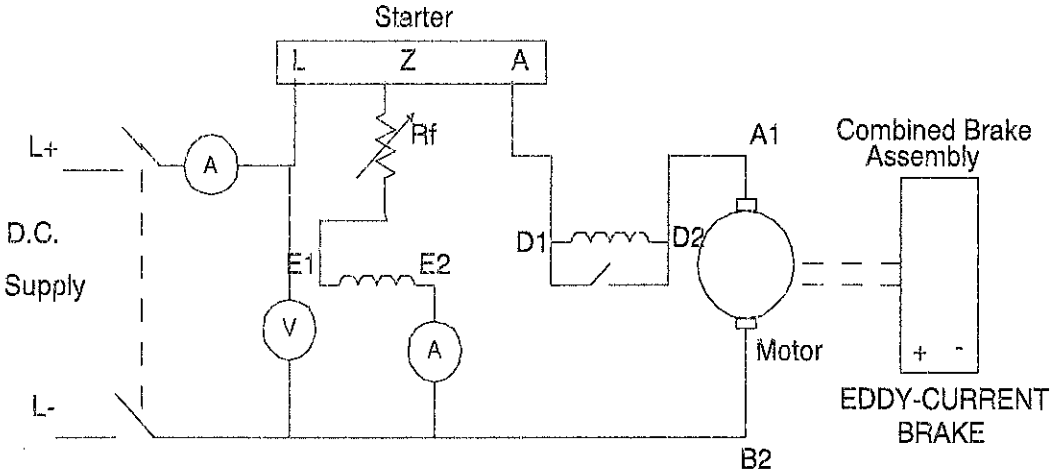


Fig.6 Compound Motor Connecting Diagram

EQUIPMENT:

1 Ammeter, 0-30 A.

1 Voltmeter, 0-260 V.

E.2 Data table for series motor operation

Input Current	Applied Voltage	Torque (N_M)	Speed (rpm)	P_{out} (kv)

E.2 Data table for shunt motor operation.

Input Current	Field Current	Applied Voltage	Torque (N_M)	P_{out} (kv)

E.3 Data table for compound (additive) motor operation.

Input Current	Field Current	Applied Voltage	Torque (N_M)	P_{out} (kv)

EXPERIMENT #8

SPEED CONTROL OF D.C. SHUNT MOTORS

A. THE OBJECT OF THE EXPERIMENT

The object of the experiment is to investigate three different speed control techniques for a shunt DC motor, namely the field control, armature resistance control and terminal voltage control techniques. Moreover, experience will be gained in the usage of a three-phase half-wave rectifier.

B. THEORY

The shunt connected DC motor is essentially a constant speed motor because of its almost flat load characteristics. Consider the following three equations for a DC motor:

The back emf equation:	$E_a = K_g \, \Phi_f \, \omega$	(1)
The torque equation:	$T = K_g \, \Phi_f \, I_a$	(2)
Terminal voltage equation:	$V_t = E_a + r_a \, I_a$	(3)

As the field is connected in parallel to the supply, the field current is independent of the armature current. Hence, we have a constant field flux. Assuming linear behaviour (i.e., ignoring saturation, armature reaction effects etc.), as the load torque increases, the armature current will increase by the same ratio (eqn.2). Considering eqn.3, this increase in armature current will increase the voltage drop on armature resistance. Hence, for constant terminal voltage, the back emf will decrease slightly, causing a slight drop in the speed (eqn. 1). This voltage drop is usually a small fraction of the rated terminal voltage, so the reduction in speed is very slight. Consider a typical DC motor used in the lab: For an armature resistance of 0.6W, a rated armature current of 22A and a rated terminal voltage of 220V, the voltage drop at rated current is 0.6Ωx22A=13.2V, which is only 6 % of the rated voltage. Hence, if the no-load speed of the motor is 1500rpm, the full-load speed will be (1 - 0.06) x 1500 = 1410 rpm.

The ability to preserve its no-load speed under loaded conditions is an important advantage of shunt motors, because it allows the user to adjust the speed almost independently of the load.

On the other hand, in order to adjust the speed to desired values, three different speed control methods exist. The following section discusses these techniques in detail.

