مرجع بالتجارب المعملية التي يمكن اجراؤها بمعملي الآلات الكهربية (أ، ب)

Electrical Machines Lab Manual

Single-Phase Transformers
Electrical Machines Laboratory (A)

SAFETY

You can work individually or with a partner. Groups of three or more are allowed.

Please be aware of the following hazards:

- ❖ You will be working with voltages up to AC 220 V and currents up to 20 A AC. These levels of voltages/currents are dangerous. To avoid electric shock, connecting circuits is permitted only after power has been disconnected. Circuits should be inspected by a demonstrator before they are powered on.
- ❖ Do not connect any equipment on your bench to the power supply from an adjacent bench; this might connect the equipment to a different phase.
- ❖ Note that power will be supplied to a circuit only if the variable voltage control is initially set to zero. This prevents the circuit from being accidentally operated at high voltage/current. Set this control to zero every time before you switch on the circuit.
- ❖ Do not connect two or more short leads to make one long lead. Remove unused leads from the bench.
- ❖ Transformers, inductors, resistors and power supplies are quite heavy. In general, you will not need to move this equipment during the laboratory exercise. However should you need to move the equipment, a proper handling technique must be used. Before moving any of the above equipment considers a possibility of moving the measurement instruments instead. Also, consider using longer leads if necessary.

REPORT

Each student must submit an individual report. The pre-lab report must be completed prior the laboratory exercise. The final report must be submitted in the end of the laboratory class.

Status Reports

- Introduction
- Analysis/Summary
- Attached Files (Outputs, Plots, Schematics, etc.)

A brief description of each section of the reports is provided below. Use the descriptions as an outline of what should be included in the report.

Title Page: The title page should include, in the following order, the course number, the title of the experiment, your name, your lab partners name, the TA or professors leading the lab section, and the date the report was submitted.

Objectives: The abstract should be a very concise, clear, and complete summary of the experiment. Do not include specific details or references to figures, etc. The abstract should be written after completing the lab report, and should be written in less technological terms that can be easily read and understood by a variety of individuals with different backgrounds.

Introduction: The introduction should discuss the purpose or objective of the lab experiment. It should also include a brief summary of the processes or procedures used in performing the lab experiment. Related history of the subject under investigation in the lab may also be included when appropriate. The introduction should be relatively short.

Methodology/Theory: The section on methodology or theory should discuss the experiment performed in lab. Theoretical development associated with design procedures should be discussed, particularly in the cases where it influences the choices you make in completing the lab experiment. This includes the work done in pre-lab, simulation, and hardware. The methodology presented should be sufficiently complete for someone reading the report to reproduce the experiment and verify the results.

Analysis/Results: The final data collected or measured should be placed in the results section. This would apply specifically to data or measurements associated with the purpose and design specifications of the experiment. Diagrams, numerical data organized in tables, etc. should be placed in this section, and any pertinent analysis (but not concluding remarks) should be included. Any intermediate results that were used to obtain the final results of the experiment do not need to be included in the report.

Summary: The summary section is for informal and status reports only. This section is a brief combination of the methodology/theory and analysis/results sections. One brief statement of what was done in the experiment and another brief statement summarizing the results (along with the pertinent figures, numerical data, etc.) is all that is necessary for the summary.

Conclusion: The conclusion should respond to the goals and objectives discussed in the introduction of the report. A general discussion of how well the experiment did (or did not) fulfill its objectives should be presented without getting personal. Applications using the results from the experiment, or a forecast of future events that relate to the work done in the experiment may also be included.

Attached Files: Any supporting documents, outputs, figures, .. etc. that are not included directly in the report should be placed at the end of the report.

RATINGS

Operating the equipment at voltage or current higher than the rated voltage and current is unsafe and may damage the equipment. Before you start connecting circuits write down the ratings for the load resistor, capacitor, inductor and the transformer shown on the rating plates. Also, look at current ratings shown near fuses. These ratings must not be exceeded at any time during the laboratory exercises.

CAUTION

Do not turn the power on before your circuit has been checked by your TA!

When the layout has been completed, have your TA to check your circuit connections and get his/her signature in your log book.

CLEAN UP

This must be done prior submitting the lab report.

1- Turn off the power supply switches and the switch that powers digital meters. The load switch must be turned off.
2- Disconnect the equipment and remove all leads from the bench.
3- The load inductor and load resistor must be set to the minimum current position.

Experiment №.1:
Transformer Equivalent Circuit

OBJECTIVES

1. To determine the transformer turns ratio,
2. To perform the no-load and short circuit tests,
3. To find the variation of transformer losses when varying applied voltage and load current,
4. To find the parameter variation with applied voltage and load current, and
5. To calculate the transformer's equivalent circuit.

INFORMATION

A single-phase transformer will be investigated in this lab. It is a step-up transformer 110/220V with the rated power of 2000VA and rated frequency of 50 Hz.

BACKGROUND

1. Ideal Transformer

A transformer is a device used to change voltages and currents of AC electric power. In the simplest version it consists of two windings wrapped around a magnetic core; windings are not electrically connected, but they are coupled by the magnetic field, as it shown in Figure 1. When one winding is connected to the AC electric power, the electric current is generated. This winding is called the primary winding. The primary current produces the magnetic field and the magnetic flux links the second winding, called the secondary winding. The AC flux through the secondary winding produces an AC voltage, so that if some impedance is connected to the terminals, an AC electric current is supplied.

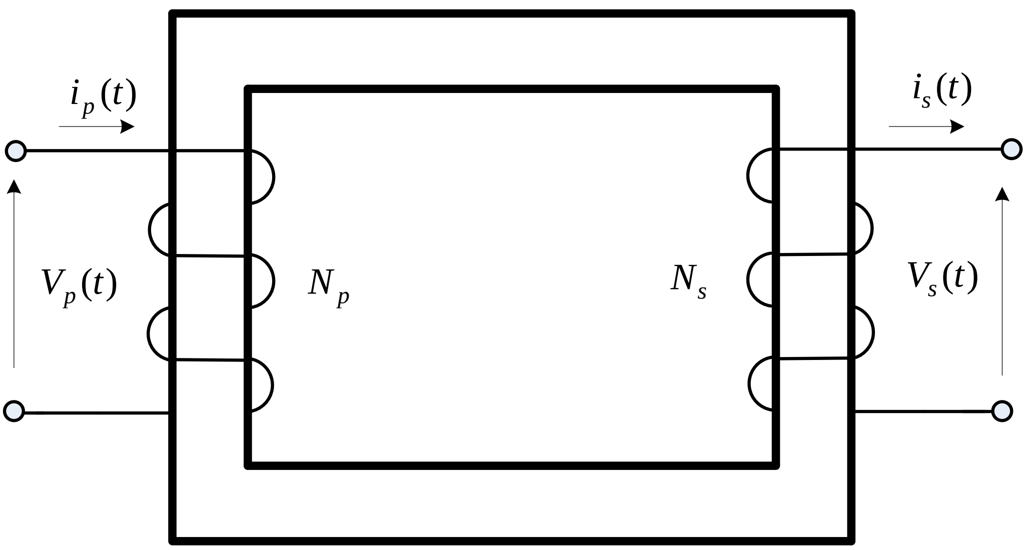


Figure 1: Sketch of an ideal transformer

Figure 2 shows the schematic symbols of a transformer.

Figure 2: Schematic symbols of a transformer.

The simplest model of the transformer is called the ideal transformer and it neglects any power losses and leakage magnetic fluxes. Assuming that the primary winding has N_p turns of wire, and the secondary winding has N_s turns, the relationship between the primary voltage and the secondary voltage is:

$$\frac{V_p(t)}{V_s(t)} = \frac{N_p}{N_s} = a$$

where ***a*** is the turns ratio in the primary and secondary windings

$$a = \frac{N_p}{N_s}$$

Similarly, for the primary and secondary currents

$$\frac{i_p(t)}{i_s(t)} = \frac{N_s}{N_p} = \frac{1}{a}$$

2. Real Transformer

The ideal model of the transformer is sufficient for approximate analysis of the electric circuits only. For full analysis a more complete model is needed and it should include: core losses, winding losses, magnetizing current and all leakage magnetic fluxes. It can be shown that the equivalent circuit in Figure 3 fully represents all these effects.

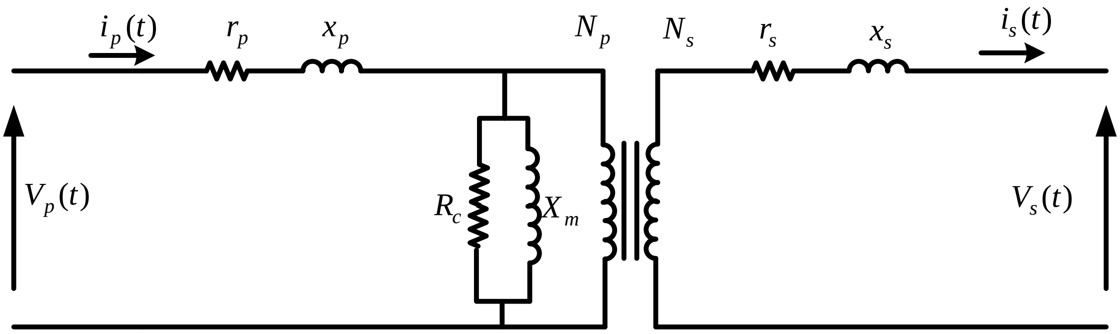


Figure 3: The model of a real transformer

The resistance r_p and r_s represent the ohmic resistance of the primary and the secondary windings. The reactance x_p and x_s model the leakage flux of the primary and secondary windings, respectively. The resistance R_c is responsible for the core losses due to hysteresis and eddy currents, and X_m for the generation of the main flux (magnetizing reactance).

All impedances on the secondary side of the transformer can be recalculated for the primary side. This is also known as the referring to the primary side and results in the equivalent circuit shown in Figure 4.

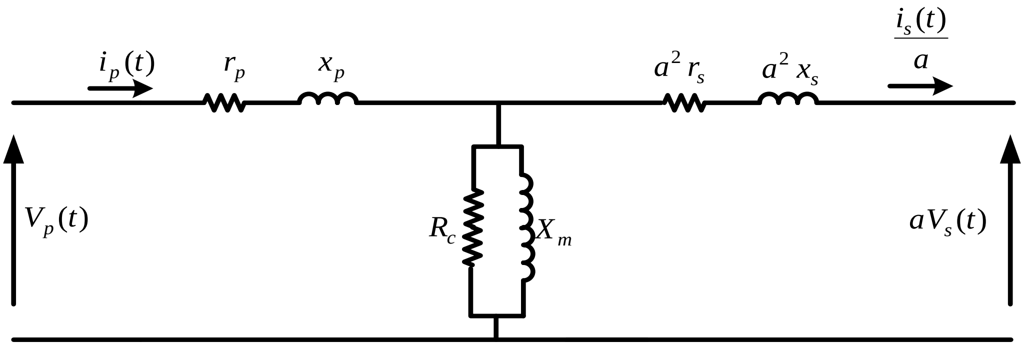


Figure 4: The transformer model referred to the primary voltage level

Determining The Equivalent Circuit

Experimental determination of all elements in the transformer equivalent circuit involves three tests:

• Measurement of the winding resistances,

• Open-circuit test, and

• Short-circuit test.

Measurement of the Primary Resistance

A DC ohmmeter should be connected across the primary terminals and r_p should be recorded, also it can be performed by using dc test (see Figure 5)

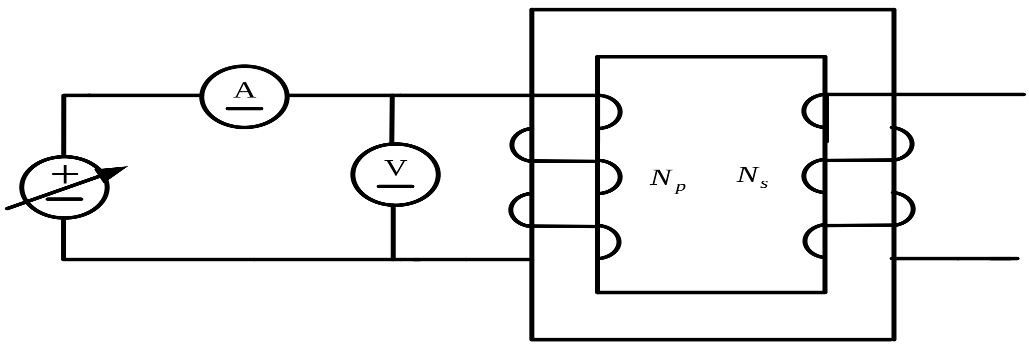


Figure 5: The dc test of primary windings

V							
I							
$r_p = \frac{V}{I}$							

$$r_p = \ldots\ldots\ldots\ldots\Omega$$

Measurement of the Secondary Resistance

A DC ohmmeter should be connected across the secondary terminals and r_s should be recorded, also it can be performed by using dc test (see Figure 6)

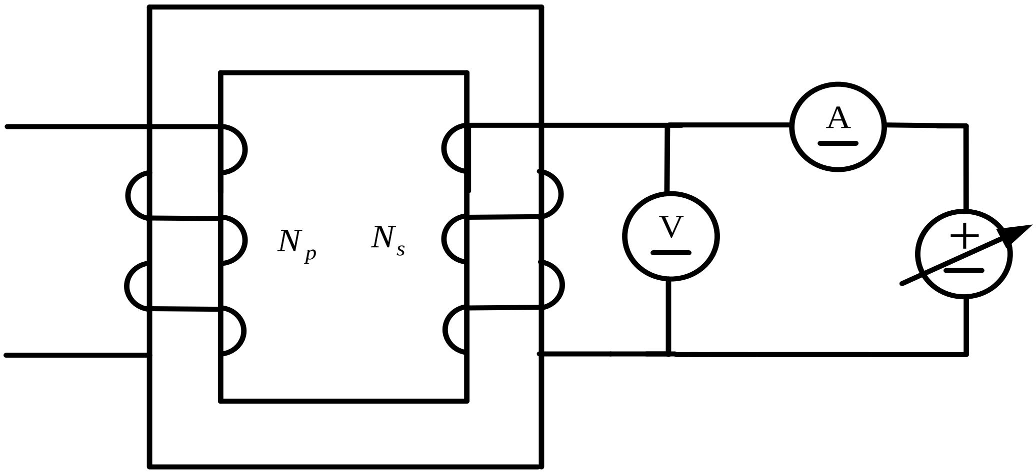


Figure 6: The dc test of secondary windings

V							
I							
$r_s = \frac{V}{I}$							

$$r_s = \ldots\ldots\ldots\ldots\Omega$$

Turns Ratio

The turns ratio of a transformer is equal to the ratio of primary and secondary voltages at no-load

$$a = \frac{N_p}{N_s} = \frac{V_{p0}(t)}{V_{s0}(t)}$$

where: V_{p0} – no-load primary voltage

V_{s0} – no-load secondary voltage

In order to determine the turns ratio, connect the circuit as shown in Figure 7. The transformer is supplied with a variable voltage and both primary and secondary voltages are measured and recorded.

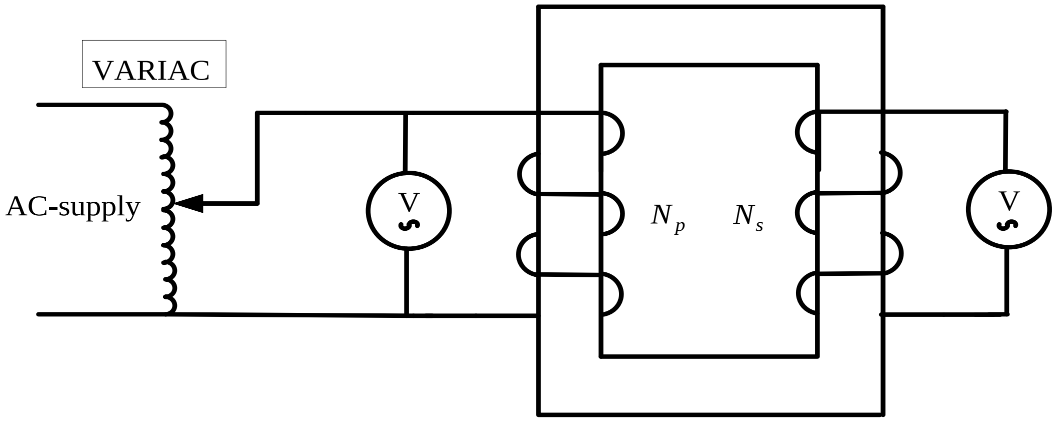


Figure 7: Transformer ratio measurements

Starting from V_{p0} =20V turn the variac knob and slowly increase the input voltage.

Measurements and calculations of the turns ratio should be done for V_{p0} = 20, 40, 60, 80, 100 and 120 V. Complete all the data in the following table.

V_{p0} (V)	V_{s0} (V)	Turns Ratio
20		
40		
60		
80		
100		
120		
Average Turns Ratio		

No-Load Test

The experimental procedures:

1- Connect the apparatus as shown in Figure 8.

2- Adjust the autotransformer to its minimum output voltage and switch the supply on.

3- Starting from V_{oc} =20V turn the variac knob and slowly increase the input voltage up to the transformer rating and record V_{oc}, I_{oc} and P_{oc} for each step.

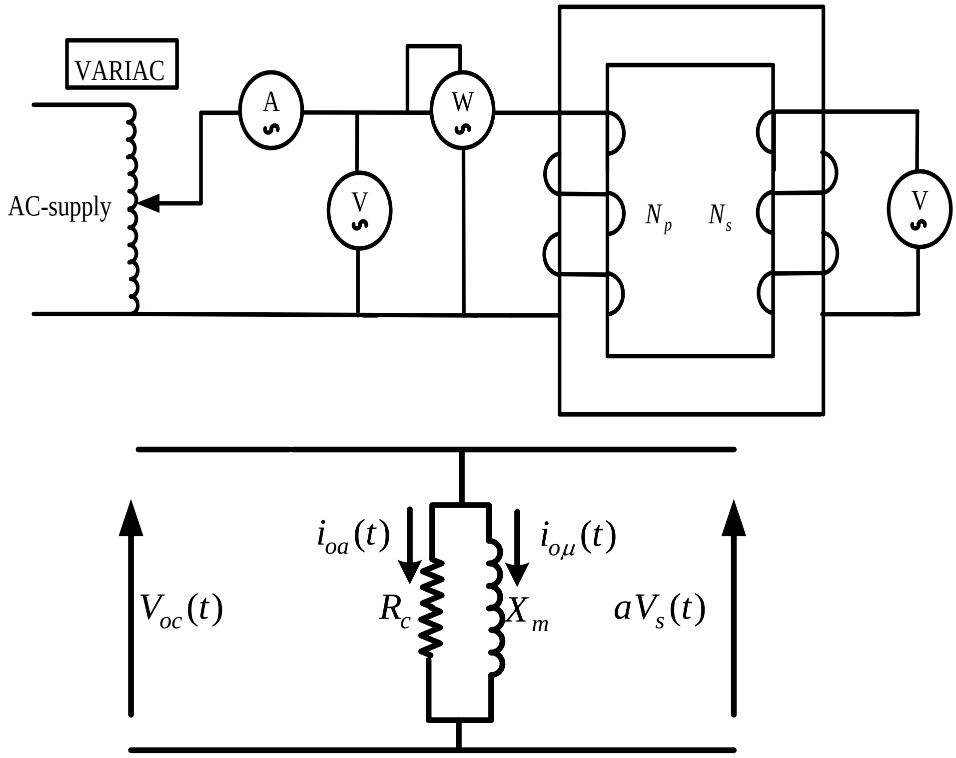


Figure 8: Transformer no-load test measurements and its equivalent circuit

4- Determine the parameters of the magnetizing branch using the following equations:

$$\cos\varphi_0 = \frac{P_{oc}}{V_{oc}\, I_{oc}}$$

$$I_{oa} = I_{oc}\cos\varphi_0$$

$$I_{o\mu} = I_{oc}\sin\varphi_0$$

$$R_c = \frac{V_{oc}}{I_{oa}}$$

$$X_m = \frac{V_{oc}}{I_{o\mu}}$$

$$\text{Rated Iron Losses} = P_{oc}\left(\frac{V_{rated}}{V_{oc}}\right)^2$$

Results:

V_{oc}									
I_{oc}									
P_{oc}									
Cos φ_0									
Sin φ_0									
I_{oa}									
$I_{o\mu}$									
R_c									
X_m									

Output results:

a) Plot R_c and X_m as a function of V_{oc}, and

b) Plot the variation of I_{oc}, P_{oc}, and cos φ_0 versus V_{oc}.

Short-circuit Test

The experimental procedures:

1- Connect the apparatus as shown in Figure 9.

2- Short-circuit the primary winding through an ammeter as shown in Figure 9.

3- Adjust the autotransformer to its minimum output voltage and switch the supply on.

4- <u>Slowly</u> and gradually increase the applied voltage and <u>carefully</u> watch the primary and secondary currents until its rated values.

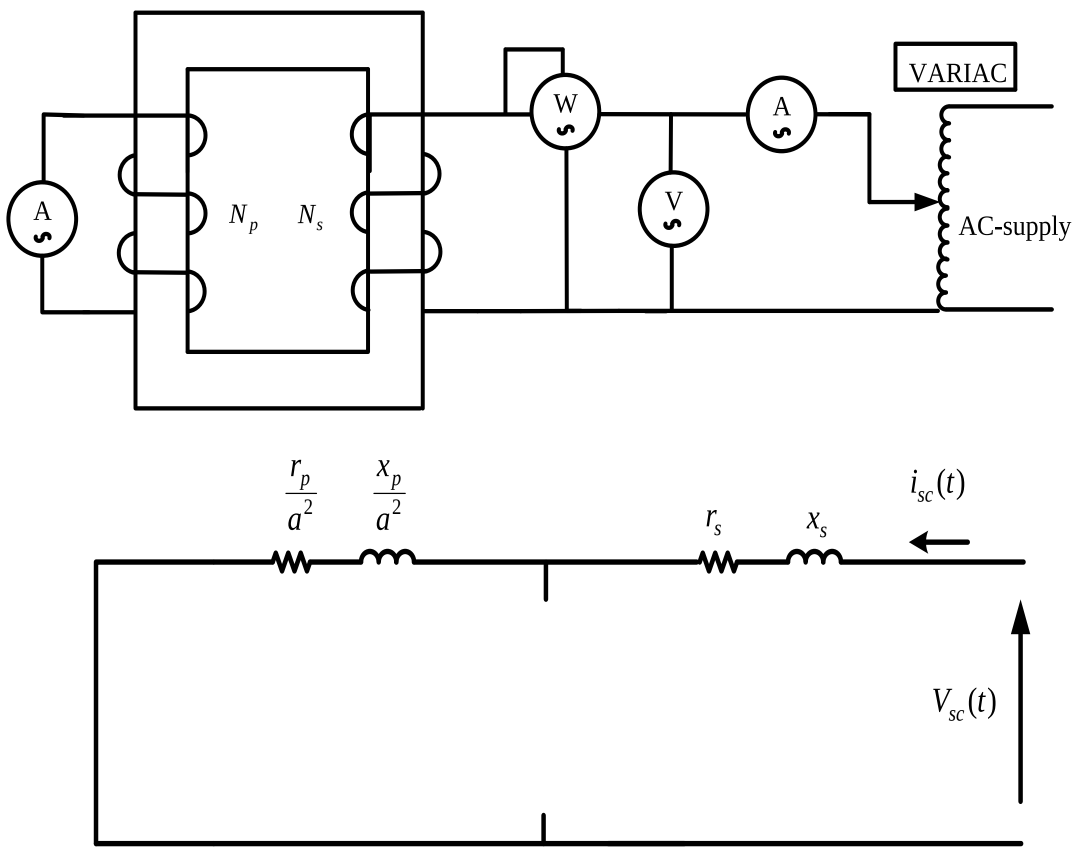


Figure 9: Transformer short-circuit test measurements and its equivalent circuit

5- Calculate the short circuit impedance as measured from the secondary using the following equations:

$$Z_{sc} = \frac{V_{sc}}{I_{sc}}$$

$$R_{sc} = r_s + \frac{r_p}{a^2} = \frac{P_{sc}}{I_{sc}^2}$$

$$X_{sc} = \sqrt{Z_{sc}^2 - R_{sc}^2}$$

$$r_s = \frac{r_p}{a^2} = \frac{R_{sc}}{2}$$

$$x_s = \frac{x_p}{a^2} = \frac{X_{sc}}{2}$$

$$\text{Rated copper Losses} = P_{sc}\left(\frac{I_{rated}}{I_{sc}}\right)^2$$

Results:

I_{sc}									
V_{sc}									
P_{sc}									
R_{sc}									
Z_{sc}									
X_{sc}									

Output results:

a) Plot R_{sc} and X_{sc} as a function of I_{sc}, and

b) Plot the variation of V_{sc}, and P_{sc} versus I_{sc}.