1. Field Current Control

This is the simplest speed control method for shunt motors. The field current is controlled by connecting a rheostat to the field circuit. For a linear magnetic characteristics, the field flux will be directly proportional to the field current, or

$$\Phi_f = K_f I_f \tag{4}$$

Therefore, this technique can also be named as "field flux control". The effect of varying the field flux can be seen easily by considering equations (1), (2) and (3). Under constant armature current, the voltage drop on the armature resistance is constant. Since the terminal voltage is also constant, the back emf will be constant as well. From eqn.(1), for constant back emf, the speed and field flux will be inversely proportional. Hence; an increase in field current will result in a decrease in speed, or vice versa.

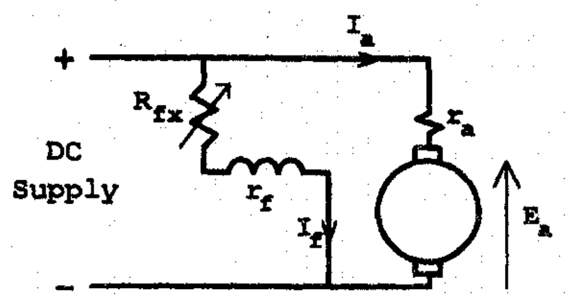


Figure 1. Speed control by varying the field current

Note that as the maximum armature current is limited by the rated value, the output torque will be directly proportional to the field flux (eqn.2), hence field current (eqn.4). This means that the output power, given by

$$P_{out} = T \cdot \omega = K_g \Phi_f I_a \cdot \sqrt{Pm,in.Pg,out} \tag{5}$$

will remain constant. Hence, this method is also referred to as a *constant-power drive.* When the speed of the motor is decreased (by adjusting the field current), the torque output will increase by the same ratio, keeping the output power constant for the same armature current.

The advantage of this method is, the speed control is accomplished in the field circuit, which is a low power circuit (the field current rating is only a small percentage of the armature current rating). Therefore, a rheostat with low current rating is sufficient for speed control. This also means that all resistive losses due to the field rheostat will be small, compared to the overall power rating of the motor; hence a high efficiency will be maintained.

The main disadvantage of this method is its limited speed range. For example, in order to decrease the speed by half, the field current must be doubled. The upper bound of field current will be limited by the rating of the field winding. Moreover, due to saturation, doubling the field current will not double the field flux; the actual value of the flux will be less than the expected value. Practically, the lowest speed that can be obtained by this method will be about 1000 rpm for the machines used in the lab. Moreover, the upper bound for speed (obtained at low field currents) will be limited by the effects of armature reaction, due to field-weakening. Stabilizing windings and compensating windings may be used to improve the speed ranges of these motors. However, for an average sized motor, the practical speed range will be usually limited to a maximum/minimum speed ratio of 4:1.

2. Armature Resistance Control

By connecting an external resistance in series with the armature circuit, the voltage appearing across the armature terminals (i.e., terminal voltage) can be varied. Note that the field is connected directly across the supply terminals so that the field current (hence field flux) is constant. Under constant load torque, the armature current will be constant. Therefore, when the external armature resistance is increased, the voltage drop on it will increase, decreasing the back emf. Consequently, this will cause a decrease in the motor speed, due to the back emf equation. The relation for the back emf in this case is:

$$E_a = V_t - (R_x + r_a).I_a \qquad (6)$$

Where R_x is the external resistance used for controlling the speed.

Note that as the field flux is constant, the output torque will be constant when the armature current is constant at its rated value (eqn.2). Therefore, this method allows constant torque operation while the speed is varied. It is essentially a *constant-torque drive.* As the speed increases, the output power will increase by the same amount.

The main advantage of this method is the increased speed range. If the external resistance is large enough, the speed can be reduced down to zero rpm. Another advantage is, the external resistance can also be used as a starter during starting, to avoid high currents.

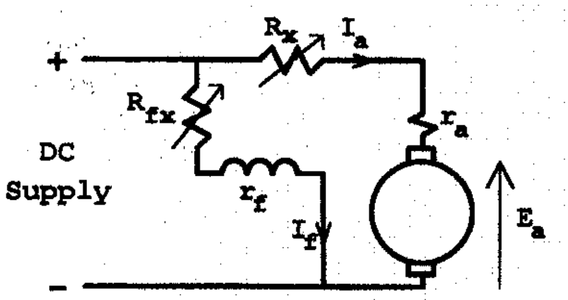


Figure 2. Speed control by varying the armature resistance

However, this speed control method has some serious disadvantages: First of all, the speed regulation under load is very poor. Consider the same motor with the voltage and current ratings given previously. Under full load current (22A) and a terminal voltage of 220V, in order to reduce the speed to zero, the back emf should be zero. From eqn.(6), the external resistance should be set to 9.4Ω (also taking into account the internal armature resistance). However, for the same resistance setting, the motor will run at much higher speeds for light-load conditions: If the armature current decreases to 2A, the back emf turns out to be 200V. Hence, the speed will be quite close to the no-load speed of 1500 rpm. As a result, in this speed control method, the speed is not independent of the load torque any more, which is undesirable.

Another disadvantage is the high power rating needed for the external resistor: This resistor will carry large currents (equal to armature current) and dissipate large amounts of power as heat. For the same example as above, when the resistance is adjusted to 9.4Ω, the power dissipated on it will be $9.4.(22)^2 = 4550W$, which is almost as large as the motor rating (4.84kW) itself. Hence, a very large resistor is required for speed control. As a side effect, the efficiency of this speed control method is also very poor. The efficiency will decrease as the speed is reduced (by increasing the external resistance).

Due to the above disadvantages, this type of speed control is essentially suitable for low power motors only.

3. Terminal Voltage Control

The best speed control method possible for shunt motors is the terminal voltage control technique. Here, the field is excited separately, from an independent DC supply and the field current is maintained constant.

To supply the armature, a variable DC supply is used. Assuming that we have an ideal DC voltage source whose output can be adjusted from zero to rated terminal voltage (i.e., 0-220V), the

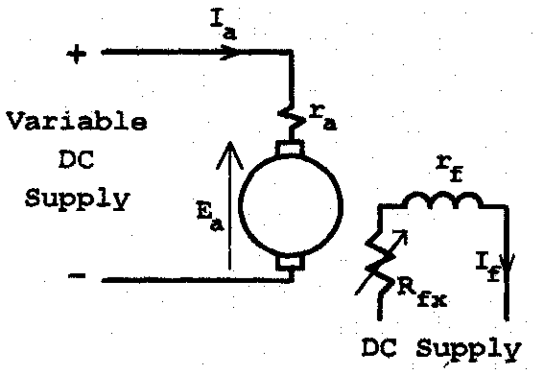


Figure 3. Speed control by varying the armature voltage

motor speed can be varied from zero to rated value (i.e., 0-1500 rpm). If the load torque is constant, the armature current is also constant (eqn.2). Therefore, the voltage drop on the armature resistance is constant. Hence, a change in the terminal voltage will change the back emf by the same amount. As a result, the speed will change in proportion to the terminal voltage. Usually, the voltage drop on armature resistance is small (60 % at full-load in our previous example) and can be ignored.

Since the field flux is maintained constant in this method, the torque will be constant at rated armature current so this is also a *constant-torque drive.* The output power will increase in proportion with the increase in speed.

This method eliminates the advantages of the previous two speed control methods: The motor speed can be varied from zero to rated speed with a high efficiency under all conditions.

One point worth noting here is, the speed regulation under loaded conditions will get worse as the speed is decreased. Considering the same motor investigated in the previous examples, it was seen that the speed of the motor decreased by 6% (from 1500 rpm to 1410 rpm) from no-load to ful-l-load conditions when operating at a rated voltage of 220V. Now assume that the terminal voltage has been reduced to 50V so that the motor is operating at 340 rpm at no-load conditions. When the load is increased so that the armature current increases up to its rated value of 22A, the voltage drop on the armature resistance will be again 13.2V, so the back emf will drop to 36.8V. As a result, the speed will drop to 250rpm, or by 26.4% compared to no-load speed. Hence, the speed regulation will get poorer as voltage is decreased.