Experiment №.2:
Transformer Loading Test

OBJECTIVES

1- To determine the rated load of the transformer and the temperature rise.

2- To determine the efficiency and voltage regulation of a single-phase transformer.

INTRODUCTION

Transformer can be tested for efficiency and voltage regulation using direct load test. Load test gives accurate results, however it is not economic and is only suitable for small transformers. To implement the test, the transformer is supplied from power mains of rated voltage and the output power is wasted in an artificial load (often test resistor). Under this test, the transformer should be switched on and left for sufficient time to reach a steady-state temperature rise. After that, the readings can be recorded to get real data from the test.

Experimental procedures

1- Connect the circuit as shown in Figure 10.

2- Adjust the load resistance to its maximum value and switch on the supply.

3- Increase the primary voltage to its rated value and should be constant during the load test.

4- Decrease the load resistance in steps until the transformer rated current and record V_1, I_1, P_1, V_2, I_2 and P_2 for each step.

5- Change the load type to pure inductor and repeat the test.

6- Change the load type to pure capacitor and repeat the test.

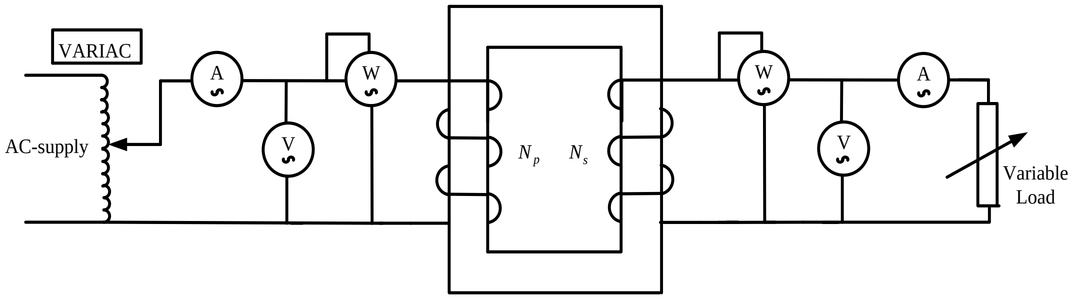


Figure 10: Transformer load test measurements

Results: (pure resistive load)

V_1 (constant)									
I_1									
P_1									
V_2									
I_2									
P_2									
$\eta = \frac{P_2}{P_1} \times 100$									
$\text{Reg} = \frac{V_{20} - V_2}{V_2}$									

Results: (pure inductive load)

V_1 (constant)									
I_1									
P_1									
V_2									
I_2									
P_2									
$\eta = \frac{P_2}{P_1} \times 100$									
$\text{Reg} = \frac{V_{20} - V_2}{V_2}$									

Results: (pure capacitive load)

V_1 (constant)									
I_1									
P_1									
V_2									
I_2									
P_2									
$\eta = \frac{P_2}{P_1} \times 100$									
$\text{Reg} = \frac{V_{20} - V_2}{V_2}$									

Output results:

a) Plot the efficiency versus load current,

b) Plot the voltage regulation versus load current, and

c) Plot the voltage regulation versus load power factor.

Load characteristics

This is representing the relation between the primary voltages versus the load current at constant load voltage.

Results:

V_1									
I_1									
P_1									
V_2 (constant)									
I_2									
P_2									
$\eta = \frac{P_2}{P_1} \times 100$									

Experiment №.3:
Back-to-Back Test for Single-Phase Transformers

OBJECTIVES

The objective of this test is to determine the performance characteristics of large transformers.

BACKGROUND

Two very simple tests are used to determine the constants of equivalent circuit and the power losses in the transformer. These consist in measuring the input voltage, current, and power to the primary, first with the secondary short circuited and then with secondary open circuited. The core losses are determined from the open circuit test. The copper losses are determined from the short circuit test.

Stray load loss consists of the losses arising from the non-uniform current distribution in the copper and the additional core losses produced in the iron by distortion of the magnetic flux by the load current. It is difficult to determine such losses accurately by conventional no-load and short circuit load tests.

To obtain exact equivalent circuit and losses, the input and output parameters are directly measured under different loading conditions. This is easy for small rating transformers. However for large transformers, it is difficult and expensive to take direct measurements.

A Back to Back Test is used in this case. This test requires two identical transformers having some tapping in the windings.

Why Back-to-back test is used in case of large transformers?

First, the short circuit test is difficult to be applied, since applying a reduced voltage is very difficult and unpractical. Second, this test can simulate the loading conditions on the transformer without using real loads. Third, a large transformer supplying large essential loads has usually a second identical transformer installed in the same location for back-up, so using back-to-back transformer in this case is very practical.

In this test two identical transformers are needed. The two primary windings are connected in parallel across the supply having the normal voltage rating of the transformers. The two secondary windings are connected in phase opposition such that the voltage measured across them is zero. If the voltmeter gives a reading twice the voltage rating of the secondary, the terminal connections should be reversed. While the two secondary windings are connected back-to-back, no current will flow if they are short-circuited. Current can be allowed to flow in the secondary windings by injecting certain amount of voltage from an autotransformer. The injected voltage can be adjusted such that the full-load current circulates in the secondary windings. In such case, a full-load current also will circulate internally between the primary windings. The power drawn from the primary side is twice the core losses of one transformer, while the power drawn from the secondary side is twice the copper losses of one transformer.

Experimental Procedure

This test requires two identical three phase transformers. Take complete particulars of either of the two transformers.

Connect the two transformers as shown in Figure 11 and check the correct polarity using a voltmeter connected across the switch. The reading of the voltmeter should be zero for correct polarity connection. Then carry out the following procedures:

1. With the switch open, apply the rated voltage across the primary side and read the various instruments. The input power in this case covers

the iron losses of the two transformers, thus the parameters R_c and X_m of the transformer equivalent circuit can be determined.

2. Switch on the secondary switch and cautionary increase the secondary voltage till the full-load current circulates in the transformer windings this case covers the iron losses of the two transformers as well as their corresponding copper losses.
3. Record the readings of the primary and secondary windings.

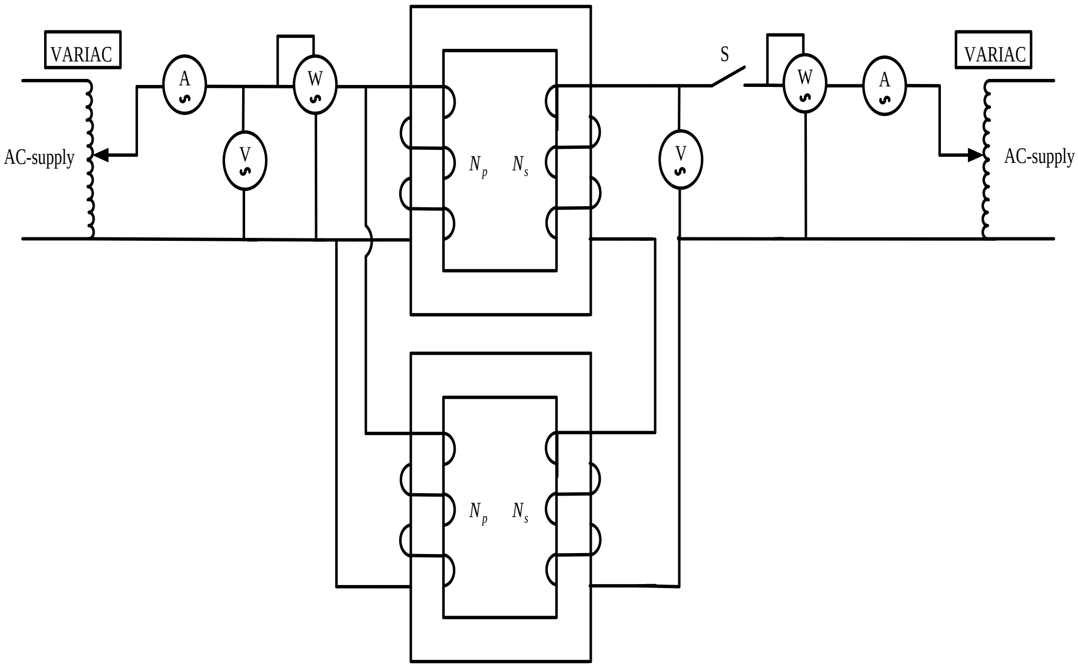


Figure 11: Back-to-back test measurements

Experiment №.3:

Three-Phase Transformers

OBJECTIVES

1- To connect transformers in delta and Y configurations
2- To study the voltage and current relationships.

BACKGROUND

Single-phase transformers can be connected to form 3-phase transformer banks for 3-phase power systems. Four common methods of connecting three transformers for 3-phase circuits are Δ-Δ, Y-Y, Y-Δ, and Δ-Y connections. An advantage of Δ-Δ connection is that if one of the transformers fails or is removed from the circuit; the remaining two can operate in the open-Δ or V connection. This way, the bank still delivers 3-phase currents and voltages in their correct phase relationship. However, the capacity of the bank is reduced to 57.7 % ($1/\sqrt{3}$) of its original value.

In the Y-Y connection, only 57.7% of the line voltage is applied to each winding but full line current flows in each winding. The Y-Y connection is rarely used.

The Δ-Y connection is used for stepping up voltages since the voltage is increased by the transformer ratio multiplied by $\sqrt{3}$. The Y-Δ connection may be used for stepping down voltages.

The four connection types are shown in Figure 12.

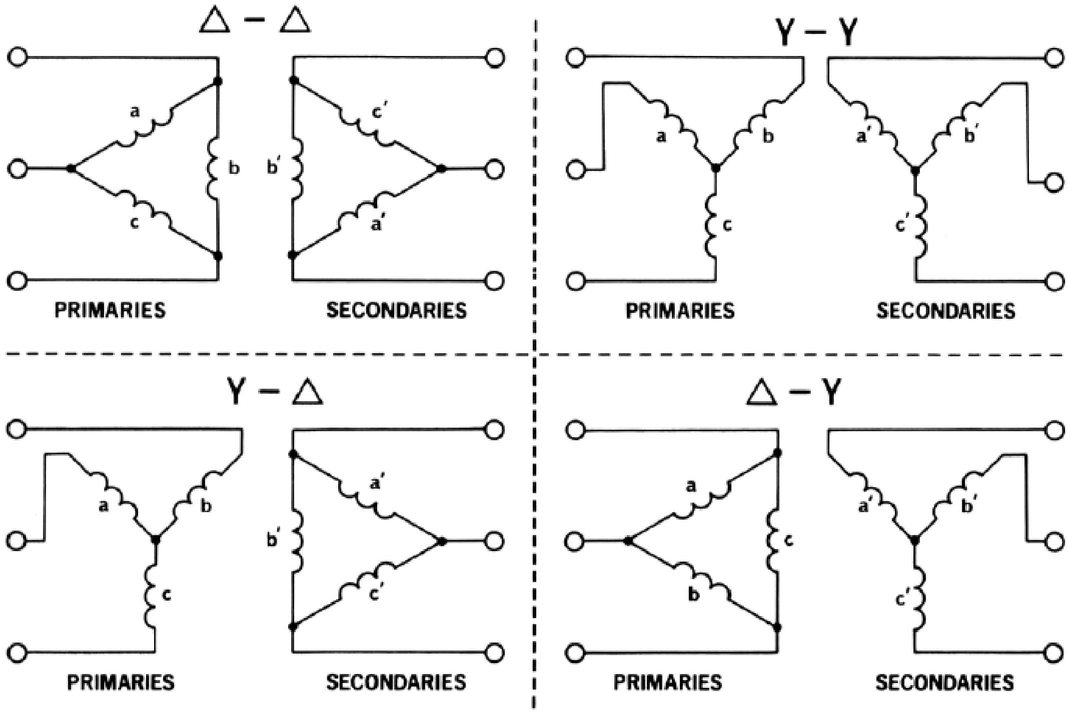


Figure 12: common connections of three-phase transformers

REFERENCES

1. “Electric Machinery”, Fourth Edition, Fitzgerald, Kinglsey, and Umans, McGraw-Hill Book Company, 1983, Chapter 1.

2. “Electromagnetic and Electromechanical Machines”, Matsch, Leander W., Intext Educational Publishers, 1972.

3. “Electromechanical Devices for Energy Conversion and Control Systems”, Del Toro, Vincent, Prentice-Hall, Inc., 1968.

DC Machines

Electrical Machines Laboratory (B)

1 – Introduction:

1.1 <u>Main features of electrical-machines:</u>

The electrical motor must be chosen suitable for the drive machine. The mechanical characteristic of both motor and drive machine must be identical. In addition to the nominal data of the machine types of its construction and protection must be also considered. Rating plate shows the important designation as well as the nominal data of the electrical machine.

1.1.1 Rating plate

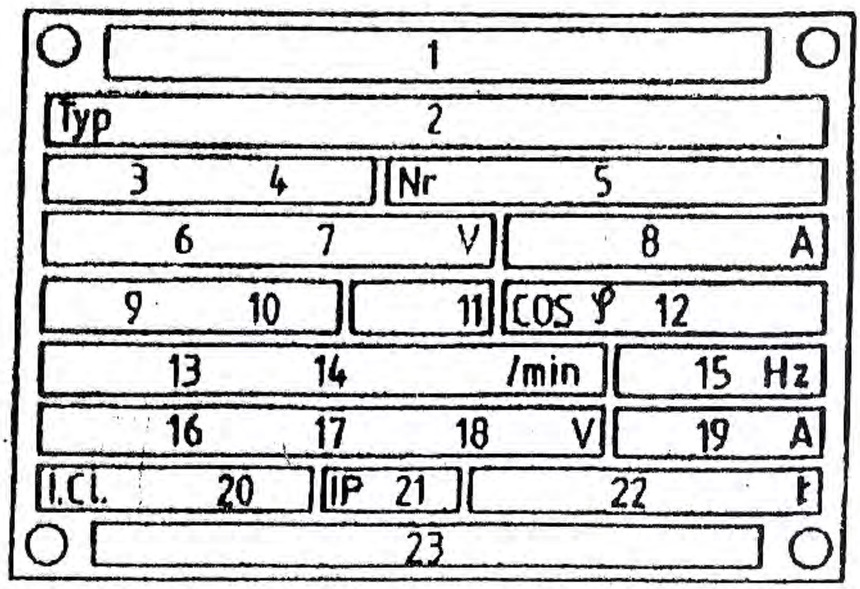


Table (1): Declaration of rating plate

Field	Declaration
1	Manufacture trade mark of the firm
2	Type - designation of model or catalogue number.
3,4	3) Kind of current Dc-direct current : Ac-Alternating current 4) Working method : Gen - generator - Mot - motor
5	Serial - succession number
6,7	6) Type of connection of stator windings: Δ - Connection Y-Connection 7) Nominal voltage
	Nominal current
9 ,l0, 11	9-10) Nominal (output power) In[kW] or [W] for motor. In [kVA] or [VA] for synchronous generator. 11) Duty type rating.
12	Nominal power factor cos ϕ
13,14	13) Direction of rotation for example clock-wise rotation of side of drive. 14) Nominal revolutions per unit time
15	Nominal frequency for ac machines
16, 17, 18	16) Excit. Exciting for direct current machines. Rot. rotor for induction machines 17) Type of connection of rotor winding 18), Nominal exciting voltage, locked-rotor voltage.
19	Nominal exciting current, rotor current.
20	Class of insulation.
21	Type of protection.
22	Weight in ton for machines > I ton.
23	Additional note for example data of cooling medium.

Construction Types and Protection

1.1.2. Construction Types.

The active electrical- and magnetic parts of an electrical machine are invariable, meanwhile arrangement of bearings, the fixing of housing and the position of drive etc. are different. There are many types of construction by which the adaption of the electrical motor and the drive machine is easy and correct. The different types of construction are defined through classification which consist from one letter and numeral.

The letters means the following:

A: Machines without bearings, horizontal arrangement.

B: Machines with end- shield bearings, horizontal arrangement.

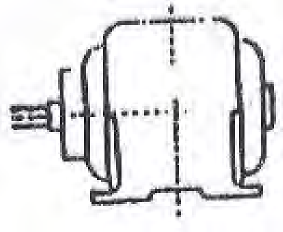
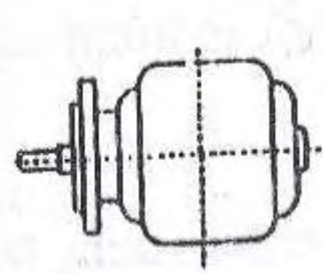
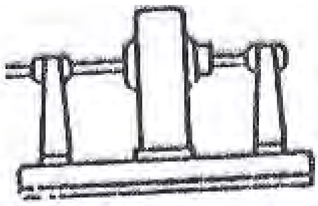
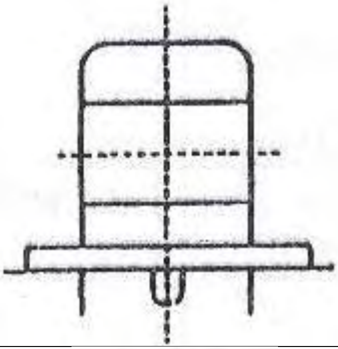
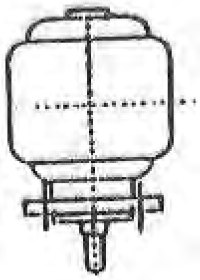
C: Machines with end-shield bearings and pedestal bearings, horizontal arrangement.

D: Machines with pedestal bearings, horizontal arrangement.

V: Machines with end- shied bearings, vertical arrangement.

W: Machines without end-shield bearings, vertical arrangement.

Table (2): Some examples of different types of constructions of electrical machines:

B3		Housing has mounting feet, two end-shield bearings, and free shaft extension. It is used for small power machines.
B5		Housing has no - mounting feet, mounting flange, two end-shield bearings, and free shaft extension. It is preferable for mounting with the driven machine.
D5		Housing has mounting feet, two pedestal bearings. The fixing is on a common-basic board. It is used for large power machines.
V1		Housing has no-mounting feet, mounting flange, two end- shield bearings and free shaft extension. It is provided with radial guide bearing and radial bearing. It is preferable for direct mounting with the driven machine in vertical direction.
W1		It has coupling flange. This type is preferable for generators of water power stations and exciters.

Types of Protection

The manufacturing of the external surface of an electrical machine is co-determined through the necessary protection. The type of protection is assigned by two numbers (X^+ , X^{++}) with the combination IP as follows:

* General identification litters for type of protection IP
* Characteristic number for protection against solid bodies X^+
* Characteristic number for protection against water X^+

The first characteristic numeral (X^+) is against the touching-and entering of foreign bodies.

The second characteristic numeral (X) is against the entering of water.

Table (3): Protection-degree against touching- and entering of strange bodies:

		Protective extend
	Naming	**Declaration**
0	No-protection	No - special protection for - people against accidental touching the standing-or movable parts, which are connected with low voltage,.No- protection against entering of solid foreign particles.
1	Protection Against big foreign bodies	Protection against - accidental touching of standing or movable large areas, which are connected with low voltage. Protection against entering of solid foreign bodies , which each of them has a diameter great than 50 [mm]

2	Protection against- middle size foreign bodies	Protection against touching of standing or internal movable parts, which are connected with low voltage with finger. Protection against entering of solid foreign bodies which one of them has a diameter great than 12 [mm].
3	Protection Against- small size foreign bodies	Protection against touching of standing or internal movable parts, which are connected with low voltage with tools, wires or others of thickness more than2.5 [mm]. Protection against entering of solid foreign bodies which each of them has a diameter great than 2.5 [mm].
4	Protection Against granular foreign-solid bodies	Protection against touching off standing or internal movable parts, which are connected with low voltage with tolls, wire or others of thickness more than 1 [mm]. Protection against entering of solid foreign bodies, which each of them has a diameter great than 1 [mm], except opening of cooling air and cooling water outlets for enclosed machines.
5	Protection against- deposit dust	Complete protection against touching of standing or internal movable parts. Protection against harmful deposit dust.

Table (4): protection degree against entering of water:

X^{++}	Naming	Declaration
	No- protection -	**No- protection**
1	Protection against fall of water simpleton in vertical direction.	The fall of water simpleton in vertical direction must cause no harmful action.
2	Protection against fall of water simpleton in oblique direction.	Water simpletons, which, fall from an direction till 15 [°] from vertical axis, must not cause any harmful action.
3	Protection against spray water.	Water, which falls from any direction till 60 [°] from vertical axis, must not cause any harmful -action.
4	Protection against injected water.	Water, which will be injected from all directions on the machine, must not cause any harmful action.
5	Protection against water beam.	Beam of water, which falls from all directions on the machine, must not cause any harmful action.
6	Protection against overflowing (flood).	Water-overflow from transitory flood must not entering in the machines with large quantities.
7	Protection against dip in water for a certain time.	Water must not entering the machine with harmful quantities when the machine is in water under a certain pressure and for a certain time .
8	Protection against dip in water.	Water must not entering the machine with harmful quantities when the machine is in water under a certain pressure and for indefinite time.

Some examples for protection:

Symbol	Protection against
IP00	No- protection
IP11	Protection against accidental touching of standing or movable large areas, which are connected with low voltage. Protection against entering of solid foreign bodies, which each of them has a diameter greater than 50[mm]. Protection against fall of water simpleton in vertical direction must cause no- harmful action.
IP23	Protection against touching of standing or internal movable parts, which are connected with low voltage, with forgers. Protection against entering of solid foreign bodies, which one of them is great than 12 [mm]. Protection against water, which falls from any direction till 60 [^{0}] from vertical axis, must not cause any harmful action.

In addition to the protection against touching. Foreign bodies and water, there are special protection like that one against flame profanes and explosion-proof protection.

1.1.3 Insulating materials:

The permissible temperature rise of an electrical machine is defined through the heat stability of the used insulating materials. They are hot spots at different positions inside the machine. There is maximum permissible temperature rises corresponds to each insulating material for continuous running duty of the machine. The usage of a complete insulating system for insulating an electrical machine means a safely operation as well as a long service life of the machine.

Kinds of insulating systems

Insulating system are subdivided according to operating voltage as follows:

1) Low voltage induction motors up to 660 [V]. .

2) High voltage induction motors up to 10 [kV].

3) Dc motors up to 3 [kV].

4) Synchronous motors up to 10 [kV].

5) Motors of special types of constructions and utilization's.

Insulating system of low-voltage machine.

Nr.	Usable insulations
I	Insulated conductor.
2	Insulation of slot, inter-layer insulation, under plate of Key.
3	Insulation of overhang windings.
4	Key of slot.
5	Insulating tubes.
6	Fastening of overhang windings.
7	Brush Leads.
8	Impregnate

<u>The insulation's will be also subdivided due to another criterion such as:</u>

1. Origin	Natural or synthetic.
2. Chemical composition	Organic of inorganic.
3. State	Gaseous, liquid, solid (crystal, amorphous).
4. Thermal stability	Y, A, E, B, F, H, C.

In addition to the above criterion, the solid insulation's, which are used in electrical machines, must have also suitable electrical, mechanical, thermal, chemical and physical characteristics.

Classes of insulating system:

Normally the insulation, which insulates the machine electrically have bad thermal conducting characteristic. The permissible temperature rise of an electrical machine depends upon the thermal stability of the used insulating materials. There is a maximum permissible steady state temperature for each type of insulating materials. The service life of an electrical machine depends upon the compliance with permissible temperature.

The following table shows the classes of insulation's and the different materials as well as the maximum permissible temperature of each class.

Table (5): Class of insulating materials:

Class	Maximum permissible steady state temperature.	Insulating materials.
Y	90 [°c]	Cotton, natural silk, synthetic wool, rayon (artificial silk), polyamide, fiber, paper, presspan, Vulcanized fiber, wood, formaldehyde synthetic resin
A	105 [°c]	Like those of class Y but after treatment with natural or synthetic resin, varnish, shellac etc, wire enamel, which is of resin-oil base.
E	120[°c]	Wire enamel of different sorts, molded (pressed) parts with filling material of cellulose laminated paper.
B	130[°c]	Glass fiber, asbestos, products of, mica, molded (pressed) parts with filling material.
F	155[°c]	Glass fiber, asbestos, products of mica, wire enamel with base of amide polyester.
H	180[°c]	Glass fiber, asbestos treated with silicone-resin, silicone-rubber.
C	Over 180[°c]	Mica, porcelain, ceramic substances, glass, quartz.

Testing of DC Generator

2.1 No – Load operating case:

2.1.1 No – Load (Magnetization) curve:

It represents the relation between the induced voltage in armature windings (E) and the exciting current (I_e) for non loaded dc machine (I_a=0) under constant drive speed (n).

- The exciting current will be increased in steps and the corresponding induced voltage (E = V_0) will be noted. The test is carried out till a value of voltage little more than the normal value (1, 2 V_N).
- The exciting current will be reduced also in steps till zero and the corresponding voltage will also be noted.