The main disadvantage of this speed control method is the requirement of DC supplies: One for the armature, the other for the field. Moreover, the armature supply should be a *variable DC supply* with the same power rating as the motor itself (e.g, 4.5kW), which is not always available.

Note that a variac (or transformer) cannot be used to vary DC voltages because transformers can only operate with AC. Moreover, a resistive voltage divider will not work either because of its inefficiency: Most of the power will be lost on the resistors, so only a small fraction will be available at the output. Practically, to drive a 4.5kW motor, one may need to use 50kW resistors to transfer the required 4.5kW to the motor!

One method for obtaining a variable DC supply is to use two additional machines: One motor (usually an AC motor) running at constant speed and driving a DC generator. The DC voltage produced by the generator can be varied by varying the generator field current. This setup is called a *Ward-Leonard system.* Obviously, the main disadvantage of this method is using two additional machines to control the speed of a third machine, our DC motor.

The second method is to use some type of controlled rectifier that uses power semiconductors (i.e., diodes, thyristors, transistors etc.) to convert an AC source into variable DC. Various AC to DC converters with different circuit topologies are available. A simple converter that uses a variac and three power diodes, called a *three-phase halfwave rectifier* will be used in the Procedure section to obtain variable DC. The operation of this rectifier is outlined in the next section.

C.PROCEDURE

1. Variation of Resistance in Series with the Armature

1.1 While the R_S being shorted, adjust the field resistance until the motor runs at rated speed on no load.

1.2 Switch off the supply. Disconnect the cable which shorts the R, manually and set the resistance R_S (in series with the armature) to its maximum value. Disconnect the field circuit connection at point Z on the starter box. Switch on the supply and brind the starting handle of the starter full over to the normal run position and hold it that position while the field circuit is disconnected.

(NOTE: There will be a small torque due to the interaction of the armature m.m.f. and the residual flux, with the rotor held in the locked position (i.e. at zero speed.)).

Adjust the series resistance, R_S until the armature current reaches 65% of the rated value. Switch off the supply. Reconnect the field circuit to terminal Z on the starter box. Switch on the supply.

1.3 Carry out a load test as described in part 1.10 of the procedure. At each step also record the voltage across the resistance.

1.4 Adjust the series resistance, R_S until the armature current reaches 40% of the rated value as described in part 1.12 of the procedure. Repeat procedure.(1.13)

2. Voltage Control Using a Static Converter

Important note: In this test do not use d.c. motor starter. Because armature winding is directly connected to the supply. Before starting the d.c. motor by the method of armature voltage control, armature voltage should be equal to zero. Now increase the armature voltage gradually and carefully until the required value is reached for the test.

1.5 Connect the circuit as shown Fig.2.

1.6 Using voltage divider circuit (V.D.1) adjust the motor field current until the same value is obtained in Experiment 10 Procedure (1.3) while the armature is stationary. (Hence rated speed is reached).

1.7 Gradually increase the motor armature voltage until the motor runs at rated speed carry out a load test using the circuit diagram given in figure.5. Increase the load step by step using the other voltage divider circuit (VD2) until the motor armature current reaches the rated value.

At each step, record the motor armature current and voltage, field current.

1.8 Measure the resistance of the armature winding using a digital ohmmeter (i.e.Fluke).

1.9 Connect the circuit as shown in Fig.1. (Rs being shorted by cable manually).

1.10Start the motor and adjust the field resistance until the motor runs at rated speed on no-load; record the value of field current.

1.11Carry out a load test on the motor with the aid of eddy current brake. Keeping field current constant, increase the load step by step using single-phase variac until the armature current reaches the rated value. Record the value of field current .

At each step record the supply voltage of the motor, motor input current, armature current, torque meter reading and armature speed.

1.12Increase the motor field current to the maximum possible value at no-load and repeat procedure (1.4).

1.13Decrease the field current until the motor speed exceeds the rated value by 25% at no-load and repeat procedure (1.4).

D. RESULTS AND CONCLUSIONS

1. For each set of result calculate the shaft torque.
2. Plot on the same graph curves of torque against speed for each method of speed control.
3. Calculate the speed regulation as percentage of no-load speed at each

value of field current using $\text{Reg} = \dfrac{n_{no-load} - n_{full-load}}{n_{no-load}} * 100$

4. Plots in variation field flux control:

(4.1) Plot speed vs. field current for the no-load case.