The test will be carried out on the different types of the dc machines as follows.

A) Separately excited dc generator

1 – Data of the testing machine (rating plate):

2 – Wiring diagram:

The terminals of the machine on the terminals plate are connected as shown in the wiring diagram.

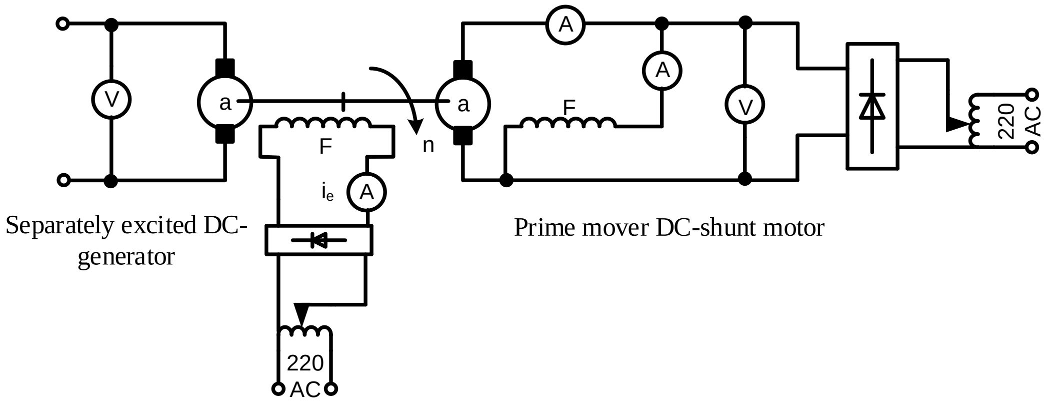


Fig. (2 – 1) Wiring diagram of separately excited dc generator for no- load test

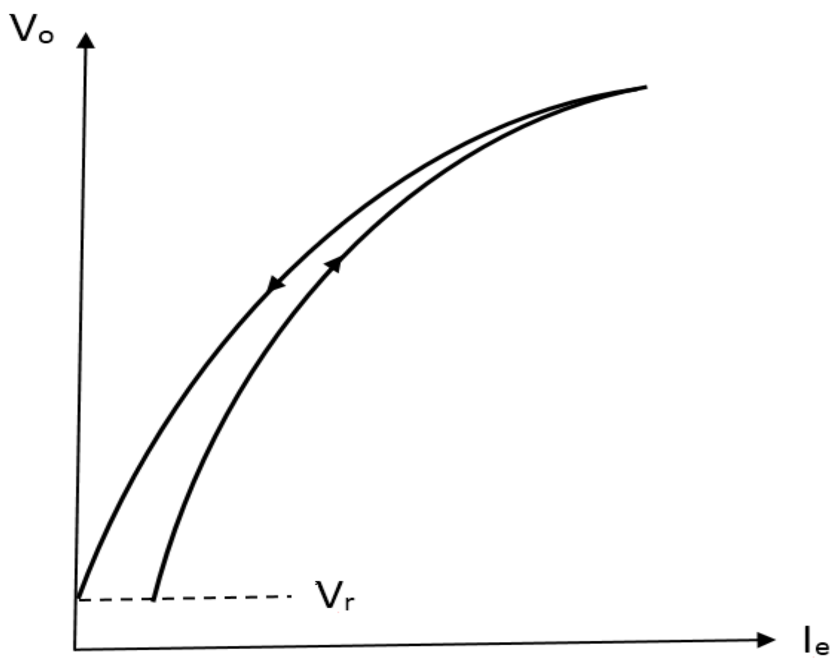
The readings of the measuring instruments are recorded in the following table

Table (1): For n = …………. r.p.m.

I_e [A]							
V_0 [v]							

I_e [A]							
V_0 [v]							

The (V_o – I_e) relation is as shown in the figure.



No-load characteristic (magnetization) curve of separately excited dc machine

From the figure

1 – The difference between both curves is due to the hysteresis of iron in magnetic circuit.

2 – At no excitation the induced voltage is due to rest magnet.

3 – The curves are not linear due to magnetic saturation.

The curves are drawn by the help of table (1) as shown in the following plate.

B) Series excited dc generator:

1 – Data of the testing machine (rating plate):

2 – Wiring diagram:

The terminals of the machine on the terminal plate are reconnected to become as a separately excited dc generator

The exciting current in this case is equal to its loading currents and the drive speed can be equal to the speed of shunt excited type of the same power size and must kept constant during the test.

The readings of the measuring instruments are recorded in the following table.

Table (2) for n = ……. r.p.m

I_e [A]							
V_0 [v]							

I_e [A]							
V_0 [v]							

No-load characteristic (magnetization) curve of series excited dc machine

The (V_o –I_e) elation is as shown in the figure (such like that one of the separately excited dc generator

The curves are drawn with the help of table (2) as shown in the following plate.

C) Shunt (self – excited) dc generator:

1 - Data of the testing machine (rating plate):

2 - Wiring diagram:

The terminals of the machine on the terminal plate are connected as shown in the wiring diagram.

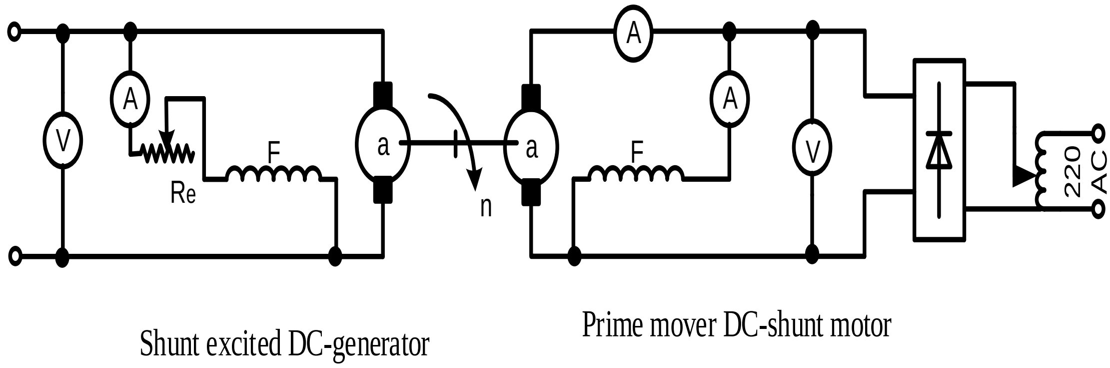
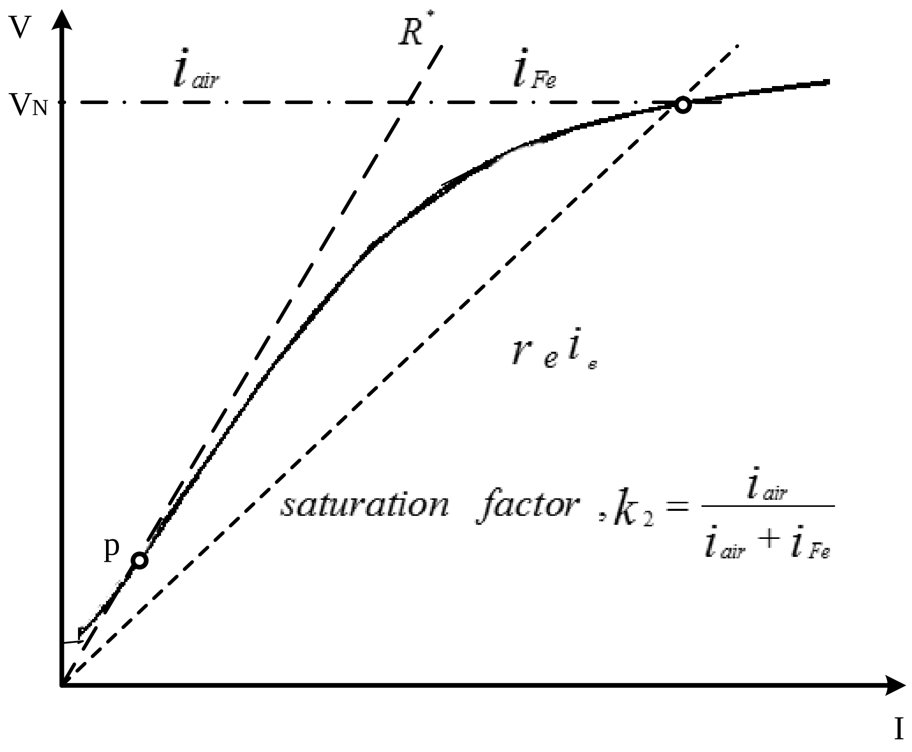


Fig. (2.2) Wiring diagram of shunt excited dc generator for no-load test

The value of the exciting current is adjusted in step by means of the variable resistance in the exciting circuit. The corresponding induced voltage is calculated as follows:

$E = V_0 – R_A I_e$

The ($E – I_e$) relation is as shown in the figure



The readings of the measuring instruments are recorded un the following table

Table (3) for n = ……… [1/min]

I_e [A]							
V_0 [v]							
I_e [A]							
V_0 [v]							

The curves are drown by the help of table (3) as shown in the following plate

from the figure it is to be noted that:

Point (p) represents the critical operating point on the magnetization curve and the line (R_eI_e) represents the critical resistance line. The no-load curve lies normally about 80 [%] of the total normal curve.

No-load characteristic (magnetization) curve of shunt excited dc machine and saturation factor

D) Compound excited dc generator:

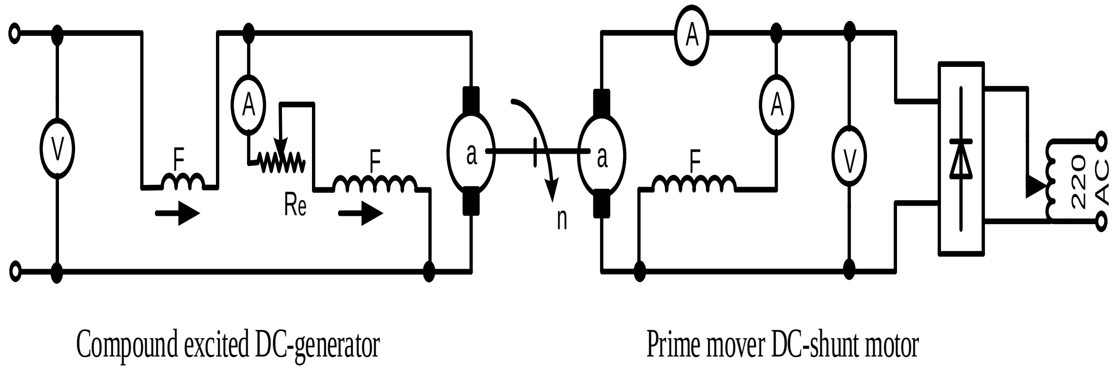
1 – Data of the testing machine: (rating plate):

A) Cumulative type:

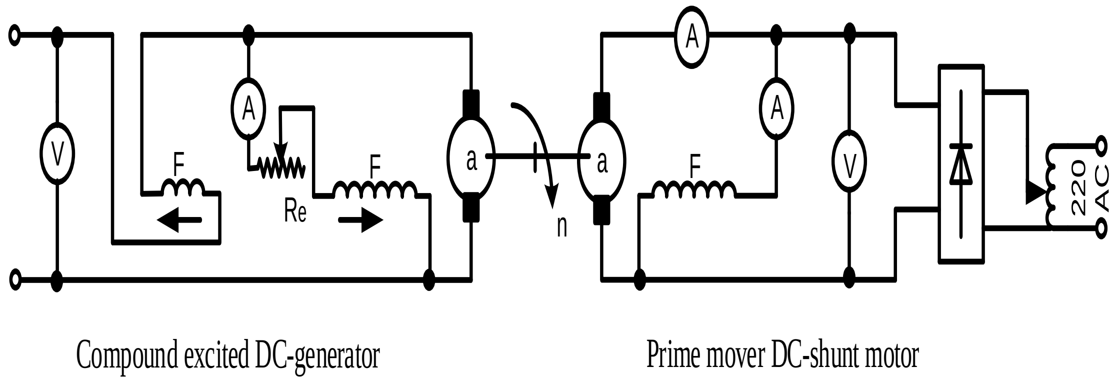
B) Differential type:

2 – Wiring diagram:

The terminals of the machine on the terminals plate are connected as shown in the wiring diagram.



(a)



(b)

Fig. (2-3) Wiring diagram of compound excited dc generator

a) Cumulative type b) Differential type

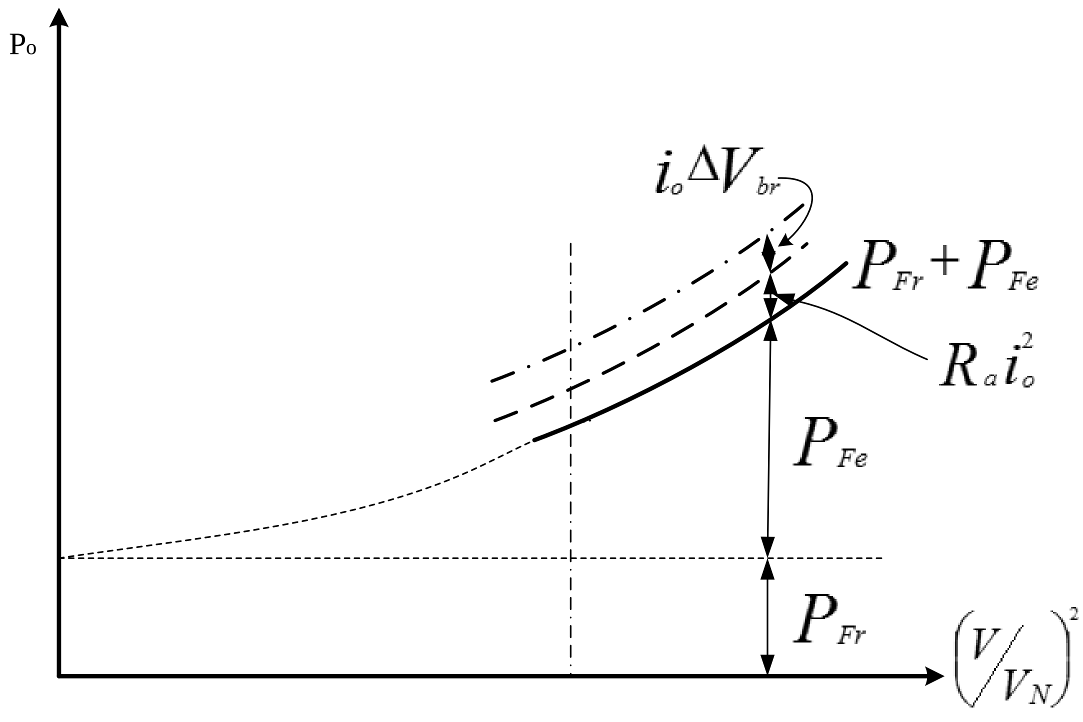
Both two types of this machine have the same magnetization curve of the shunt excited dc generator.

Measurements of the no- load power loss from no – load test:

1 – Separation of no-load power-losses:

Let the no – load test be carries out on a shunt excited dc motor. The test begins with a voltage equal to its nominal value and decreases gradually in steps till the speed is not more constant, then the test is stopped. The input power consist mainly from friction – and iron power – loss together with small percentage of cupper –loss and the power loss of the brushes. Location of power – loss versus voltage is indicated in the following figure.

Separation of power losses can be carried out by extra polation of the curves.



Separation of no-load power-losses

Both two power – loss – friction and iron can be defined in details as follows.

A) Friction Power loss:

It depends mainly on the temperature rise. It consists of:

1 – Friction power loss in bearing

2 – Friction power loss between brushes and commutator surface.

3 – Friction power loss between armature surface and cooling medium in the air-gap.

Measurements of friction power-loss:

The dc machine is driven externally by a drive motor. The machine is free from currents and its consumed power represents the total power–loss.

The test is repeated but without brushes and the corresponding power losses of brushes can be estimated.

B) Iron – Power – loss

It consists from:

1 – Hysteresis power-loss $P_{hys} \sim n$, $P_{hys} \sim B^{1,6}$

2 – Eddy – currents power-loss $P_{edd} \sim n^2$, $P_{edd} \sim B^2$

Loading of dc machines:

Generators:

A – Separately excited dc generator:

1 – Data of the tested machine: (rating plate)

2 – Wiring diagram:

Terminals of the machine on the terminals plate are connected as shown in the wiring diagram.

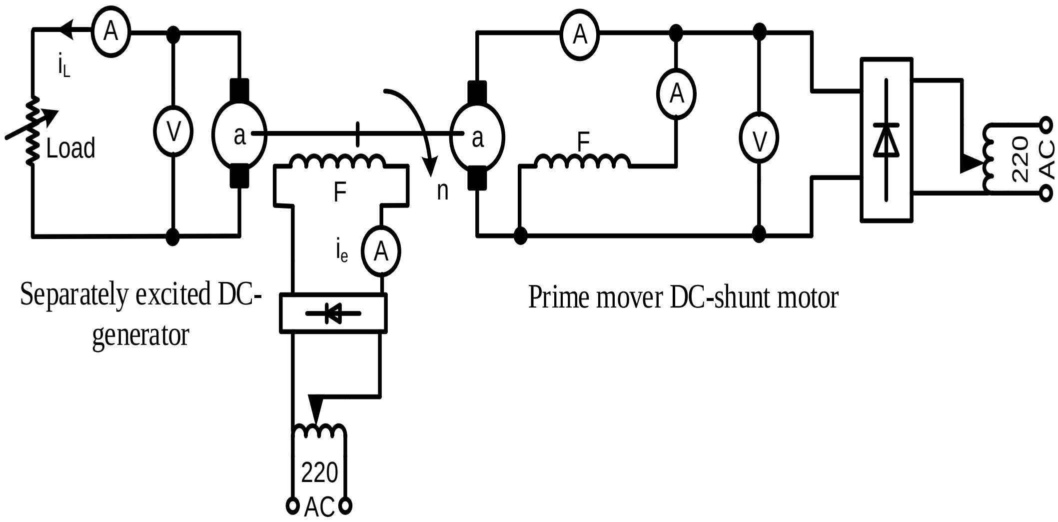


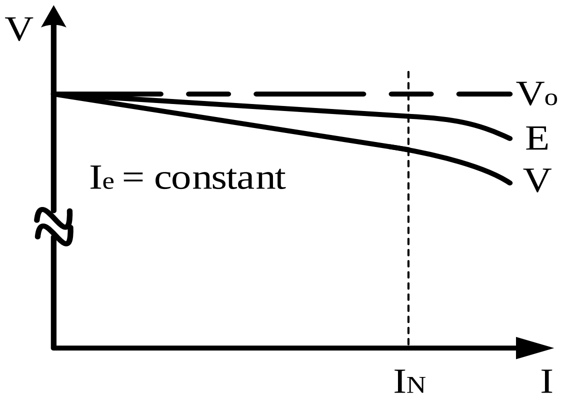
Fig. (2-4) Wiring diagram of separately excited dc generator under loading

The machine is driven externally by a suitable drive motor with constant speed (nominal speed n_N) and it is excited with a constant exciting current (nominal excitation I_{eN}). The terminal voltage (V) and current are recorded in the following table

Table (4)

I [A]							
V [v]							

The external characteristic curve (V = f (I)) is shown in the figure. By calculating the copper power-loss of armature circuit ($I_A^2 R_A$) at every measuring point, the corresponding armature reaction can be also calculated and the internal characteristic curve (E = f (I)) can be also drawn as shown in the following plate.



External characteristic of separately excited dc generator

External characteristic curve of separately excited dc generator

B) Shunt excited dc generator:

1 – Data of the tested machine

2 – Wiring diagram:

The terminals of the machine on the terminal plate are connected as shown in the wiring diagram.

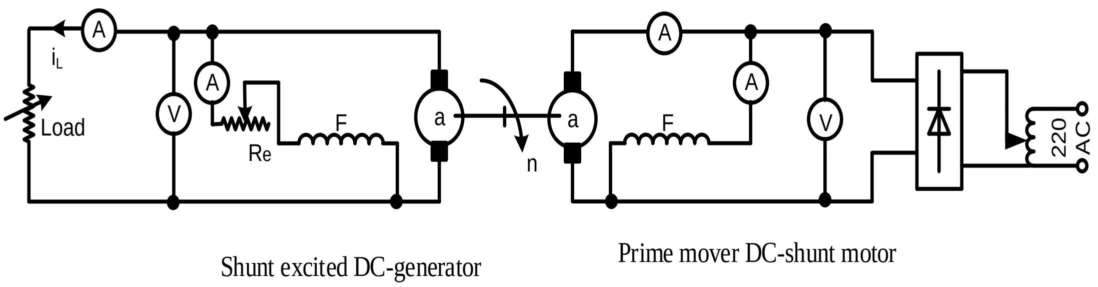


Fig. (2-5) wiring diagram of shunt excited dc generator under load

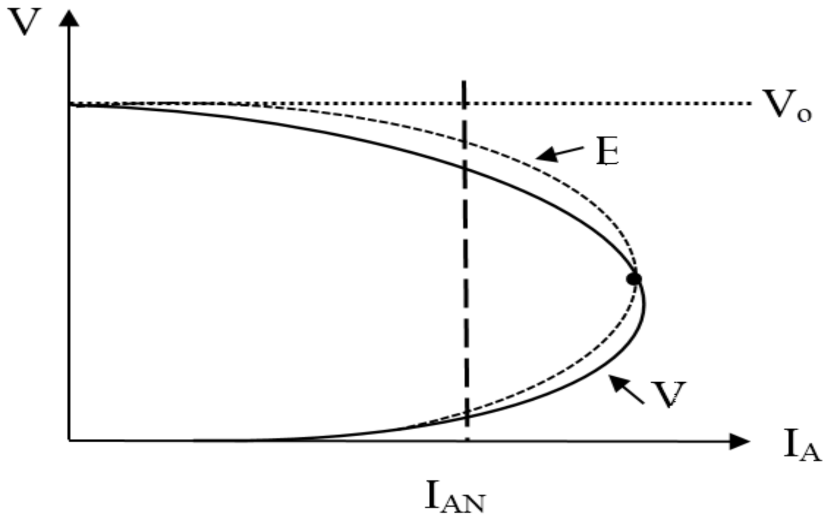
The generator is loaded gradually in steps under constant speed and excitation, the terminal voltage and the corresponding current are recorded in table (5) below.

Table (5)

I [A]							
V [v]							

The external characteristic curve is shown in the figure. Point (P) on the curve is the break – down point after which the machine becomes unstable. At V = 0 represents the short-circuit at which the short circuited current is about 10 [%] of its nominal value. The voltage here is due to the residual magnet in the iron core of the main poles of the machine.

It is to be noted that the drop of terminal voltage is due to copper – loss of armature, armature reaction and also due to the decreasing excited voltage which in turn decreases the main magnetic field.



By the help of measuring quantities, the external characteristic curve can be drawn in the following plate

C) Series excited generator:

Data of tested machine:

Wiring diagram

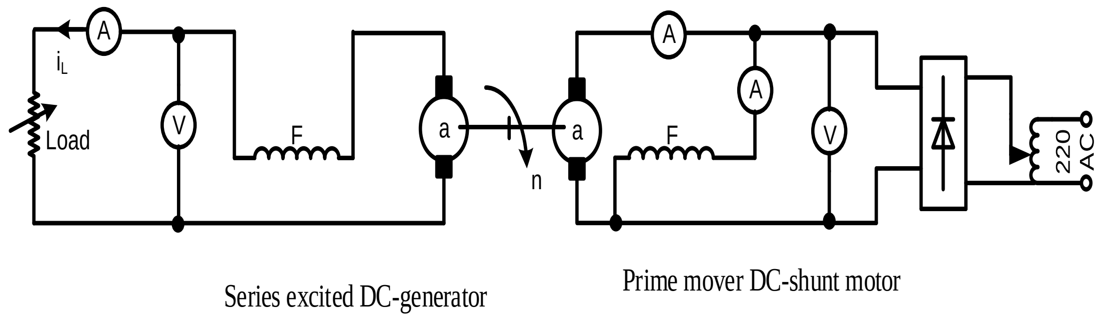


Fig. (2-6) Wiring diagram of series excited dc generator under load.

The test can be carried out by the following manner:

The load resistance must be smaller than the resistance R^* shown in the figure and the load resistance (R_L) will be decreased gradually, the terminal voltage and the current will also be increased gradually till a value after which the voltage stay nearly constant mean while the current

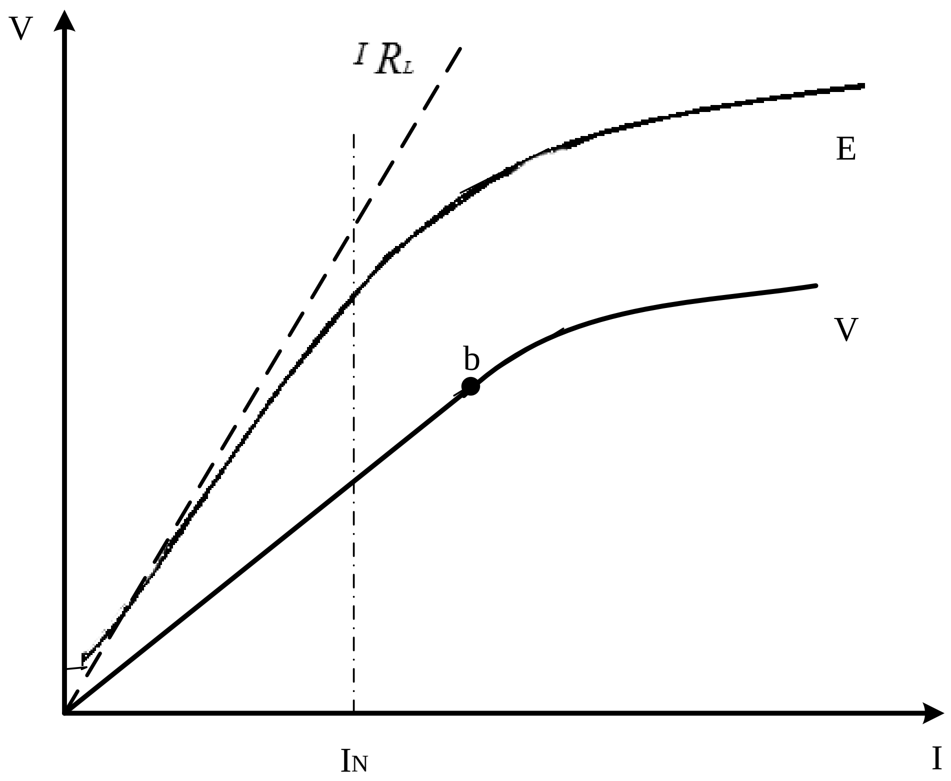
External characteristic curve of shunt excited dc generator increases till point (b) there after the voltage decrease mean while the current continues its increase.

The loading current and the corresponding voltage will be recorded in the following table.

Table (6):

I [A]							
V [v]							

The external characteristic is as shown in the following figure.



The curves are drawn by the help of table (6) as shown in the following plate:

D) Compound excited dc generator

1 – Data of tested machines:

Cumulative type:

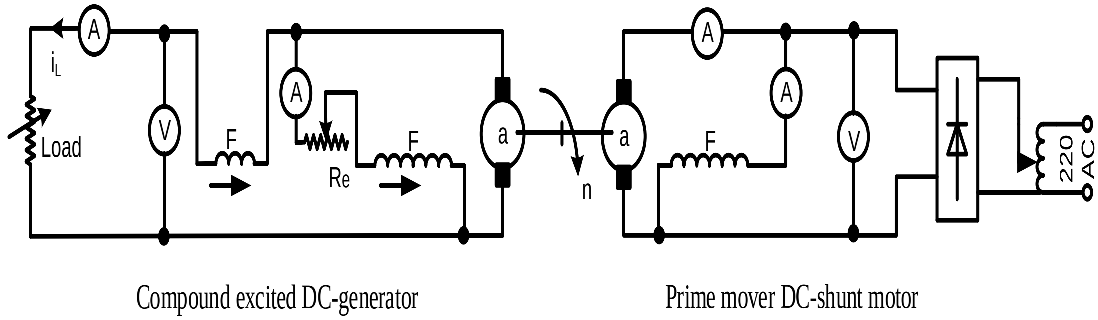
The rating plate:

External characteristic curve of series excited dc generator

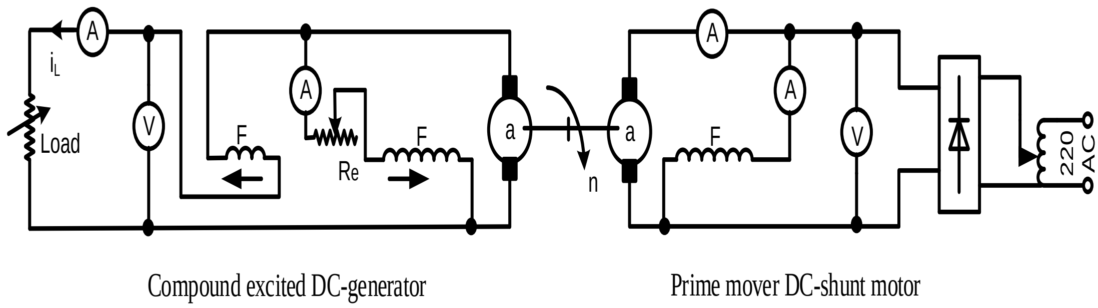
Differential type:

The rating plate:

2 – Wiring diagram:



(a)



(b)

Fig. (2-7): Wiring diagram of compound excited dc generator under load

a) Commutative type b) Differential type

The machine is driven by an external drive motor with constant speed, normally nominal speed (n_N). The load is increased and in steps by the loading resistance (R_L) till a load current of about 1, 2 its nominal value, there after the load is decreases again gradually and also in steps till no-load. The test is carried out for cumulative-as well as for differential type. The loading currents and the corresponding voltages will be recorded in the following tables.

Table (7)

1) Cumulative compound type:

I [A]							
V [v]							

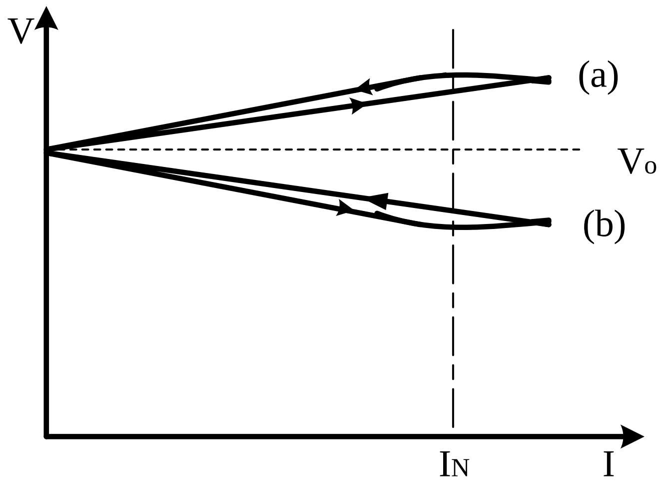
I [A]							
V [v]							

2 – Differential compound type:

I [A]							
V [v]							

I [A]							
V [v]							

The external characteristic curves are shown in the following figure. For cumulative type, the voltage under loading can be greater than under no-load.



External characteristic of compound excited dc generator

a) Differential type b) cumulative type

With the help of the measuring quantities in table (7), the external characteristic curve can be drawn for the compound excited dc generator for both types.

External characteristic curves of compound excited dc generator

a) Differential b) Cumulative

3) Testing of dc motors:

Mechanical characteristic (T – n) curve:

The different types of the dc motors will be tested by load test to see how the different types of dc motors having different types of mechanical characteristic curves. In practice where an electric drive motor is needed to be used as mechanical power supply in an elctro-mechanical project, the suitable motor can easy be chosen. In this test the motor is mechanically loaded gradually and in steps and the corresponding operating parameters such as speed, current, electrical input power, developed torque, mechanical output power as well as the rate of temperature rise during the test are recorded.

The tested motor are to be loaded, normally by a brake. There are different types of brakes such as electrical or hydraulic type. Choose of the type of brake is according to the power of the tested motor as well as its speed. Mechanical brakes are only used for small power motors.

Loading test of separately excited dc motor:

1 – Data of the tested motor (rating plate):

2 – Wiring diagram:

The terminals of the machine on the terminals plate are connected as shown in the wiring diagram.

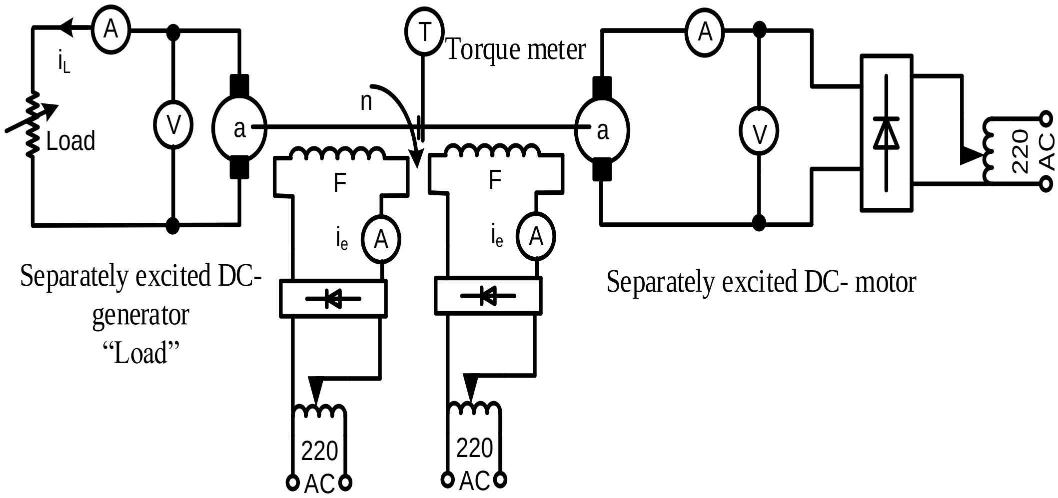


Fig. (2-8): Wiring diagram of separately excited dc motor for load test

The armature of the motor is supplied from constant dc supply voltage and the exciting terminal are also connected across another constant dc supply. The motor is loaded by means of the (eddy – current) brake gradually from no-lad and in steps. The measuring values such as current, speed and the weight on the Penndel arm of the brake are to be recorded in the following table.

Table: (   )

I [A]							
V [v]							
F [N]							
T [Nm]							
P_{out} [w]							
P_{in} [w]							
η [%]							

With:

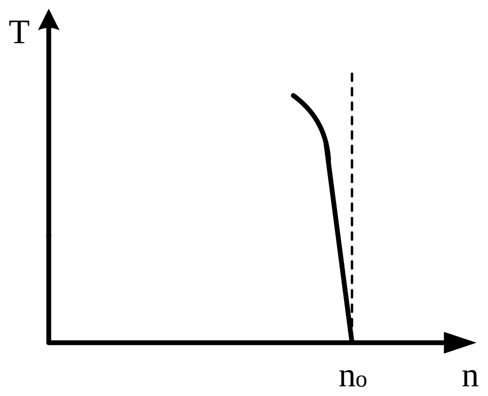
$T = r\,F$ [Nm]

$P_{out} = \omega\ T = \frac{2IInT}{60}$ [W]

$\eta = P_{out} / P_{in}\ 100$

No : natural speed in [1/min]

The (T-n) curve is as shown in the following figure



With the help of the measuring quantities, the load characteristic curves can be drawn as shown in the following plate.

Mechanical characteristic (T-n) curve of separately excited dc motor.

2 – Loading of shunt excited motor:

1 – Data of the tested motor (rating plate):

2 – Wiring diagram:

The terminals of the machine on the terminals plate are connected as shown in the wiring diagram.

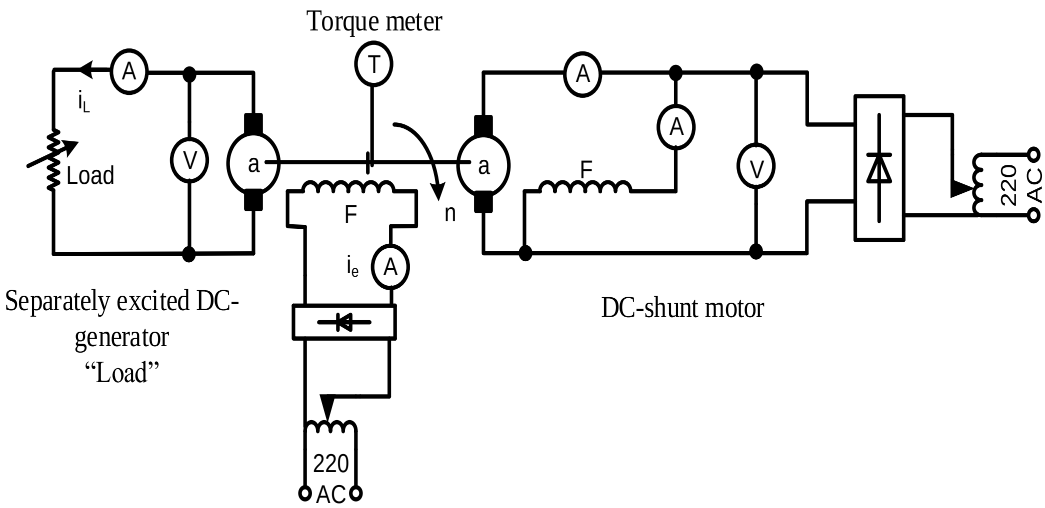


Fig. (2-9) Wiring diagram of shunt excited dc motor under load

The test is carried out as for the separately excited type and the measuring quantities are also be recorded in the following table.

Table (9):

I [A]							
V [v]							
F [N]							
T [Nm]							
P_{out} [w]							
P_{in} [w]							
η [%]							

The (T – n) curve is like that of separately excited motor and the loading characteristic curves are similar to those of separately excited type.

Mechanical characteristic (T-n) curve of shunt excited dc motor.

3 – Loading of series excited dc motor:

1 – Data of tested motor (rating plate):

2 – Wiring diagram:

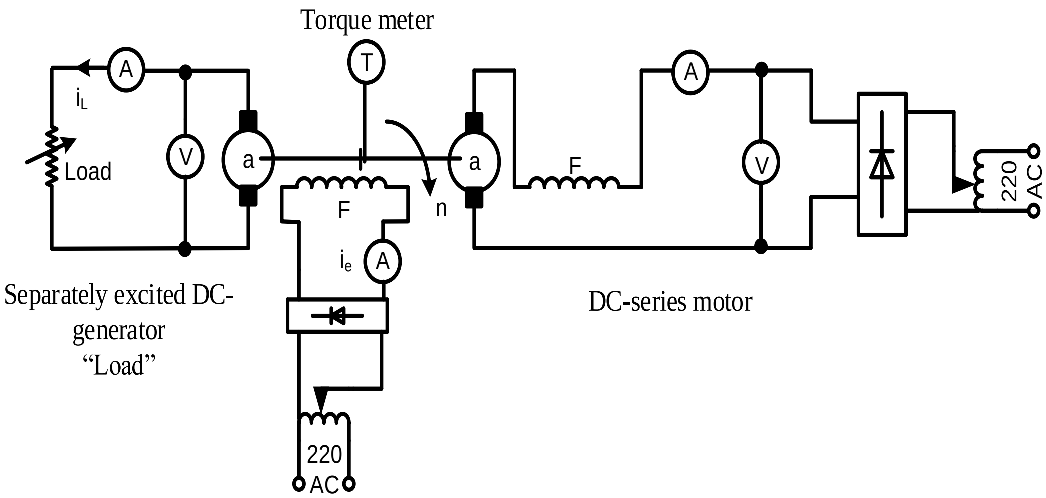
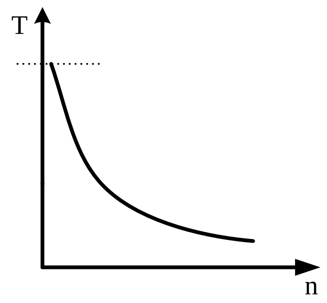


Fig. (2-10) Wiring diagram of series excited motor under load.

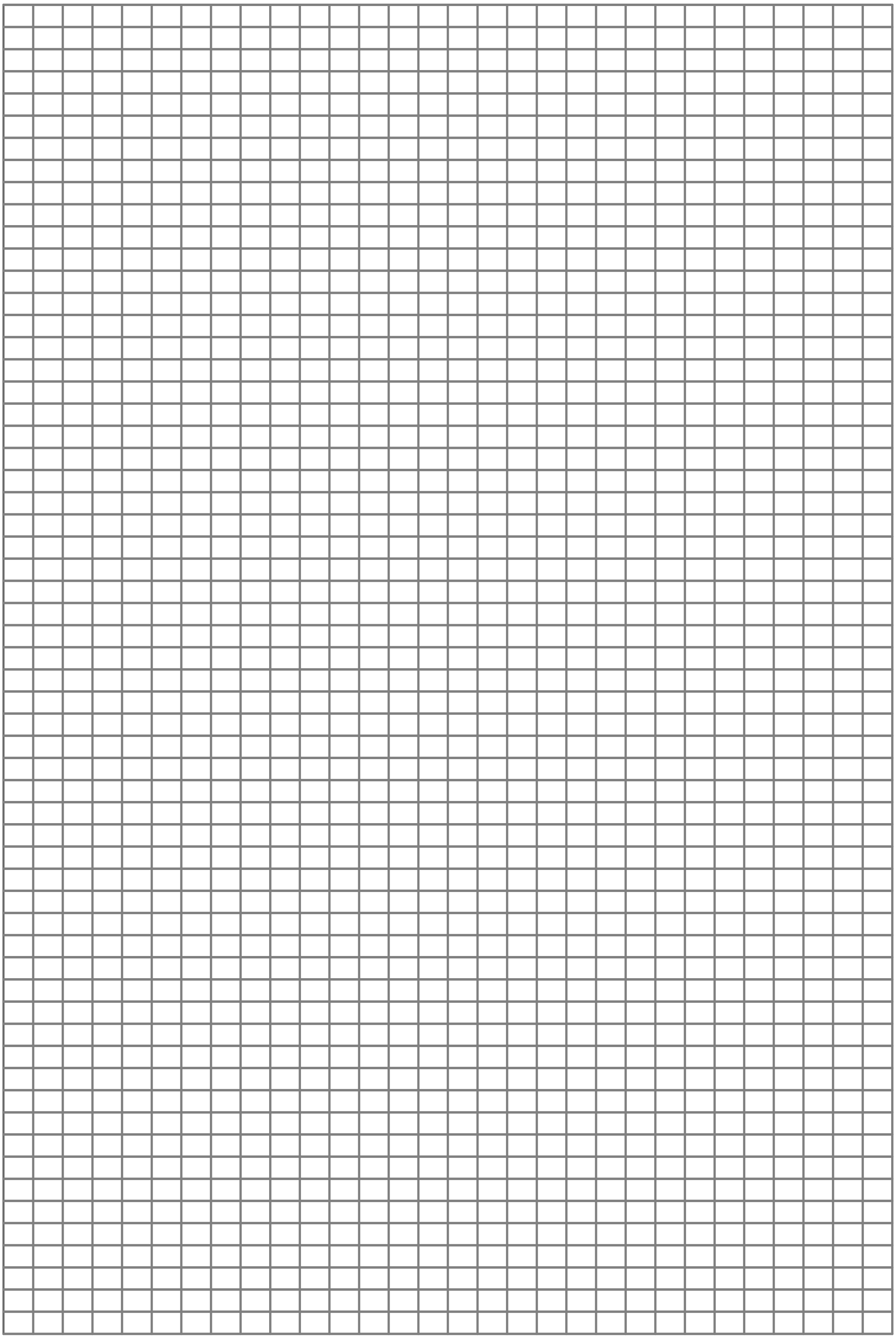
The motor is supplied from a constant dc supply voltage of nominal operating value. The motor is firstly supplied with maximum braking torque and there after the load is decreased slowly and in steps till a speed within safely value. The measuring quantities are recorded in the following table.

I [A]							
V [v]							
F [N]							
T [Nm]							
P_{out} [w]							
P_{in} [w]							
η [%]							

The (T-n) curve in shown in the following figure.



With the help of the measuring quantities the load characteristic curves can be drawn as shown in the following plate



Mechanical characteristic (T-n) curve of series excited dc motor.

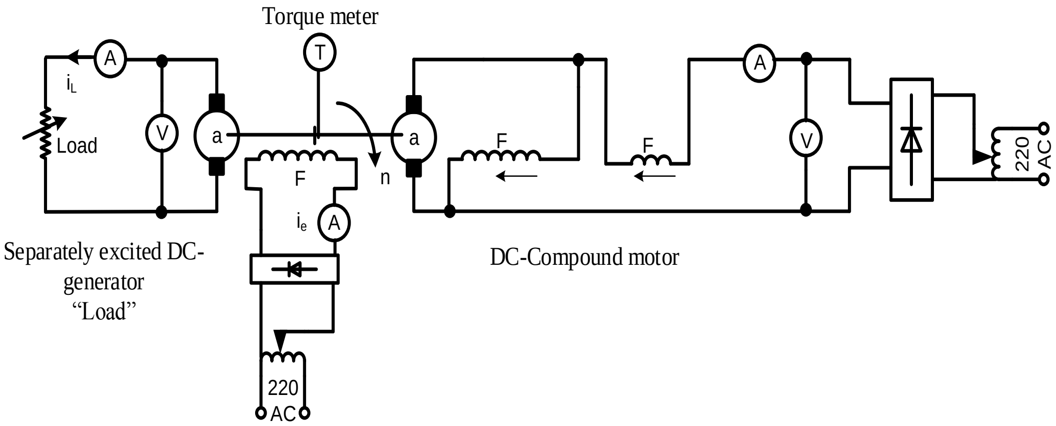
4 – Loading of compound excited dc motor:

1 – Data of tested motor (rating plate):

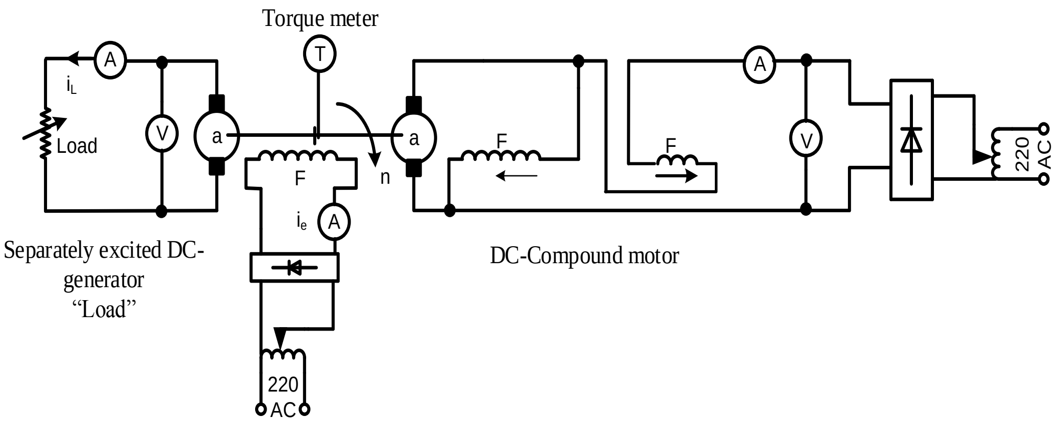
Cumulative type:

Differential type:

2 – Wiring diagram:



(a)



(b)

Fig. (2-11) Wiring diagram of compound excited dc motor under load

A) Cumulative B) differential

The loading test is carried out as for shunt excited dc motor as declared before and the measuring quantities are recorded in the following table.

Table (11)

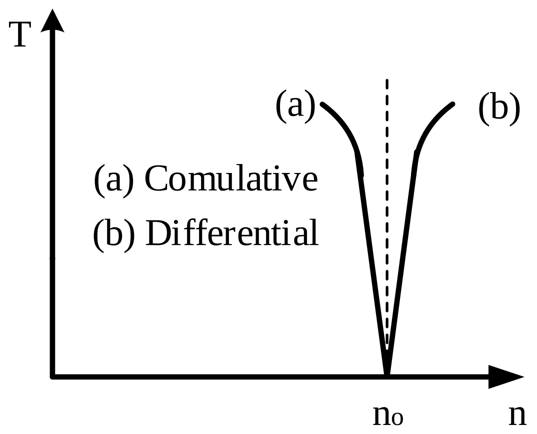
A) Cumulative

I [A]							
V [v]							
F [N]							
T [Nm]							
P_{out} [w]							
P_{in} [w]							
η [%]							

B) Differential

I [A]							
V [v]							
F [N]							
T [Nm]							
P_{out} [w]							
P_{in} [w]							
η [%]							

The (T-n) curves of both types of compound excited dc motors are as shown in the following figure.



Mechanical characteristic (T-n) curve of compound excited dc motor.

a) Differential b) Commulative

By the help of the measurable quantities, the characteristic performance of both types of the compound dc motor will be drawn in the following table.