(4.2) Plot the speed regulation vs. field current on a separate graph.

(4.3) Plot the motor efficiency vs. field current on a separate graph.

5. Calculate the speed regulation as percentage of no-load speed at each value of external armature resistance in variation of resistance speed control method.

6. Plot in variation of resistance in series with armature speed control method :

(6.1) Plot speed vs. external armature resistance for the no-load case.

(6.2) Plot the speed regulation vs. external armature resistance on a separate graph.

(6.3) Plot the drive efficiency vs. external armature resistance on a separate graph.

7. Calculate the speed regulation as percentage of no-load speed at each value of terminal

voltage in Speed Control by Varying Armature Voltage.

8. Plot in Speed Control by Varying Armature Voltage:

(8.1) Plot speed vs. terminal voltage for the no-load case.

(8.2) Plot speed vs. terminal voltage for the full-load case on the same graph.

(8.3) Plot the speed regulation vs. terminal voltage on a separate graph.

(8.4) Plot the motor efficiency vs. terminal voltage on a separate graph.

9. According to the results obtained in the experiment, which speed control method has the widest speed range under no-load? Which method has the smallest range under no-load?

10. Which speed control method has the best speed regulation under all speeds? Which method has the worst speed regulation?

11. Which speed control method has the best drive efficiency? Which one has the worst drive efficiency?

12. Comment on the shape of all curves and hence discuss briefly the advantages and disadvantages of each method of speed control.

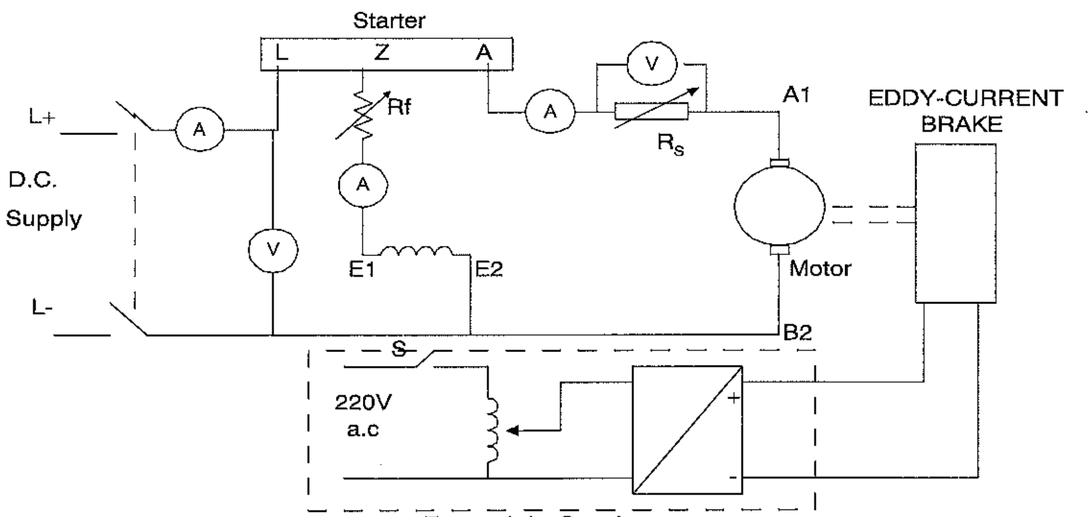


Fig.1.Speed Control of a d.c Shunt Motor connecting diagram

Note: The R_s being shorted by a cable manually for C.1

EQUIPMENT:

Ammeter 0-30 A

Ammeter 0-30 A

Ammater 0-1.2 A

Voltmeter 0-520 V

Voltmeter 0-520 V

Rheostat 1320 ohm for 0.6 A for R_f

3-phase Resistive Load for R_s

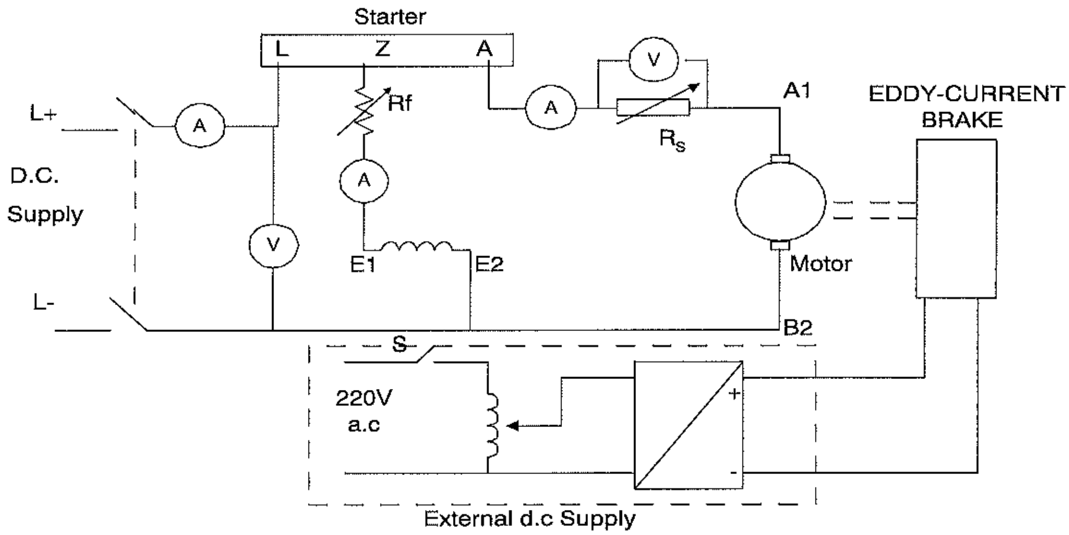


Fig.1.Speed Control of a d.c Shunt Motor connecting diagram

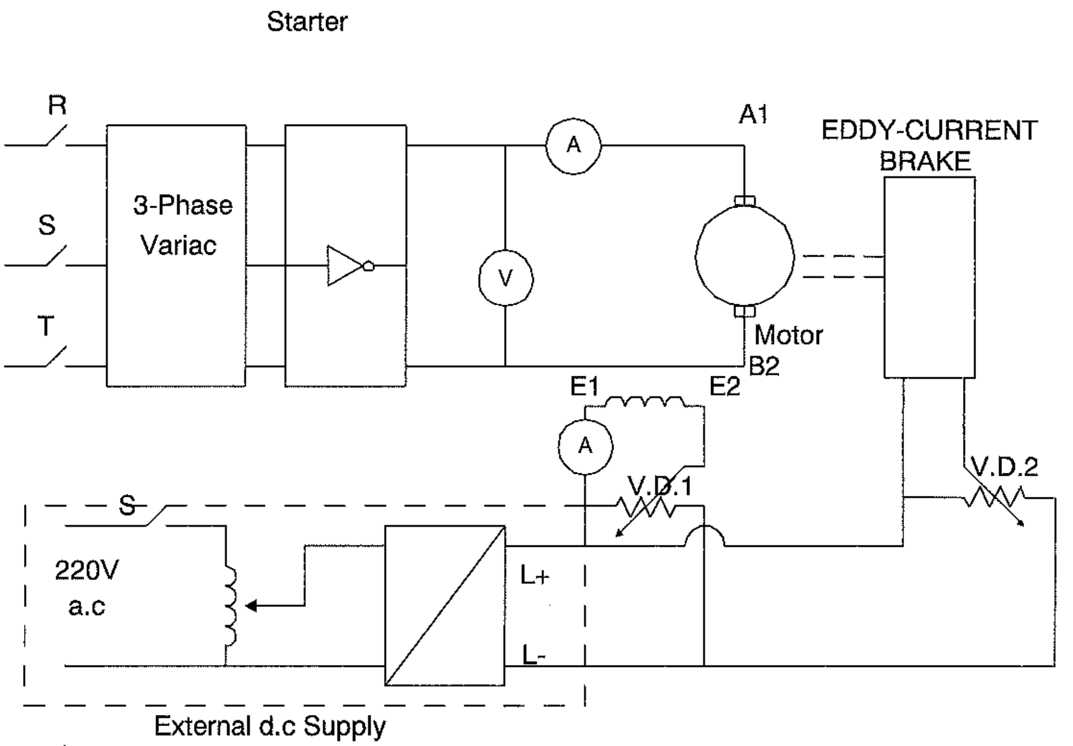


Fig.3 Circuit diagram for Static Voltage Control Experiment

E.1.Data table for speed control by variation of field flux

Armature Voltage	Total Current	Field Current	Armature Current	Torque (NM)	Armatur Speed	
						No-Load