Efficiency

1 – Direct method estimation: $\eta = \frac{P_{out}}{P_{on}} 100$

2 – Indirect method estimation:

For generator: $$\eta = (1 - \frac{\Sigma P_{loss}}{P_{out} + \Sigma P_{loss}})100$$

For motor: $$\eta = (1 - \frac{\Sigma P_{loss}}{P_{in}})100$$

Where ΣP_{loss} = $P_{Fr} + P_{Fe} + P_{cu} + P_{add}$

The additional power loss is about 0.5 [%] from the nominal output power for machines with compensating windings and about 1 [%] for machines without compensating windings

3 – Back to back method:

It is suitable for small – and extra powerful machines. In this method, two identical dc machines are coupled with one another. One of both machines operates as a motor and the other as a generator. Electrical connection of both machines is for motor and the other is for generator. The induced electrical power of the generator is supplied to the other machine (motor). Each machine can be operated with nearly full load. The sum of power – losses of both machines are fed externally from an external supply, by this method both machines can be full – loaded. The total power losses can be fed electrically or mechanically through an auxiliary motor coupled with the machine set through their common shaft, or it can be supplied with both two methods, it depends on the chosen type of connection,.

Three Phase
Induction Motor
Tests

1. RESISTANCE MEASUREMENT

a) Stator resistance measutrment

To measure the stator resistanse

1- connect the wirring diagram Fig.(1).

2- Apply a dc voltage of 2V and record the ammeter reading.

3- Vary the variable resistance, and repeat step (2).

4- Repeat step (3), and record the measuring data.

5- Plot the relation between the volage and current

6- Calculate the slop of the curve to find the resistance.

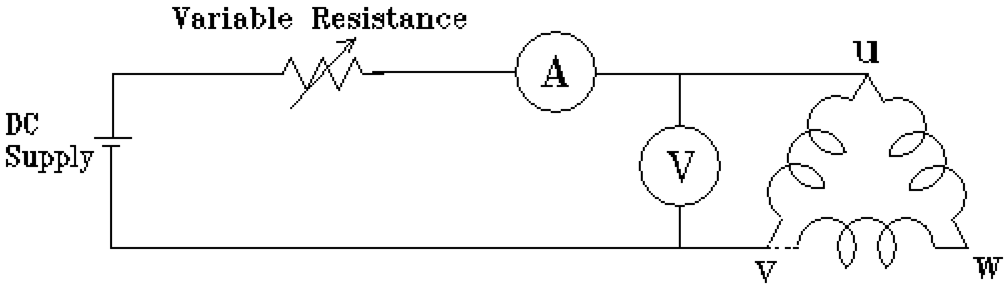


Fig.(1): Wirring diagram of resistance measurement

Vdc [V]						
I [A]						

$R_{ph} = 3/2\ R_m$ (delta connection)

where; R_{ph} = phase resistance Ω and R_m = measured resistance Ω

Note; take into account the skin effect and the heat effect so

$R_{75^\circ} = R_{25^\circ}\left[1+\alpha(75^\circ - 25^\circ)\right]$* Skin effect

Where α := the heat coeffient of the copper

➢ The Stator Phase Resistance = ……………[Ω]

b) Rotor resistance measutrment

The same procedure as stator resistance measurment.

Vdc [V]						
I [A]						

➢ The Rotor Phase Resistance = ……………[Ω]

2. Three-phase Induction Motor

No-Load Test

2.1. Objectives

a) No-load characteristics (relationship between the applied voltages, rotor current, stator current, input power and power factor).

b) No-load parameters of the motor equivalent circuit (R_m, X_m)

c) Rated iron losses and friction & windage losses.

2.2. Introduction

In this experiment it is intended to study the effect of variation of applied voltage on the input power, power factor, stator and rotor currents of a three-phase induction motor running at no-load. The effects of changing the applied voltage on the above-mentioned quantities are explained as follows:

2.2.1 Rotor Current

The motor torque is proportional to air-gap flux and rotor current. The air-gap flux-is produced by the applied stator voltage. Therefore, motor torque is proportional to applied voltage and rotor current. For a constant torque, the rotor current will increase if the applied voltage is reduced. Thus, the rotor current varies in inverse proportion to the applied stator voltage.

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2.2.2 Stator Current

As applied voltage is increased, stator current rises gradually on account of the increase in magnetizing current required to reduce the stator flux. The component of the stator current, which provides the ampere-turns balancing the rotor ampere-turns, will steadily moderate as the rotor current decreases with the increase in rotor speed. The increase in the magnetizing component is, however, more than sufficient to balance this decrease. At very low voltages the in9uction is so low that almost the whole of the stator current is employed in balancing the rotor current. At normal voltage the rotor current requires only a small proportion of the stator current to balance them. The higher saturation of the magnetic circuit requires a much stronger magnetization current to maintain the air-gap flux.

2.2.3 Power Factor

As explained above, the magnetizing component of the stator current becomes larger as the voltage increases. Thus, there is a continuous increase in the power factor angle and hence a fall in power factor.

Frictional losses of the motor are practically constant as the speed does not change with voltage. The losses component of the stator current is due to frictional and iron losses. As voltage is increased, iron loss component and magnetizing component will increase. The increase in magnetizing current will be more than the increase in iron loss component of stator current. Thus there will be' a fall in power factor as the voltage is increased.

2.2.4 Input Power

No-load input power is spent in overcoming both iron and frictional losses. As stated above, frictional losses are nearly constant at all excitation voltage levels (until the motor speed falls rapidly), while the iron losses continue to increase with the increase in the applied voltage.

2.3. Experimental Procedure

Table (1): Induction motor & DC generator system name-plate

DC Generator			
V_n 240 [V]	I_n 7.92 [A]	P_n 1.9 [kW]	N_n 1430 rpm
Excitation Separate			
V 110 [V]		I 0.91 [A]	
Three-Phase Slip-ring Induction Motor			
V_n 380/220 Y/Δ	I_n 7.4/12.7 [A]	P_n 3 [kW]	N_n 1400 rpm
F 50 c/sec		Cos φ 0.77	
Rotor	V_n 95 [V]		I_n 20.5 [A]
Three- phase Tachogenerator			
V_n Y 30 [V]	I_n 0.115 [A]	P_n 6 [VA]	F 66 c/sec
At N 1000 rpm			

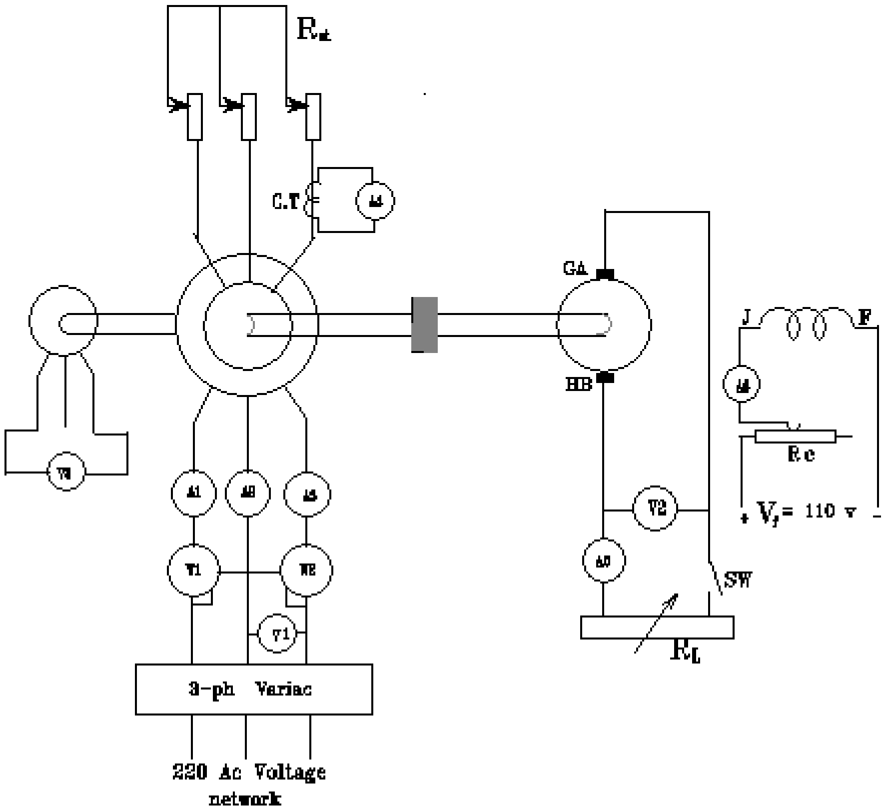


Fig.(2):Connection diagram of 3-ph slip-ring induction motor

Table (2): Apparatus ratings

R_{st}	Starting resistance for the rotor of slip-ring IM
R_c	Field controlled resistance for the dc generator
R_l	Load resistance 2kW
A_1, A_2, A_3	0-15-30 A $\simeq$ Ammeter
A_4	0-1-5 A $\simeq$ Ammeter
A_5	0-2-10 A $=$ Ammeter
A_6	0-1-5 A $\simeq$ Ammeter
C.T	25/5 A current transformer
V_1	0-300 V $\simeq$ Voltameter
V_2	0-240 V $=$ Voltameter
V_3	0-50 V $\simeq$ Voltameter
W_1, W_2	0-10-20 A / 0-60-120-240 V Wattmeters

2.3.1 Determination of Stator iron and cupper losses

1- Connect the circuit as shown in Fig.(2).

2- Disconnect the starting resistance from the rotor terminals (open circuit of rotor terminals through moving iron voltmeter V_4 with range 0-100 V).

3- Keep the switch (SW) open in this test.

4- Start the results recording from 0 up-to 120% of stator rated voltage, Table (3)

Table (3): Results and calculations

Measured Data													
V_1 [V]	20	40	60	80	100	120	140	160	180	200	220	240	260
V_4 [V]													
I_1 [A]													
W_1													
W_2													
Calculated Data													
W_1+W_2													
P_{cu1}													
P_{iron}													

Where; $P_{iron} = W_1 + W_2 - P_{cu1}$ and $P_{cu1} = 3*(I_1)^2 * R_{ph}$

2.3.2 Determination of Friction& windage losses and equivalent circuit parameters

1- Connect the circuit as shown in Fig.(2).

2- Keep the switch (SW) open in this test.

3- Apply 20% of the motor rated voltage to the stator terminals. The motor will start rotating near to its rated speed. Increase the input voltage upto the rated voltage (220 V).

4- Start the results recording from 120% of stator rated voltage (220V) decreasing to 20% of the rated voltage, Table (4)

Table (4) Results and calculations

Measured Data													
V_1 [V]	260	240	220	200	180	160	140	120	100	80	60	40	20
I_o [A]													
I_4 [A]													
W_1													
W_2													
Calculated Data													
P_o [W]													
Cos φ													

$P_o = W_1 + W_2$ $\qquad$ $\text{Cos}\,\varphi = \dfrac{P_o}{\sqrt{3} * V_1 * I_o}$

2.4 Investigation of the Experimental Results:

1. Use the readings recorded at the motor rated voltage (V_o, I_o, P_o) to calculate the no-load parameters of the equivalent circuit R_m and X_m. These parameters can be obtained as follows; (*all the values are per phase*)

$$\phi_o = \text{Cos}^{-1}\frac{P_o}{V_o I_o}$$

$$I_{oa} = I_o \text{Cos}\,\phi_o$$

$$I_{o\mu} = I_o \text{Sin}\,\phi_o$$

$$R_m = \frac{V_o}{I_{oa}}$$

$$X_m = \frac{V_o}{I_\mu}$$

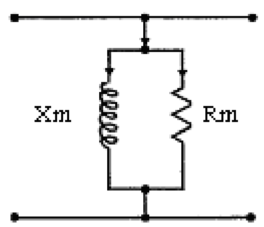


Fig. (3): The no-load equivalent circuit

1. Plot I_o, I_4, P_o and Cosφ_o as a function of the applied phase voltage V_o.
2. Also, plot the relationship between V_1 and V_4 to find the transformation ratio.
3. Calculate the rated iron losses (P_{iron}) at the rated voltage from Table (1).
4. Calculate the friction & windage losses at the rated voltage from Table (2) as follows;

$P_{f\&w} = P_o - P_{iron} - P_{cu1}$, then divide this value by two to get the friction & windage losses of each machine (IM and DC gen.)

2.5. Discussions

Answer the following questions in your report:

1. From the power input curve determine the value of friction and windage loss. State why friction and windage loss for an induction motor remains approximately constant with change of stator voltage.
2. Express the no-load stator current corresponding to rated stator voltage as a percentage of rated full-load current.
3. Explain why the no-load current of an induction motor is much higher than that of the transformer of the same rating.
4. The power factor of an induction motor decreases as the applied voltage is increased. Explain this with help of phase diagram.
5. An induction motor picks up its rated speed at about 25 to 30% of rated input voltage. Explain why it is necessary to apply more voltage than 25 to 30% of the rated voltage.

3. Three-phase Induction Motor

Locked -rotor Test

3.1. Objectives

a) Locked-rotor characteristics (relationship between the applied voltages, rotor current, stator current, input power and power factor).

b) Short-circuit parameters of the motor equivalent circuit (R_{eq1}, X_{eq1})

c) Rated copper losses.

.

3.2. Introduction

This experiment can be performed on either three-phase slip-ring or squirrel cage induction motors with its rotor is not allowed to rotate. When the rotor is blocked, only a small voltage can be applied to the stator terminals to allow up to normal fullload current to flodv through the stator windings. The iron losses will be very small as. that for low voltage the magnetization current will be low. The power taken by the motor, when the rotor is locked, is therefore, almost entirely due to copper losses. With the increase in the applied voltage the losses will increase as the square of the current. Also, the stator current will increase in proportion to the rotor current, as in the transformer, in order to balance the rotor current.

3.3. Experimental Procedure

1- Connect the circuit as shown in Fig.(2).

2- Keep the switch (SW) open in this test.

3- Prevent the rotor from rotation (Locked- the rotor)

4- Start the results recording from 0 up-to 120% stator rated current, Table (5)

Table (5): Results and calculations

Measured Data							
I_{SC} [A]	2	4	6	8	10	12	14
I_4 [A]							
V_{SC} [V]							
W_1 [W]							
W_2 [W]							
Calculated Data							
P_{SC} [W]							
Cos φ_{SC}							

Where; $P_{SC} = W_1 + W_2$ and $\cos\varphi_{SC} = \frac{P_{SC}}{\sqrt{3} * V_{SC} * I_{SC}}$

3.4 Investigation of the Experimental Results:

1- the readings recorded at **the motor rated current** (V_{SC}, I_{SC}, P_{SC}) to calculate the short-circuit parameters of the equivalent circuit R_{eq1} and X_{eq1}. These parameters can be obtained as follows;

$$R_{SC} = \frac{P_{SC}}{I_{SC}^2}$$

$$Z_{SC} = \frac{V_{SC}}{I_{SC}}$$

$$X_{SC} = \sqrt{Z_{SC}^2 - R_{SC}^2}$$

$$R_1 = R'_{20} = \frac{R_{SC}}{2}$$

$$X_1 = X'_{20} = \frac{X_{SC}}{2}$$

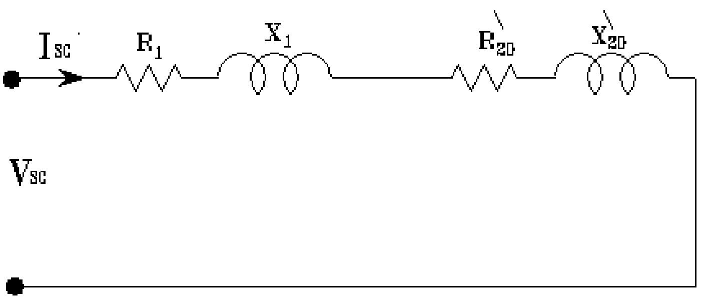


Fig.(4): The locked-rotor equivalent circuit

2. Plot I_{SC}, I_4, P_{SC} and Cosφ_{SC} as a function of the applied phase voltage V_{SC}.

3. assigned the numerical values of all parameters on the equivalent circuit Fig.(5).

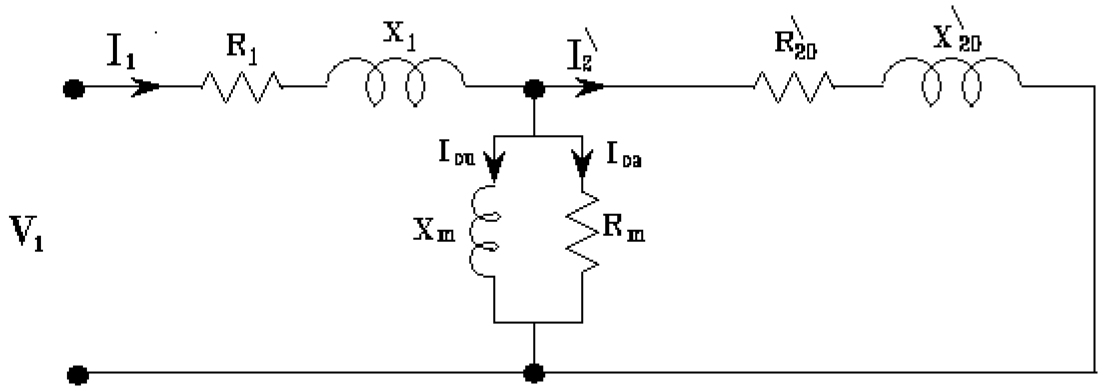


Fig.(5): Induction motor equivalent circuit

5. Draw the circle diagram of the motor as shown in Fig.(6).

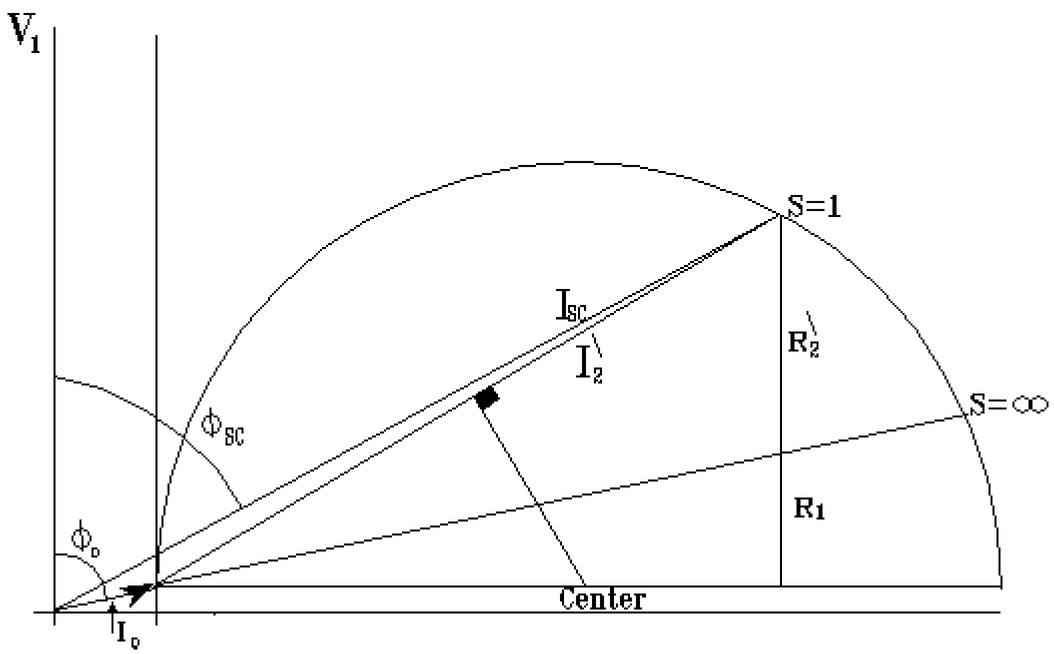


Fig.(6): Induction motor circle digram.

3.5. Discussions

Answer the following questions in your report:

1- Explain why the input power is nearly equal to copper losses at locked-rotor condition.

2- Show how to calculate torque, slip and efficiency from the circle diagram at the following condition:

a) stand-still b) rated load c)max. power d) max. torque

e) max. power factor

4. Induction Motor Load Test

4.1.Objective

To determine how the speed, efficiency, power factor, stator current, torque and slip of an induction motor vary with the load.

4.2. Introduction

The induction motor can be loaded either by applying a brake on its shaft or by loading a do generator of known efficiency. In this experiment an electromagnetic brake is used for the load test. The effects of applying a load on the motor behavior are discussed as follows:

4.2.1 Speed

At no !oad the speed of the induction motor is slightly below the synchronous speed. As the load is increased the rotor speed is reduced. The rotor emf and hence the rotor current increase also with the load to produce the required torque.

4.2.2 Slip

Slip is expressed as the difference in the rotor speed relative to that of the rotating magnetic field which rotates at synchronous speed. Slip is expressed as a percentage of the synchronous speed thus:

$$s = \frac{N_s - H_r}{N_s} \times 100$$

where N_s and N_r are the synchronous and rotor speeds in rpm respectively., and,

$$N_s = \frac{120f}{2P}$$

Therefore, if **the supply frequency.(t) and** the number of poles (2P) are constant, then . the synchronous speed Ns is constant for a particular motor. Thus with increase in the load applied to the motor, the slip will be increase.

4.2.3 Stator Current

The current drawn by the stator is determined by the vector sum of two components. One component is the magnetizing current required to maintain the rotating magnetic field. The second i component produces a field, which is equal and opposite to that formed by the rotor current. Since the rotor current increases with the load, the stator current will therefore, increase with the load.

4.2.4 Power Factor

Power factor of an induction motor on no-load is very low because of the high value of the magnetization current. With load the power factor increases because the power component of the current is increased. Low power factor operation is one of the disadvantages an induction motor. An induction motor draws a heavy amount of magnetization current due to presence of air-gap between the stator and rotor. To reduce the magnetization current, the air-gap is kept as small as possible. It is therefore; usual to find the air-gap of an induction motors smaller than any other type of electrical machines.

4.2.5 Torque

The efficiency of the induction motor depends on the output power and the total losses of the motor;

$$\text{Efficiency} = \frac{\text{Output}}{\text{Output} + \text{losses}}$$

The losses of the induction motor are divided into three components;

1. Copper losses in the stator and rotor windings,
2. Iron losses, and
3. 3. Friction and windage losses.

The stator and rotor copper losses increase as the square of current. The iron loss in the stator is proportional to stator'flux dens ity.and supply frequency: The strength of the stator field is constant **at** all loads and hence the stator iron loss is almost constant with the load. The iron losses in the rotor is very small as the frequency of the rotor current is small and therefore**,** iron loss in the rotor may be neglected as compared to the stator iron loss. Thus the iron loss is independent of load. As the induction motor speed is almost constant with the load, friction and windage, losses also can be
assumed as constant. Therefore, the efficiency of an induction motor will increase with the load, however the curve would be dropping at very high loads.

4.2.6 Torque

As the speed of the induction motor is almost constant, torque will increase with increase in load.

4.3. Experimental Procedure

1- Connect the circuit as shown in Fig.(2), with switch (Sw) of the load is off . Adjust the field current of the dc generator till the generator rated voltage reached.

2- Start the motor by connecting the stator to the AC supply through the variac and the rotor terminals should be short-circuited.

3- Increase the applied voltage gradually upto the motor rated voltage

4- Record no-load speed, input power, stator current, rotor current and applied voltage.

5- Switch on the load switch (WS), and increase the load step by step upto 125% of the full load current and record the motor speed, input power, stator current and rotor current for each step keeping the applied voltage constant .

Table(6): Results and calculations

Measured Data													
V_1 [V]	Constant at the motor rated voltage (220 [V])												
I_1 [A]													
I_4 [A]													
W_1 [W]													
W_2 [W]													
Load Data													
N [rpm]													
I_5 [A]													
V_2 [V]													
Calculated Data													
P_{in} [W]													
s													
P_{out} [W]													
Cos φ													
P_g [W]													
T [kg.m]													
η %													

Where;

P_{in} = W_1+ W_2 [W], $s = \frac{N_s - H_r}{N_s} \times 100$, $\text{Cos}\,\varphi = \frac{P_{in}}{\sqrt{3} * I_{1L} * V_{1L}}$

$P_{out} = I_5 * V_2$, Efficiency $\eta = \frac{P_{out}}{P_{in}} \times 100$, Air gap power is: $P_g = \frac{3 * I_2^2 * R_2}{S}$

Induction motor torque is : $T = \frac{P_g}{2\pi \frac{N_s}{60} 9.81}$ [kg.m]

The output power can be calculated from the chart of power distribution as follows:

$$P_{out} = P_{in} - P_{iron} - P_{cu1} - P_{cu2} - P_{F\&W} - P_{brush} - P_{ad}$$

P_{in} = W_1+ W_2

P_{iron} calculated from no-load test [*point 1.3.1*] at 220V.

$P_{cu1} = 3 * I_1^2 * R_1$ where, R_1 & I_1 per phase values

$P_g = P_{in} - P_{iron} - P_{cu1}$

$P_{cu2} = 3 * I_r^2 * R_2$ where, R_2 & I_2 per phase values

$P_m = P_g - P_{cu2} – P_{brush}$

$P_{out} = P_m – P_{F\&W}$

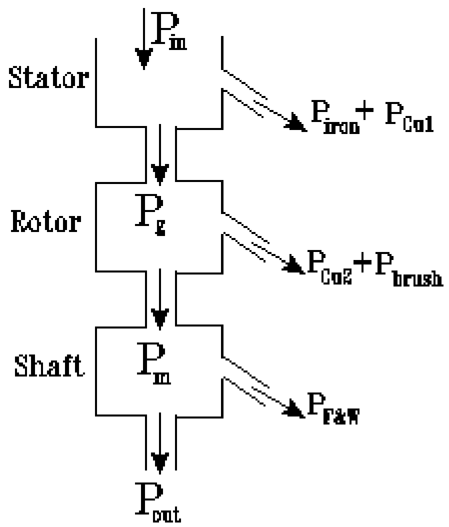


Fig.(7): The chart of power distribution

P_{brush} : = transition losses of the slip-ring and brushes

= $3*I_r*\Delta V$ (ΔV=1volt.)

$$P_{F\&W} = P_{F\&W} * \frac{N_r}{N_s}$$

P_{ad} : = additional losses, taking into account by 0.5% of the input power at rated value for different loads.

$$Pad = 0.5 \frac{Pn}{100} \times \left(\frac{I_1}{I_n} \right)^2$$

4.4. Discussions

Answer the following questions in your report:

1- Draw the variation of slip, motor torque, power factor, efficiency and speed as a function of stator current

2- Mention at what value of load, the efficiency of the induction motor under test is maximum. Explain the dropping characteristics of the effieciency curve near full-load.

3- Explain why the power factor of the induction motor on no-load is very poor.

5. Three-phase Induction Motor Effect of Rotor Resistance on Torque / Speed Characteristic

5.1. Objective

To determine how the starting torque and torque slip characteristic change with change in rotor resistance of the slip rings induction motor.

5.2. Introduction

The torque equation of an induction motors:

$$T \propto \frac{S E_{20}^{2} R_{2}}{\left[R_{2}^{2} + (S X_{20})^{2}\right]}$$

where, E_{2o} is the stand still induced emf in the rotor windings,

R_2 is the rotor resistance,

S is the slip, and

X_{2o} is the stand still rotor reactance.

If the supply voltage is constant, E_{2o} will be constant> Thus the torque is

$$T \propto \frac{S R_{2}}{\left[R_{2}^{2} + (S X_{20})^{2}\right]}$$

The value of X_{2o} is usually far greater than the resistance Rz of the rotor windings. For simplicity assume $R_2 = 1.0\Omega$ and $X_{2o} = 8.0\ \Omega$ and calculate the torque for various values of slip between 1.0 and 0.0. The results are plotted and shown as in Fig.(8). It will be seen that, for small values of slip, torque is directly proportional to the slip, whereas for slips between 0.15 and 1.0 torque is almost inversely proportional to the slip. To study the effect of variation of rotor resistance, torque/slip characteristics are calculated and plotted as shown in Fig. (9).

It wilt be seen that for a particular slip, say 0.05 the effect of doubling the rotor resistance is to reduce the torque by about 40%, whereas for slip of 1.0, i.e. at starting the torque is nearly doubled when the rotor resistance is increased from 1.0 to 2.0 Ω. Hence, if a high starting torque is required, the rotor must have a relatively high resistance. It will also be noticed that the maximum value of the torque, T_m is the same for the four values of Rz and that the larger the resistance, the greater is the starting torque. When the rotor circuit resistance is equal to the rotor reactance at stand still, maximum starting torque is developed.

Induction motor takes at starting about six to eight times its rated current. The variation of torque with speed is shown in Fig. (8). It will be difficult to determine experimentally the complete torque/speed characteristic, as the current drawn by the motor at low speed will be very high.

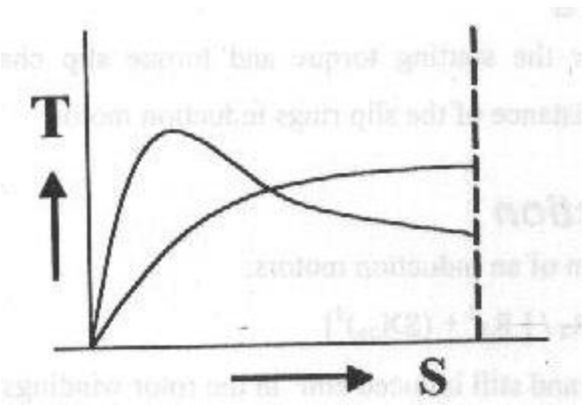


Fig.(8): Torque-speed characteristics.

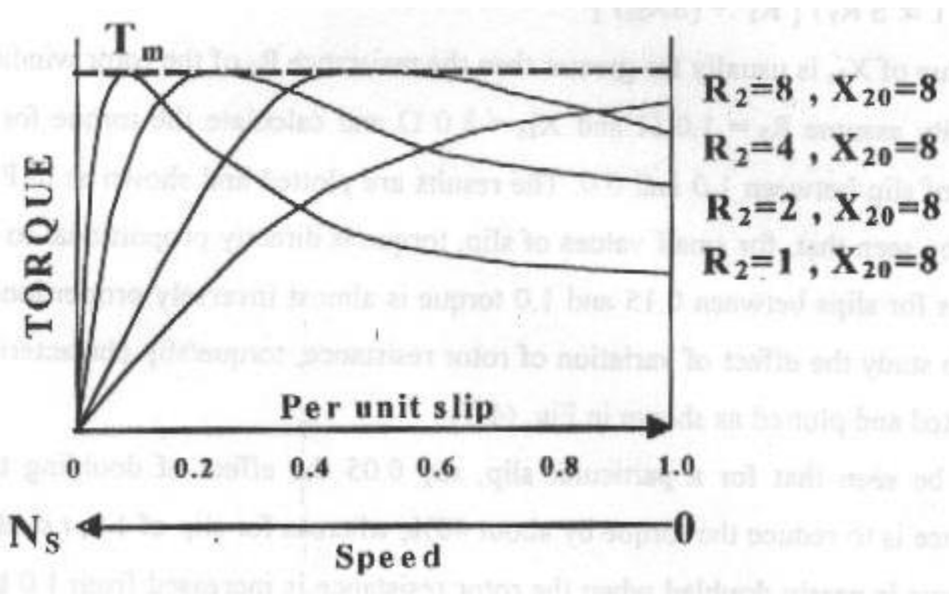


Fig.(9): Effect of rotor resistance on torque-speed characteristcs.

5.3. Experimdrital Procedure:

1. Make connections as shown in Fig.(2). Adjust the starting resistance at maximum value and start the induction motor. Record no-load speed, input power, stator and rotor current and applied voltage.
2. Load the motor step by step by loading the dc generator and record the measured quantities in the table below. Load the motor till rated current flows through the stator windings.
3. Change the value of starting resistance and record the measured values.
4. For each readings, calculate power factor and efficiency.

Table(7): Results and calculations

V_n= 220 [V], **100% R_{st}**													
I_1 [A]													
I_4 [A]													
W_1 [W]													
W_2 [W]													
N [rpm]													
I_5 [A]													
V_2 [V]													
Calculated Data													
P_{in} [W]													
Cos φ													
S													
P_{out} [W]													
η %													
T [kg.m]													

$P_{in} = W_1 + W_2$ [W], $s = \frac{N_s - H_r}{N_s} \times 100$, $\text{Cos}\,\varphi = \frac{P_{in}}{\sqrt{3} * I_{1L} * V_{1L}}$

$P_{out} = I_5 * V_2$, Efficiency $\eta = \frac{P_{out}}{P_{in}} \times 100$, Load torque is: $T = \dfrac{I_5 * V_2}{2\pi \dfrac{N_r}{60} 9.81}$ [kg.m]

Table(8): Results and calculations

V_n= 220 [V], **75% R_{st}**													
I_1 [A]													
I_4 [A]													
W_1 [W]													
W_2 [W]													
N [rpm]													
I_5 [A]													
V_2 [V]													
Calculated Data													
P_{in} [W]													
Cos φ													
S													
P_{out} [W]													
η %													
T [kg.m]													

Table(9): Results and calculations

V_n= 220 [V], **50% R_{st}**													
I_1 [A]													
I_4 [A]													
W_1 [W]													
W_2 [W]													
N [rpm]													
I_5 [A]													
V_2 [V]													
Calculated Data													
P_{in} [W]													

Cos φ													
S													
P_{out} [W]													
η %													
T [kg.m]													

Table(10): Results and calculations

V_n= 220 [V], **25% R_{st}**													
I_1 [A]													
I_4 [A]													
W_1 [W]													
W_2 [W]													
N [rpm]													
I_5 [A]													
V_2 [V]													
Calculated Data													
P_{in} [W]													
Cos φ													
S													
P_{out} [W]													
η %													
T [kg.m]													

5.4. Discussions

Answer the following questions in your report:

1- Draw the the motor characteristics (T / S)as required in load test for each value of the starting resistance.

2- Explain in brief the effect of introducing additional rotor resistance in an induction motor as evident from your experimental results.

3- If by introducing additional resistance in the rotor circuit; starting torque of an induction motor can be increased, then why we do not make rotor windings highly resistive ? Explain.

4. If three rotor circuit resistance is increased, the starting torque also increased. When rotor resistance is equal to standstill rotor reactance, maximum torque occurs at starting. Mention what would happen to the value of starting torque if rotor circuit resistance is made more than rotor reactance.

6. Induction Generator

6.1. Introduction

when the rotor of an induction motor is driven mechanically from some external source by a prime mover at speed higher than of its synchronisim, the motor acts as a generator and the rotor starts supply a current to the mains. This, the so called **induction generator**, is thus simply an induction motor (usually with a low resistance squirrel-cage rotor) which is somehow driven beyond its synchronous speed. Such machines are not capable of running independently but require for their running an ac generator of the synchronous type or a network. By rising the speed, the putput of the machine increases without any change in frequency, and for this reasone the motor is called as **synchronous generator** since it does not run.

Such machines are usefule for tractive work as in lift motors, electric railway motors while descending a steep graduient. As the train descends, the motor may aquire a speed beyond synchronism and generator power and send it to the source. It then cease to operate as a motor; and, on the other hand, then has a braking effect. This is known as regenerative braking.

6.2. Operation principle

When the speed of induction motor increases at no-load by external prime move in the same rotation diriction. The slip (s), rotor e.m.f., the rotor currents and the rotor frequency decreases to zero as the speed increases upto synchronous speed. When the rotor speed exceeds the synchronous speed, the slip will be negative; that means the direction of rotating magnetic field is reversed with respect to rotor winding. Leading to reverse the direction of e.m.f and currents of the rotor consequently, the power will be reversed to the supply (the power become deliverd to the ac netwok insteade of supplying from it). The induction motor becomes acting as induction generator. Thus the prime mover will be the source of the mechanical power that converted to electrical powe by the generator.

Keep in mind that the induction generator should be connected to ac supply to get the required magnitizing current for the rotating magnetic field. The rotor speed should be exceeded the synchronous speed of rotating magnetic field which is determined by the stator poles numbers and:

1- the frequency of network tied with the induction generator
2- the capacity of the capacitor bank connected to stator terminals is case of self excited generator to supply isolated load.

6.3. Advantages and disadvantages

The major advantages of the induction generators are :

1- required less auxiliary devices compared to synchronous generator,
2- its parallel operation can be performed at any frequency without oscillation problems,
3- the induction generator protectes itself againest short circuit because of the excitation highly dropped down.
4- Able to operate as a motor or generator immedeatly depending on slip sign (+ve as motor, -ve as generator).

There are some disadvantage, they are:

1- low power factor
2- required a reactive power source

The output power can be calculated from the chart of power distribution as follows:

$$P_{out} = P_{in} - P_{iron} - P_{cu1} - P_{cu2} - P_{F\&W} - P_{brush} - P_{ad}$$

$P_{out} = W_1 + W_2$ $\quad$ $P_{in} = I_5 * V_2$

P_{iron} calculated from no-load test [*point 1.3.1*] at 220V.

$P_{cu1} = 3 * I_1^2 * R_1$ where, R_1 & I_1 per phase values

$P_g = P_{out} + P_{iron} + P_{cu1}$

$P_{cu2} = 3 * I_r^2 * R_2$ where, R_2 & I_2 per phase values

$P_m = P_g + P_{cu2} + P_{brush}$

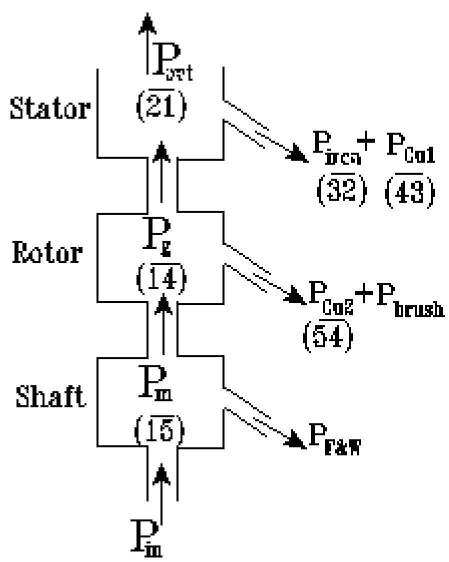


Fig.(1): generator power flow

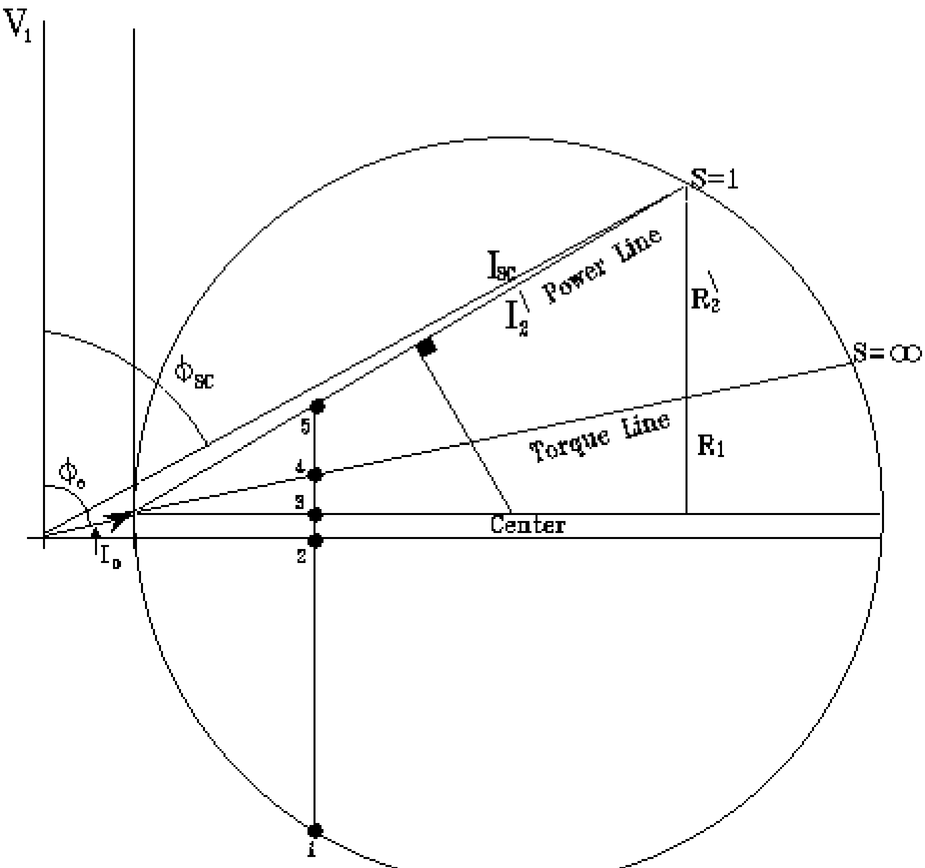


Fig.(2): Induction generator circle diagram

$\overline{15}$:= mechanical input power

$\overline{54}$:= rotor cupper loss

$\overline{43}$:= stator cupper loss

$\overline{32}$:= iron loss

$\overline{21}$:= net electrical power

6.4. Rotor resistance effect

In normal operation of induction generator, the rotor terminals should be short circuited. If using external resistance, the electrical ac power will be decreased as the external resistance increase.

6.5 Experimental Procedure

1- Connect the circuit as shown in Fig.(3), and start the induction machine as a motor with rotor terminals short circuited .

2- Adjust the field current of the dc generator till the output voltage becomes equal to the dc source voltage, with the synchronizing switch (SW) is off .

3- Ensure the same polarity and voltage in both dc source and dc machine, then close the synchronizing switch (SW).

4- Increase the speed of the dc machine which operates as a motor by decreasing the field current upto the two wattmeter read zero at this point s=0. The more speed rising the slip will be negative and the ac power is transmitted to ac network.

5- Record the measuring instruments in table (1).

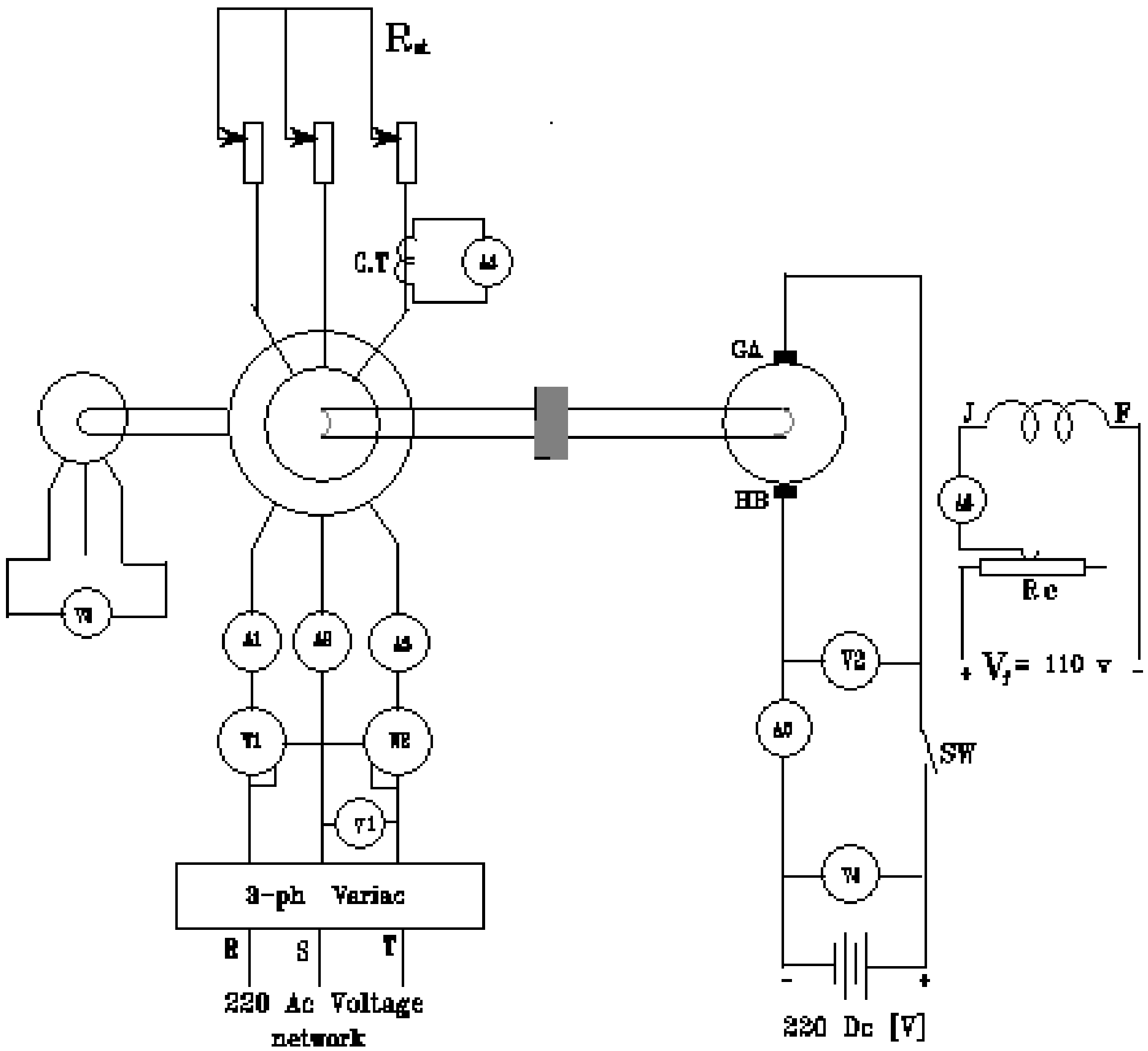


Fig.(3): Wirring diageam of induction generator .

Note: the apparatue rating in this test same as induction motor test

Results and calculations

Table(1)

V_1= 220 [V], V_2=220 [V]													
I_1 [A]													
I_4 [A]													
W_1 [W]													
W_2 [W]													
N [rpm]													
I_5 [A]													
Calculated Data													
P_{in} [W]													
Cos φ													
S													
P_{out} [W]													
η %													
T [kg.m]													

$P_{out} = W_1 + W_2$ [W], $s = \frac{N_s - H_r}{N_s} \times 100$, $\text{Cos}\,\varphi = \frac{P_{out}}{\sqrt{3} * I_{1L} * V_{1L}}$

$Pin = I_5 * V_2$, Efficiency $\eta = \frac{P_{out}}{P_{in}} \times 100$,

mechanical torque is : $T = \frac{I_5 * V_2}{2\pi \frac{N_r}{60} 9.81}$ [kg.m]

6.6. Discussion

1- Plot the electrical power transmitted to the network against the slip.

2- explain the effect of rotor external resistance

7.The synchronous induction motor

7.1 Objective

To operate a 3 phase induction motor as a synchronous motor by applying direct current to the rotor slip rings. The manner in which this should be done is described together with open circuit and short circuit tests to find the synchronous impedance of the machine.

7.2 Introduction

Consider a 3-phase slip ring induction motor running with its slip rings shorted and rotating at a speed close to its synchronous speed. If direct current of sufficient magnitude into the rotor windings the rotor will accelerate and pull into step with the rotating field. The motor can then operate as a synchronous machine and produce a range of motoring and generating torques at the synchronous speed.

The steady field produce by the direct current, If, in the rotor windings, when rotating at synchronous speed past the stator winding induces in each phase a voltage, E, known as the excitation voltage. The magnitude of this voltage is related to the magnitude of the excitation current, If, but its phase, δ, with respect to the terminal voltage V1, is a function of the mechanical load on the shaft. This phase difference, δ, will be referred to here as the load angle.

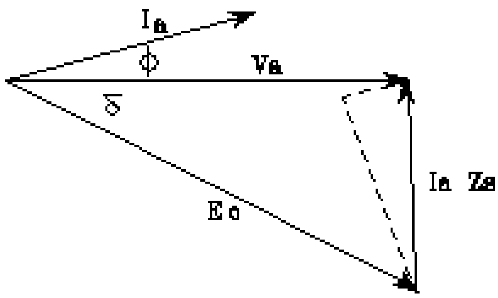


Fig.(1): Phasor diagram of the machine

Fig.(1) shows the phasor diagram for one phase of the motor from which it is seen that the difference between the excitation voltage, E, and the terminal voltage, V, is the voltage drop across the terminal impedance, ZS, of the motor. This impedance is called the synchronous impedance.

It can be shown that when iron losses are ignored, the input power per phase, Pi, is given by the expression.

$$p_i = \frac{V}{Z_s}\left[V\cos\theta - E\cos(\delta+\theta)\right] \qquad (1)$$

where Z_S is the magnitude of the synchronous impedance and θ is its impedance angle. Similarly, the gross output power, Po, is given by the expression

$$p_o = \frac{E}{Z_s}\left[V\cos(\delta-\theta) - E\cos(\delta+\theta)\right] \qquad (2)$$

from equation (2), it is seen that the output power is a maximum when δ = θ, so that the machine will pull out of synchronous when the load angle exceeds this value. The maximum value of the output power is clearly:-

$$p_o = \frac{E}{Z_s}\left[V - E\cos(\theta)\right] \qquad (3)$$

when $|E| = |V|$ the motor is said to be floating when $|E| < |V|$ it is said to be under excited and when $|E| > |V|$ it is said to be over excited. Variation of the magnitude of the excitation voltage, E, varies the power factor at which the motor operates and this is demonstrated in the experiment.