Armature Voltage	Total Current	Field Current	Armature Current	Torque (NM)	Armatur Speed	
						No-Load

E.1. Data table for speed control by using series resistance with armature

Armature Voltage	Total Current	Field Current	Armature Current	Torque (NM)	Armature Speed	
						No-Load

Armature Voltage	Total Current	Field Current	Armature Current	Torque (NM)	Armatur Speed	
						No-Load

Experiment #9
Voltage Build-up in Dc Generators by using Matlab/Simulink

Object: To learn to use the Matlab/Simulink to model and understand the voltage build-up in dc generators.

!!! Dublicated reports are evaluated as zero. Dead line is 5 th of January.

Procedure:

A) Read the tutorial (How to use Simulink in the following link:http://www.ece.osu.edu/ems under ECE 743 course material) at least up to slide number 12.

B) Voltage Buil-up in Shunt DC Generators:

1) Develop the following figure in Matlab/Simulink. This model demonstrates voltage build-up in shunt dc generators.

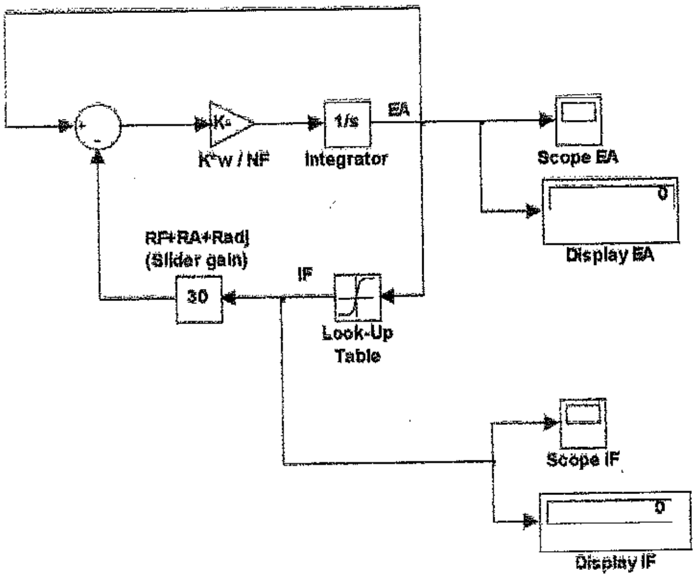
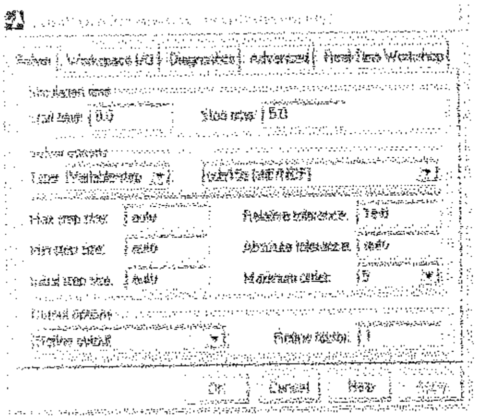


Fig.1-Modelling of voltage build-up in self-excited dc generator

2) To start simulation, adjust the simulation parameters as in the following box and then run the following simulation.



- To observe the effect of increasing the field resistance beyond the critical value, adjust the slider gain RF+RA+Radj to its highest value of 54 Ohm. Then, determine the critical value of the field resistance by reducing the gain in steps of 1 Ohm until the self-excitation of the generator can be observed.
- Place the circuit diagram in your report.

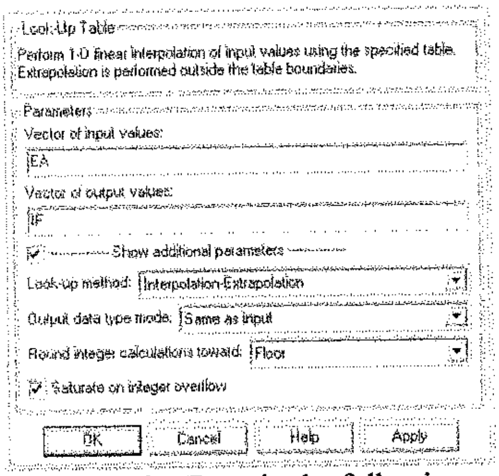
- Present the Ea-If curve for three different field resistance values (R1<Rcritical, R1>Rcritical, R1=Rcritical) in your report.
- Explain (in the report) how the terminal voltage is built up while there is no external DC source to provide field current. What causes *EA* to start from a nonzero value?
- Comment on the simulation results, in your report.From the open-circuit characteristic curve, if you are to design this machine, at which point would you select as the operating point of this machine? Explain in the report.
- Explain the shunt dc generator model by using necessary mathematical relations, in your report.

<u>Data for DC Generator:</u>

Radj= 6Ω
Rf= 30Ω
Ra= 0.18Ω
Nf= 1000
K= 63.662
w= 188.5 rpm
$Ea_{,initial}$= 1V

<u>Use the following table for look-up table:</u>

Ea	If
0	0
8	0.2
16	0.4
24	0.6
32	0.8
40	1
48	1.2
56	1.4
64	1.6
71.9	1.8
79.5	2
86.7	2.2
93.1	2.4
98.7	2.6
103.5	2.8
107.46	3
110.66	3.2
113.46	3.4
115.86	3.6
117.96	3.8
120	4
122	4.2
123.9	4.4
125.7	4.6
127.4	4.8
128.98	5
130.42	5.2
131.74	5.4
132.95	5.6
134.15	5.8
135.4	6
136.65	6.2
138	6.4
139.25	6.6
140.5	6.8
141.8	7



insert data for Ea as in the following
[0, 8 ,16...........]
or convert to mat file.

C) ***Separately excited dc generator:***

This test let you examine the relationship between the generated voltage and excitation current of a generator at no load.

1. Build a simulink model as seen in Fig. 2. The dc machine is connected in separately excited configuration. The field current (*If*) can be adjusted through *Radj*. Spend some time to familiarize with the circuit.Note that this model is done using simpowersytems. Place this model also in your report.
2. Double click on the voltage source *Vf* and set it to 120V.
3. Run the simulation (simulation/start). Double click on each scope to see the voltage and current waveforms. Note that voltage and current values can also be obtained through *Display_EA* and *Display _If*, respectively.
4. Vary the field current (*If*) in the steps of 0.1A from zero to 1.2 A. Record the open circuit generator terminal voltage (*EA*) and *If* in the following table. In order to obtain zero value of *If*, you may might want to set *Vf* to zero.

If	EA

5. Is the graph in the previous step linear? Why or why not? Explain in the report.
6. When *If* is set to zero, what is the value of *EA*? Explain in the report.

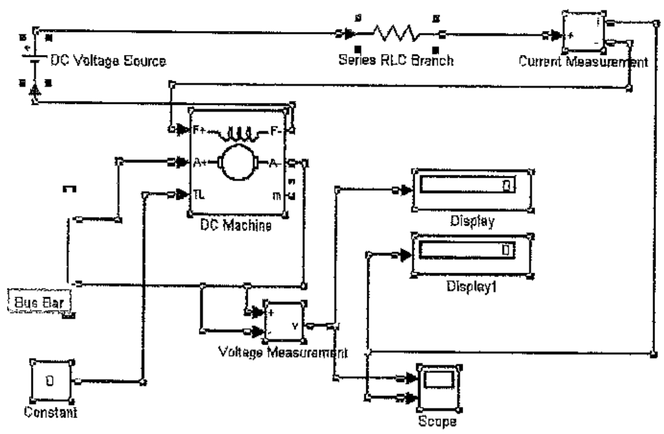


Fig. 2 Open-circuit characteristic test diagram for separately excited dc generator