7.3 Connection Diagram

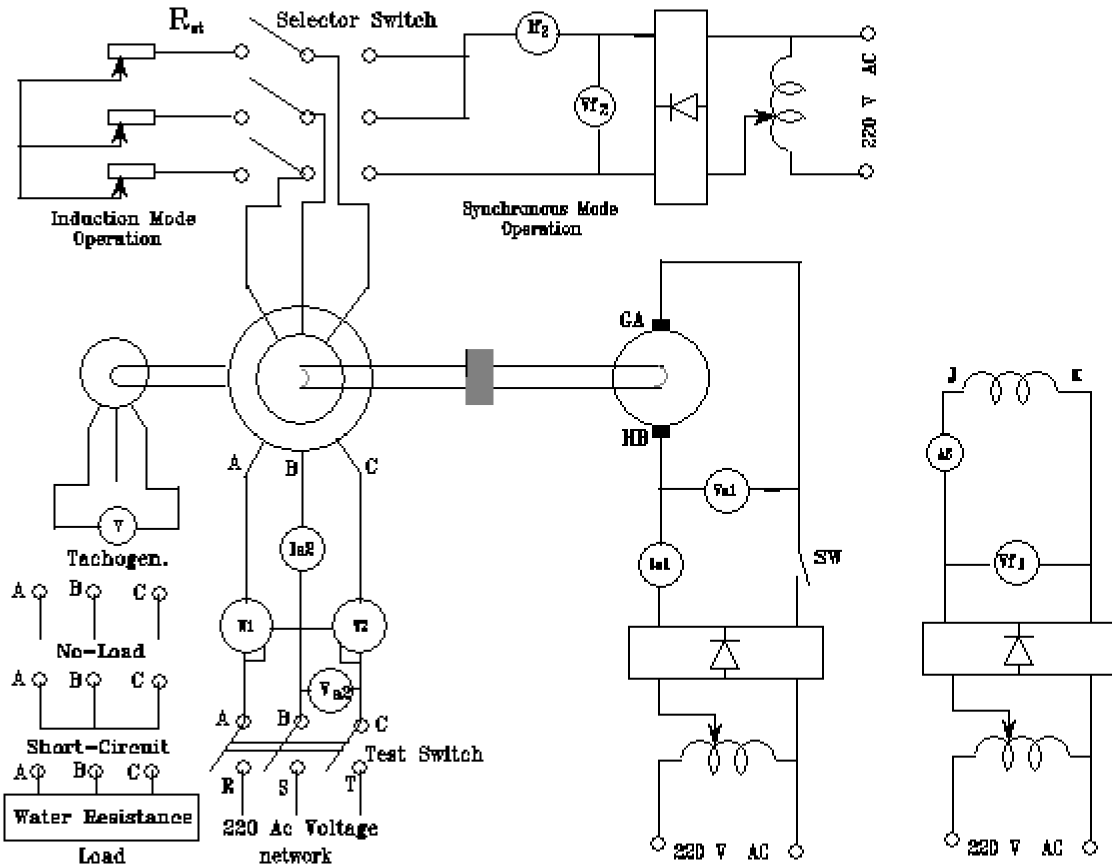


Fig.(2):Connection diagram of synchronous induction motor

7.4 Name plate of the induction machine set

DC Generator			
Vn 240 [V]	In 7.92 [A]	Pn 1.9 [kW]	Nn 1430 rpm
Excitation Separate			
V 110 [V]		I 0.91 [A]	
Three-Phase Slip-ring Induction Motor			
Vn 380/220 Y/Δ	In 7.4/12.7 [A]	Pn 3 [kW]	Nn 1400 rpm
F 50 c/sec		Cos φ 0.77	
Rotor	Vn 95 [V]		In 20.5 [A]
Three- phase Tachogenerator			
V_n Y 30 [V]	I_n 0.115 [A]	P_n 6 [VA]	F 66 c/sec
At N 1000 rpm			

7.5 Experimental Procedure

2.5.1 Open circuit and Short circuit tests

1) Make the connections to the test and load machines as shown in Figure 2, and have your circuits checked by the supervisor
2) Ensure that the selector switch is open, then start the dc-machine as a motor and adjust the field current until the speed of the system reaches 1500 rpm maintain this speed constant.
3) With the selector switch turned to the synchronous mode operation. Switch on the 1-phase supply. Now increase the variac output to give steps of excitation current, I_{f2}, up to 20.5 A. at each step record both I_{f2} and the voltage, E, generated between the stator terminals ABC. Remember to keep the speed constant and the test switch is open.
4) Reduce the variac output voltage to zero and switch off the 1-phase supply. Connect the test switch on the Short circuit mode, the stator terminals ABC is shorted. Switch on the 1-phase supply in synchronous mode and slowly increase the output voltage from the variac to give steps of short circuit current, I_{SC}, up to 12.7A. Again keep the speed constant at 1500 r.p.m. At each step record the value of I_{SC} and the corresponding excitation current I_{f2}.

5) Reduce the output from the variac to zero and switch off the 1-phase supply. Turn off the system.

Results

I_{f2} [A]												
O.C. (E) Volt/ph												
S.C.(I_{SC}) Amps/ph												
Z_s [Ω]/ph =(E\ I_{SC})												

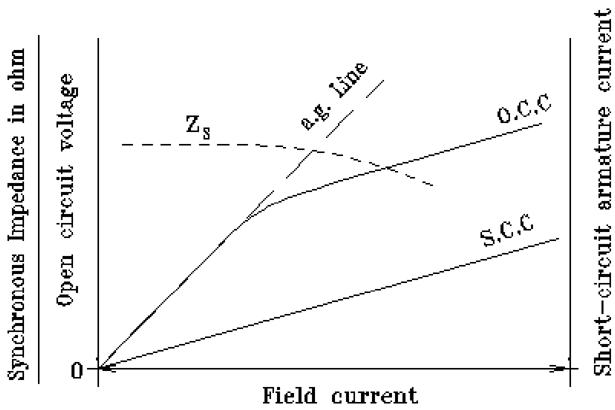


Fig.(3): Synchronous impedance calculation

7.5.2 Load test as induction motor

1. Connect the selector switch to induction mode operation with the starting resistance in the rotor Rst at its maximum value. Exchange the d.c. supply connected to the armature by a water resistance load. Keep the armature switch (SW) open.
2. Connect the armature terminals (A-B-C) of the induction machine to the 3-phase ac network (R-S-T), with closing the test switch, now this machine operates as an induction motor. Decrease the starting resistance R_{st} to its minimum value so the rotor terminals is shorted.
3. Close the switch (SW) of the dc generator to the water resistance and increasing the load current upto reach the rated current of the induction motor.
4. Record all instrument in Fig.(2).

Results

Measured Data													
V_{a2} [V]	Constant at the motor rated voltage (220 [V])												
I_{a2} [A]													
W_1 [W]													
W_2 [W]													
Load Data													
N [rpm]													
I_{a1} [A]													
V_{a1} [V]													
Calculated Data													
P_{in} [W]													
s													
P_{out} [W]													
Cos φ													
T [kg.m]													
η %													

7.5.3 Load test as synchronous motor

1. Connect the selector switch to induction mode operation with the starting resistance in the rotor R_{st} at its maximum value. Exchange the d.c. supply connected to the armature by a water resistance load. Keep the armature switch (SW) open.
2. Connect the armature terminals (A-B-C) of the induction machine to the 3-phase ac network (R-S-T), with closing the test switch, now this machine operates as an induction motor. Decrease the starting resistance R_{st} to its minimum value so the rotor terminals is shorted.
3. Change the operation mode from induction to synchronous by turning the selector switch to the rectifier bridge terminals that was adjusted to the rated field current.
4. Close the switch (SW) of the dc generator to the water resistance and increasing the load current upto reach the rated current of the machine.
5. Record all instrument in Fig.(2).

Results

Measured Data													
V_{a2} [V]	Constant at the motor rated voltage (220 [V])												
I_{a2} [A]													
W_1 [W]													
W_2 [W]													
Load Data													
N [rpm]													
I_{a1} [A]													
V_{a1} [V]													
Calculated Data													
P_{in} [W]													
s													
P_{out} [W]													
Cos φ													
T [kg.m]													
η %													

7.6. Discussion

1. Plot the following graphs.

(a) Excitation voltage, E, against field current , I_f.

(b) Short circuit current, I_{SC}, against field current , I_f.

2. Draw the variation of slip, motor torque, power factor, efficiency and speed as a function of stator current. In both operation modes. Comment and Compare between the two modes.

8.Another Purpose Testing Using Induction Motors

(Self-synchronous Systems)

8.1 Introduction

Among the more exacting of modern control requirements is that of position control, or causing the angular position of one shaft to follow that of another as closely as possible. A group of induction machines called *self-synchronous devices* are valuable adjuncts for such control systems. They are also known by various other names, such as ***selsyn, synchro,*** **and *autosyn***. In the following test, the specific word ***selsyn*** will frequently be used. There are three general types of systems involving selsyn devices:

(1) 3-phase power selsyns for heavy torque transmission,

(2) single-phase instrument or indicator selsyns for only very light torque transmission,

(3) generator-transformer systems for indicating shaft misalignment in terms of a voltage magnitude and polarity.

8.2Three-phase Power Types Experaments

In integral-horsepower sizes, the selsyn systems consist of 3-phase wound-rotor induction machines with their primary windings excited from the same 3-phase source and their second ary windings (rotor) connected together. as shown in Fig. (1).

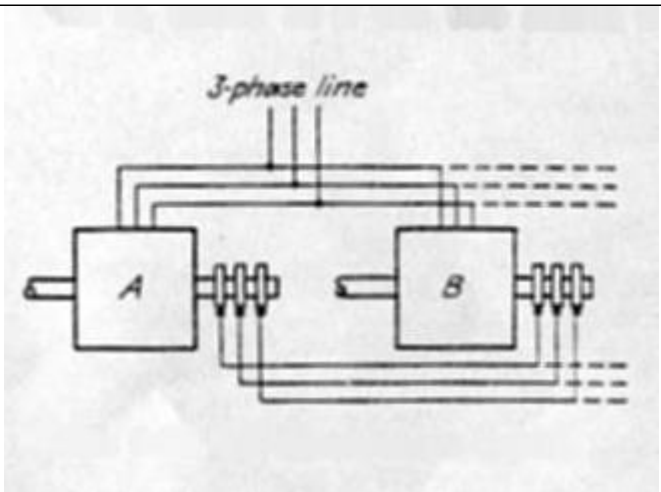


Fig.(1-a): Self-Synchronous System

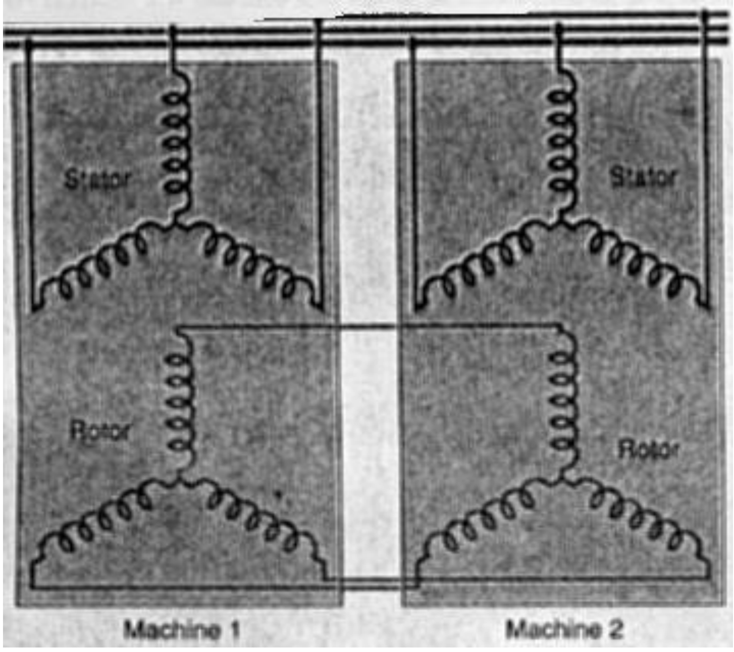


Fig.(1-b): Wiring circuit of self-synchronous system

If one of these machines is driven mechanically. the other will follow in synchronism with it, much as if the two shafts were connected mechanically. Such systems have been applied to maintain synchronism between the hoist motors raising the two ends of large lift bridges see Fig. (2), to maintain synchronism between parts of printing presses, and for many similar applications requiring speed coordination between parts of complex apparatus In Fig. (3).

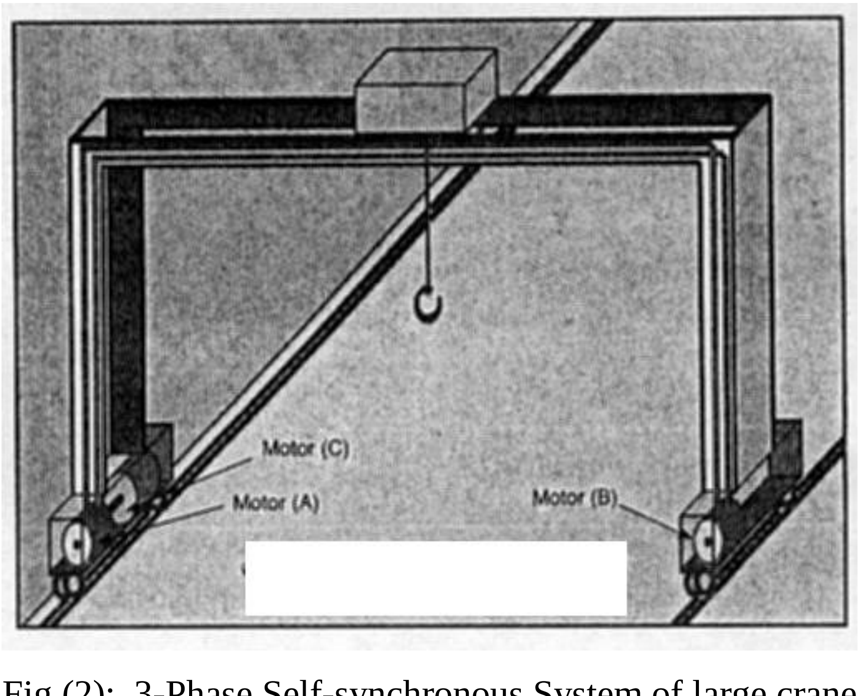


Fig.(2): 3-Phase Self-synchronous System of large crane

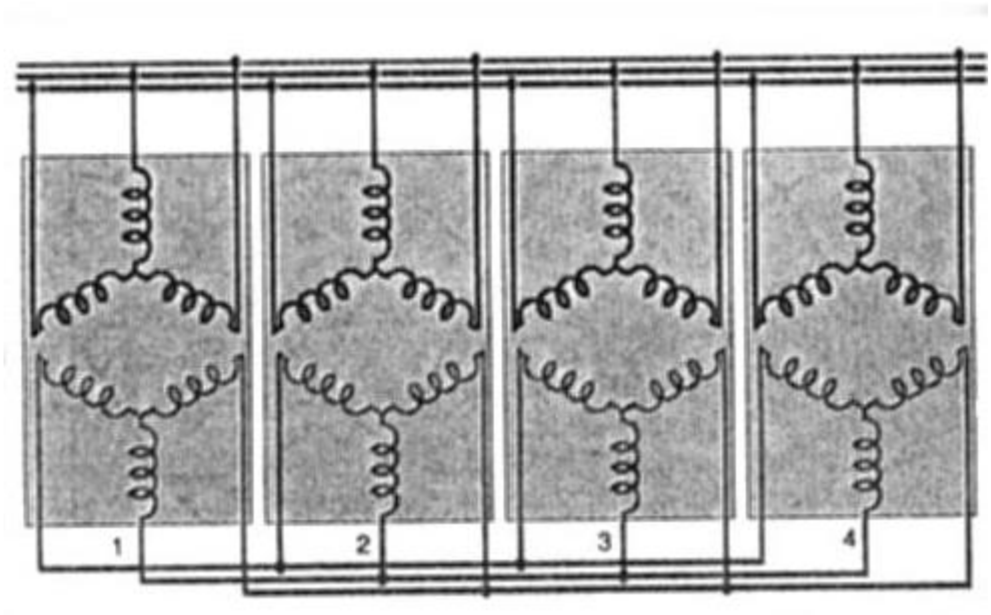


Fig.(3): 3-Phase Self-synchronous for complex ssystem

Experament Procedure :

In this system the two- motor must be identical, so the stator of each one can be connected parallel to the same power supply, while their rotors are connected together as in Fig.(1-b). No one of the two motors will rotate in either direction because the rotor currents are zero due to equal and opposite electromotive force in corresponding rotor phases of the two motors. For have good connection follow the following steps:

1- Connect the treminals of their stators parallel to the same 3-phase supply arbitrary.
2- Connect directly one terminal of the rotor of machine (A) to any rotor terminal of the machine (B).
3- Connect another rotor terminal of machine (A) to any of machine (B) through voltameters with range of douple value of the stand still voltage.
4- Manual rotation the shaft of any motor by angle upto 360° in any direction till the voltameter read zero voltage.
5- If the voltameter read a value at any angle, exchange the rotor terminal labled (a) to the free terminal (d) as shown in Fig.(4) and repeat part (4) till the voltmeter read zero voltage. This is the correct terminal, then remove the voltameter and connect directly the rotor termionals. And also connect the remaining two terminal together.

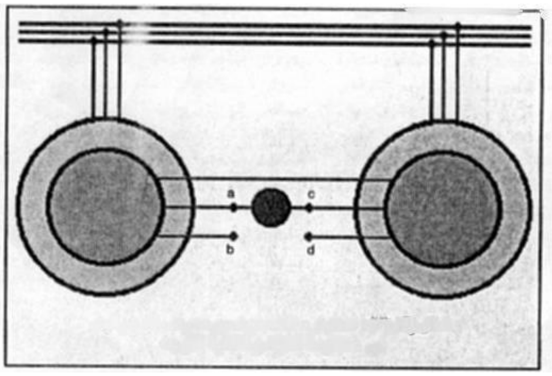


Fig.(4): wirring of the terminal test

Note:

1-If any of the two motors rotate in the opposite direction of the other, exchenge any two terminal of the stator and rotor of one motor.

2- the privious procedure can be repeated to connect any nomber ot motor (identical motors).

8.3. Single-phase Instrument Types Synchro Position Indicator Experament

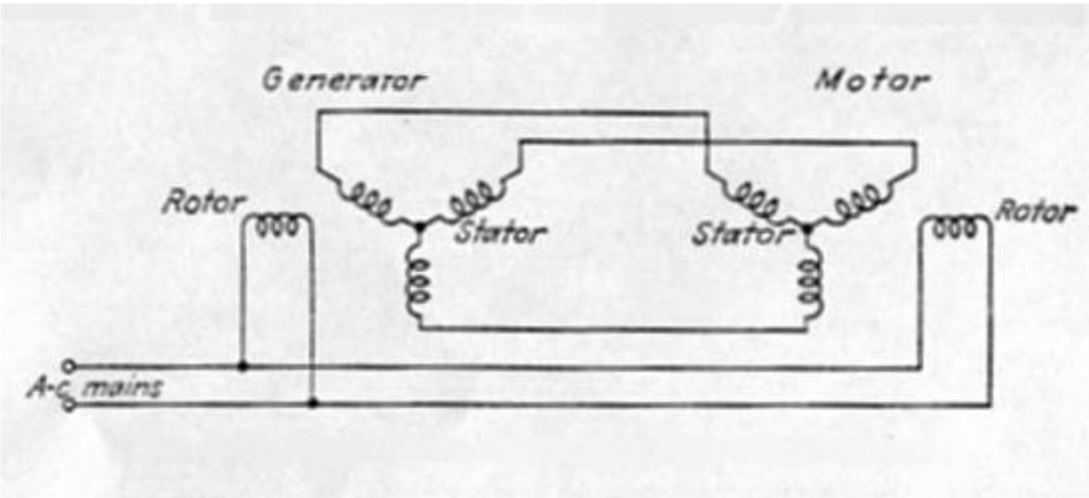


Fig.(5): Single phase selsyn generator-motor system

Substantially the same type of action is obtained when the 3-phase system is replaced by the single-phase system shown diagrammatically in Fig. (5). In most respects, the construction of the *selsyn generator,* or *transmitter, is* similar to that of the *selsyn motor,* or *receiver.* Both have a single-phase winding (usually on the rotor) connected to a common a-c voltage source. On the other member (usually the stator), both have 3 windings with axes 120° apart and connected in Y; these windings on the generator and motor have their corresponding terminals connected together. When the single-phase rotor windings are excited, voltages are induced by transformer action in the Y-connected stator windings. If the two rotors are in the same space position relative to their stator windings, the generator and motor stator winding voltages are equal, no current circulates in these windings, and no torque is transmitted. If, however, the two rotor space positions do not correspond, the stator-winding voltages are unequal and currents circulate in the stator winding. These currents, in conjunction with the airgap magnetic fields produce torques tending to align the two rotors. Mechanically, selsyns have the same general construction features as small motors.

Note:

The same privious procedure for the rotor follow here for the stator

A modification of the selsyn system of Fig. (5) may be introduced by including a *differential selsyn*, thereby permitting the rotation of a shaft to be a function of the sum or difference of the rotation of two other shafts. In Fig. (6), the differential selsyn acts as a differential generator. The voltages impressed on its stator windings induce corresponding voltages in the rotor windings. The relative magnitudes of the three rotor voltages are the same as would exist if the differential were removed and the generator turned through an angle equal to the sum or difference of the generator and differential angles. Such differential generators usually have a bank of three capacitors connected across the primary terminals to improve power factor and hence minimize the possibility of overheating in the system. Alternatively, the differential may be used as a motor supplied from two separate selsyn generators and producing a rotation dependent upon the sum or difference of the two generator rotations. The connections in this case are the same as in Fig. (6) except that the differential is relabeled *Differential motor* and the motor on the right is relabeled *Generator*.

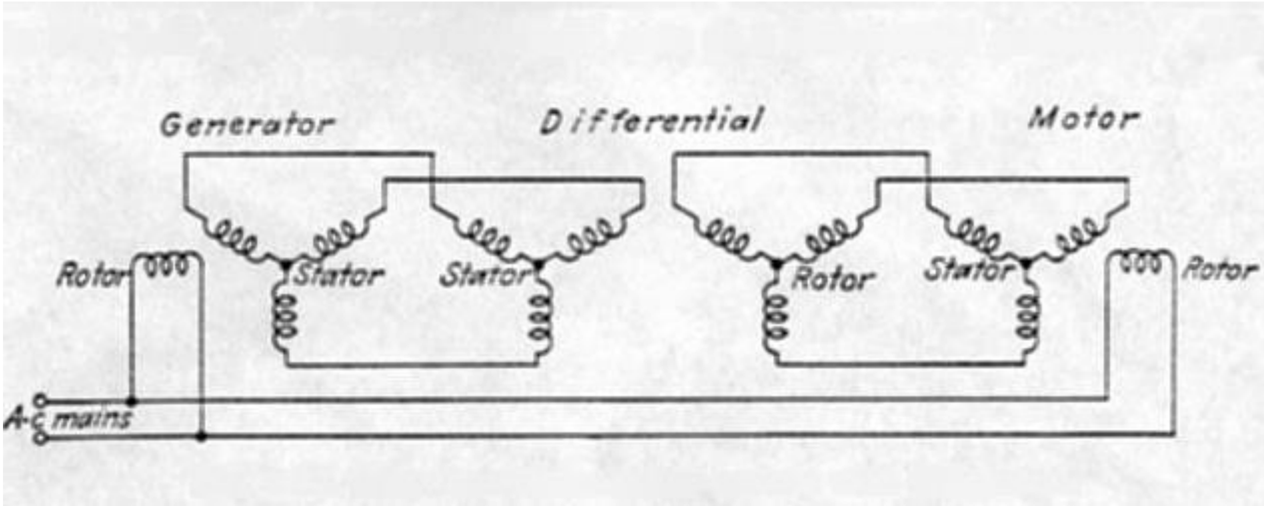


Fig.(6):Selsyn generator-motor system with differential

8.4- Synchro Control Transformers Synchro position indicator

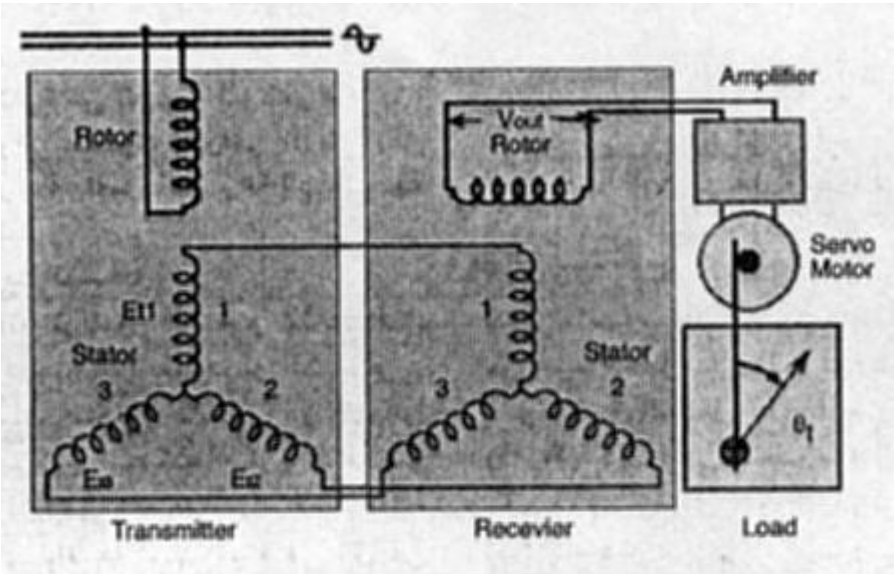


Fig.(7): Selsyn generator transformer system.

Very commonly the process of controlling with reasonable exactness the instant-by-instant angular position of a shaft calls for the exertion of large torques. When selsyn equipment must exert these torques directly, a very considerable and intolerable sacrifice in the faithfulness of position reproduction may result. For such control purposes, it is common to apply the self-synchronous principle in such a manner that a voltage is produced whose magnitude is a function of the angular displacement between the positions of two shafts. Such a voltage is an error voltage, for its presence indicates a discrepancy in the position of the shaft being controlled. The error voltage may then be fed into other devices to instigate correction of the discrepancy causing it. The selsyns themselves thus do not have to supply mechanical power. The error voltage may be referred to as an *error-modulated* signal-a carrier wave whose amplitude is proportional to the error and whose instantaneous polarity is determined by the sign of the error.

The basic method of producing the error voltage is shown by the circuit of Fig. (7). Two interconnected selsyns are again involved, one a generator and the other a very similar unit called a *selsyn* (or *synchro) control* transformer. The rotor of the selsyn generator is excited from a single phase source, producing a magnetic field in the generator and voltages in the stator windings of both the generator and the control transformer. If the voltage drops caused by exciting current are neglected, the induced voltages in the 2 stator windings must be equal. Therefore the distribution of flux about the control-transformer stator must be similar to that about the generator stator. The effect is consequently the same as it the 2 rotor windings were on the same magnetic circuit and arranged so that their axes could be given any arbitrary displacement angle in space. The arrangement is thus the equivalent of an adjustable mutual inductance between the 2 rotor windings, but with the added feature that geographical separation of the 2 windings is possible. When the angle is 90 electrical degrees, corresponding to a 90-electrical-degree displacement of the two shafts, no voltage is induced in the transformer rotor; this displacement is the equilibrium position of the two shafts. When the angle has any value except 90° and 270°, a voltage is induced in the transformer rotor. As shown in Fig. (8), the magnitude of the voltage is a function of the angular discrepancy between the two shafts, and the instantaneous polarity depends on the direction of the displacement. The function is essentially a sinusoid. Differential selsyns may also be incorporated between the generators and control transformers of these systems.

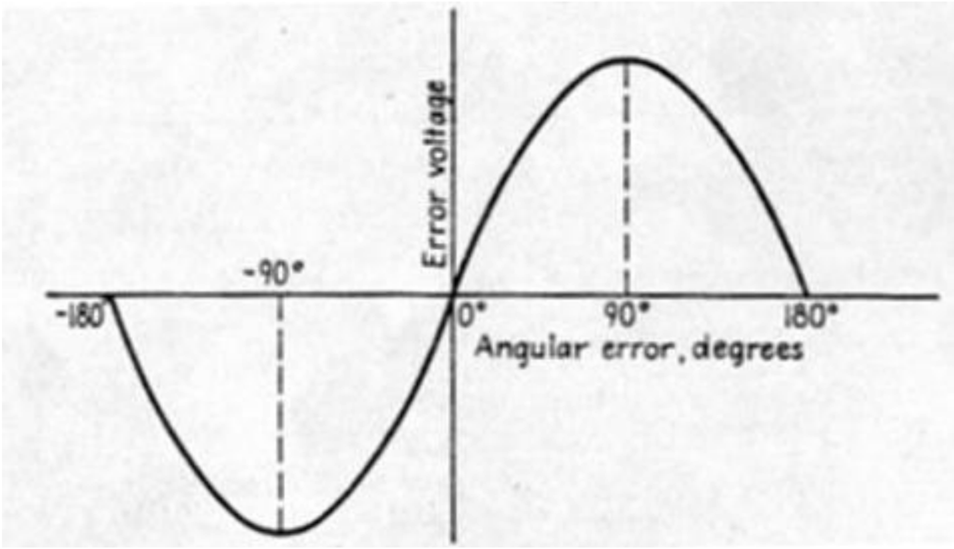


Fig.(8): Variation of error voltage with angular error.

This qualitative picture of the combined operation of generator and control transformer may be made more specific by a brief analysis in outline form for an idealized system as illustrated in Fig. (9).

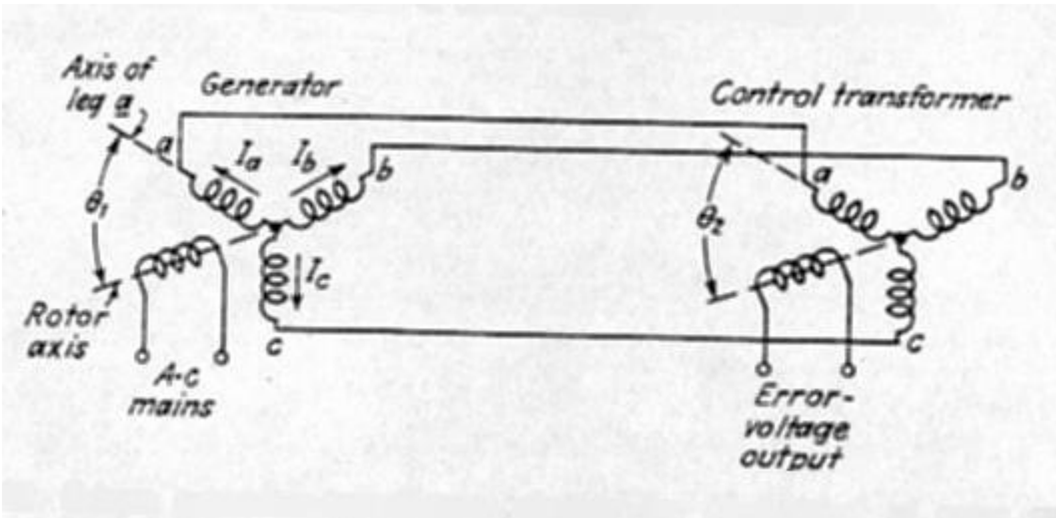


Fig.(9): Selsyn generator-transformer system for evaluation of error voltage.

9. Schrage Motor

9.1 Introduction

Schrage motor is a variable speed motor, and has the advantage that the input power factor can be controlled. Theoretically, this type of motor is capable of giving a speed range from zero to twice the synchronous speed. The rotor of this type of machine carries two windings the main winding and the regulating winding housed in the same set of slots. The main rotor winding; which is a mesh type A.C. winding, has its three terminals connected to slip- rings mounted on one end of the rotor shaft. The regulating winding is a closed commutated winding, the tapping on the winding being connected to the commutation segments. The stator has a distributed three phase winding called secondary winding. The terminals of the secondary winding are connected to sets of brushes placed on the commutation such that the voltage from the regulating winding is injected into the circuit of the secondary winding, see Fig. (1).

The two brushes of each set can be moved to vary the magnitude and phase of the voltage picked up from the commutation and injected into the secondary circuit. If the two brushes of a set are on the same commutation segment, the secondary winding is short circuited through the segment and the motor runs as an ordinary three phase induction motor, at nearly synchronous speed. By moving the brushes in one or the other direction, sub-synchronous or super-synchronous speeds may be obtained. The spacing between the brushes determines the magnitude of the voltage injected into the secondary winding and therefore the motor speed.

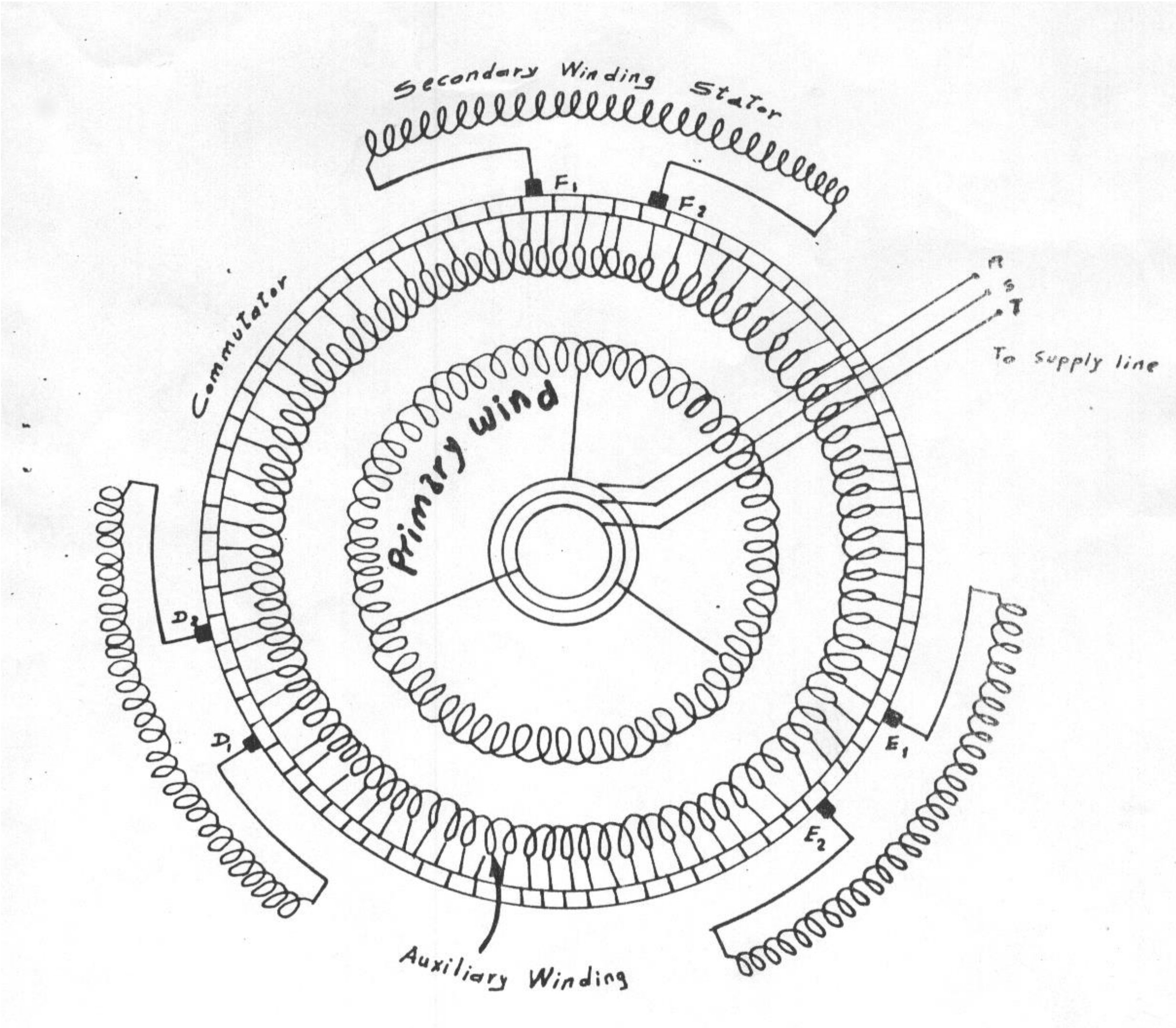


Fig.(1): Winding arrangement of scharge motor

9.2 Machine name-plat

	Two are connected Parallel	Two are connected Series
Volt [V]	220 Δ / 380 Y	220 Δ / 380 Y
Ampere [A]	23.9 Δ / 13.8 Y	26.2 Δ / 15.1 Y
Poles	6, 3-phase	6, 3-phase
HP	8 / 2.2 / 0	10 / 3.6 / 2.5
Rpm	1800 / 500 / 0	1400 / 500 /350
Sec. Volt [V]	20.4	40.8
Sec. Amps [A]	68	33

9.3 Experimental Details

The motor may be started directly from the line, provided the brushes are set to a low speed position. Under this condition, the injected e.m.f, opposes the secondary e.m.f this limits the secondary current and therefore the primary current.

4.4 No Load Test

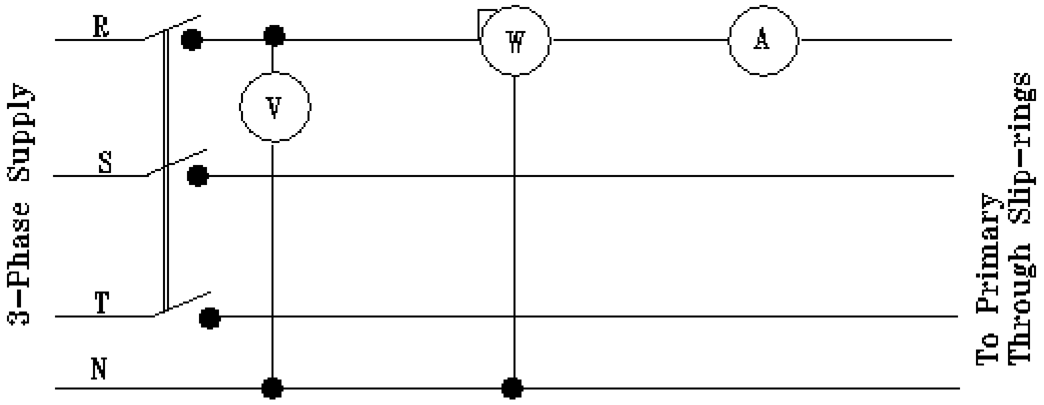


Fig.(2): Connection diagram of no-load test

At no load the motor speed can be obtained from the following equation:

$$n=n_s\,(1-E_K/E_{2o})$$

In the laboratory, schrage motor has 6 poles. The stator (secondary) winding of each phase is divided into two parts, which can be connected in parallel or in series. So, the no load test will be carried out in the following two cases:

9.4.1. Two Parts Are Connected in Series

9.4.1.1Apparatus

- Voltmeter 0/300 V. a. c.
- Voltmeter 0/30 V
- Ammeter 0/10 A. a. c.
- Wattmeter 5/10 A, 0/300 V

9.4.1.2. Experimental Procedures

1- Connect as shown in Fig. (2), with points D_1, E_1, F_1, are connected to points D_5, E_5, F_5 respectively.
2- Ensure that the brushes are set to low speed position.
3- Start the motor by closing the switch.

4- Record the values of input power, input phase voltage, input current, brushes voltage and brushes angle.
5- Change the brush spacing and then record the results, note, the relation between motor speed and angle of brushes.

6- Switch of the motor.

9.4.1.3. Results

N rpm							
Pn [W]							
V [V]							
I [A]							
E_k [V]							
β° [meach.deg]							
Cos φ							
E_{2o} [V]							

Where; $\text{Cos}\,\varphi = \frac{P_n}{I * V}$ & $E_{2o} = n_s \frac{E_k}{n_s - n}$

9.4.2. Two Parts Are Connected in Parallel

9.4.2.1Apparatus

- Voltmeter 0/300 V. a. c.
- Ammeter 0/10 A. a. c.
- Voltmeter 0/30 V
- Wattmeter 5/10 A, 0/300 V

9.4.2.2. Experimental Procedures

1- Connect as shown in Fig. (2), with points D_1, E_1, F_1, D_5, E_5, F_5 are connected to points D_4, E_4, F_4, D_2, E_2, F_2 respectively.

2- Ensure that the brushes are set to low speed position.

3- Start the motor by closing the switch.

4- Record the values of input power, input phase voltage, input current, brushes voltage and brushes angle.

5- Change the brush spacing and then record the results, note, the relation between motor speed and angle of brushes.

6- Switch off the motor.

9.4.2.3. Results

N rpm							
Pn [W]							
V [V]							
I [A]							
E_k [V]							
β° [meach.deg]							
Cos φ							
E_{2o} [V]							

Where; $\text{Cos}\,\varphi = \frac{P_n}{I * V}$ & $E_{2o} = n_s \frac{E_k}{n_s - n}$

9.5. Report

From the results plot E_{2o}, E_k,I, P_n, Cosφ, n, as a function of angle β° [meach.deg] for two connections

9.6. Discussion

10.Single Phase Induction Motor

10.1 Objective

To study the effect of capacitor on the starting and running performance of a singlephase induction motor and the method of reversing the direction of rotation.

10.2 Introduction

When single-phase supply is applied across the winding of a single phase induction motor, the nature of the field produced is alternating and as such the rotor will not develop any starting torque. It has however been observed that once the motor is given an initial rotation it continues to rotate.

In a single-phase motor to provide starting torque, an additional winding is provided, which is called auxiliary winding. The main and auxiliary windings are connected in parallel across a single-phase supply. The impedance of the two windings are made different so that currents flowing through these windings will have a time phase difference as shown in the vector diagram Fig. (1)

10.3 Need of a Capacitor in The Auxiliary Winding Circuit

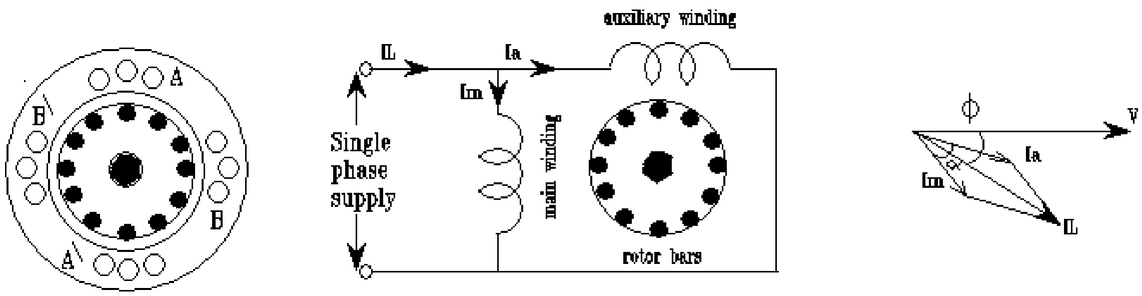


Fig.(1):Single phase induction motor winding carring current time phase different of α degrees.

A single phase motor having a main winding and an auxiliary winding fed from a single phase supply can be considered as equivalent to a two-phase motor having a single phase supply.

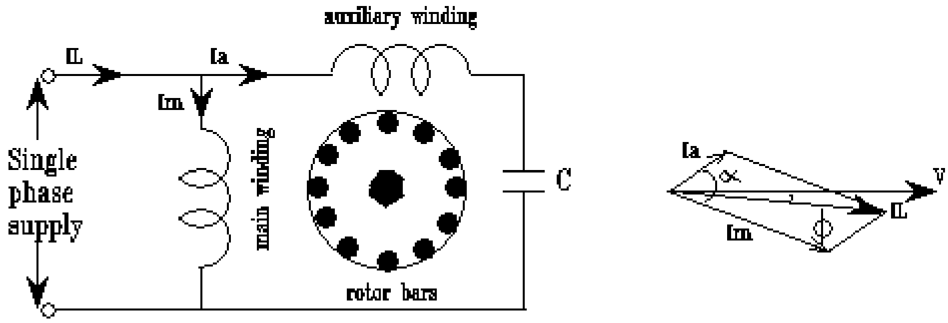


Fig. (2) Time-phase difference of nearly 90 deg, between the main and auxiliary winding currents is achieved by using a capacitor in the auxiliary winding circuit.

Since the two windings are not identical, the two currents I_m and I_a, will have a time phase displacement. Now if by any means the time phase displacement between the two currents, I_m and I_a, flowing through the two windings can be made 90 deg., a single-phase motor will behave exactly like a two-phase motor. The time phase displacement between I_m and I_a, can be increased by using a capacitor in the auxiliary windings as shown in Fig. (2). The capacitor will also improve the overall power factor of the motor. From the phasor diagrams of Figs. (1& 2) it will be observed that the power factor of the motor is improved when a capacitor is introduced in the auxiliary winding circuit. If a capacitor is to be used only for achieving high starting torque, when the auxiliary winding can be switched off when the motor picks up speed.

10.4 Method of Reversal of Direction of Rotation

The direction of rotation of split phase type induction motor having main and auxiliary winding, gets reversed if the current direction in any one of its windings is reversed. This is done by reversing the two terminal connections of the auxiliary or main winding across the supply.

The leads of the main and auxiliary windings can be differentiated from each other (if lead marks are not labeled) by measuring resistance of the two windings.

The resistances of auxiliary winding for motors of 1/16 KW and more are generally greater than the resistance of the main winding

10.5 Connection Diagram

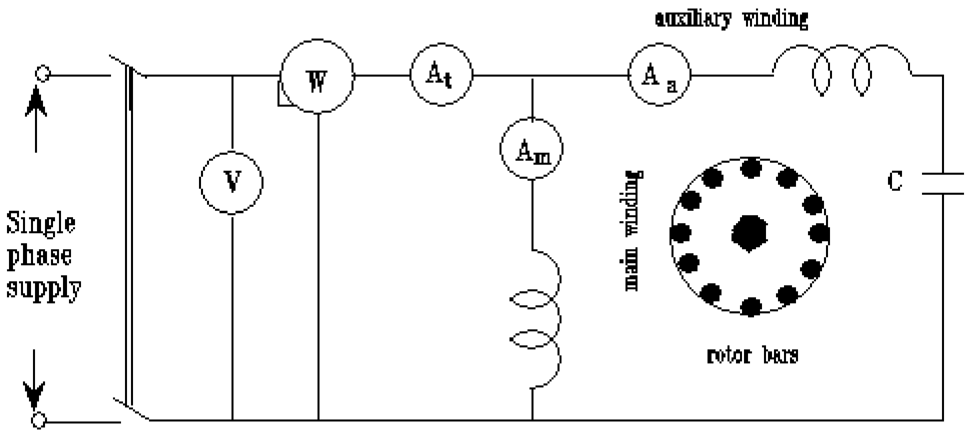


Fig.(3): Connection diagram for determine the effect of capacitor on the performance of a single-phase induction motor.

10.6 Machine-set nameplate

Single phase IM		**3-ph. IM (used as a break)**	
220 [V]	6.3 [A]	380 Y / 220 Δ [V]	
0.75 [kW]	p.f. 0.85	2.3 Y / 4.5 Δ [A]	
1370 rpm	50 Hz	1400 rpm	1.1 [kW]
C = 25 μF , 400 [V]		p.f. 0.85	

10.7 Experimental Procedure

1-Measure the resistances of both the main winding and auxilary winding at temperature rise 75° and take into account the sken effect (multiply by1.5).

2-Connect the single phase induction motor to the main supply at no-load to rotate at 1370 rpm and record the value of the wattmeter. This value presents the no-load losses which consists of iron loss and friction loss.

3-Make connections as shown in Fig. (3). Switch on the supply. Note the direction of rotation of the rotor. Remove the auxiliary winding connections after switching off the supply. Switch on the supply and note that the rotor does not rotate. Give a slight rotation to the rotor in a particular direction and note that the rotor picks up speed in that direction.

4-Reconnect the auxiliary winding across the supply but without the capacitor in the circuit. Switch on the supply and observe if the rotor starts rotating. In case the rotor rotates, feel the magnitude of starting torque by holding the shaft. Allow the rotor to rotate and then record the readings of the instruments.

5-Run the motor with auxilary winding connected across the supply with the capacitor in the circuit. At starting feel the magnetude of starting torque by holding the rotor. Release the rotor and record the meters readings.

6-For loading the machine connect a DC supply to the stator of the three-phase induction motor as shown in Fig.(4). Increase the DC volt from zero in small steps and recoed the meters of the single phase I.M. upto the rated current record all readings.

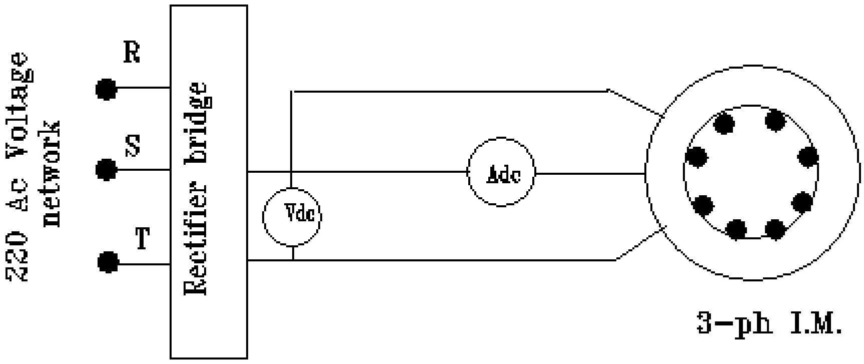


Fig.(4): 3-phase induction motor connected as dc break

10.8 Results.

Measured data

DC. B	I_{DC} [A]						
	V_{DC} [V]						
Single phase induction motor	V [V]	220 [V]					
	I_m [A]						
	I_a [A]						
	I_t [A]						
	P_n [W]						
	N [rpm]						
Calculated data							
Single phase induction motor	P_{loss} [W]						
	P_{out} [W]						
	T [N.m]						
	p.f.						
	η %						

Where;

$$P_{loss} := \text{the recorded value of wattmeter at no load} + I_a^2 R_a + I_m^2 R_m$$

$$P_{out} = P_n - P_{loss}$$

$$T = \frac{P_{out}}{2\pi \frac{N}{60}} \quad , \quad \cos\phi = \frac{P_n}{I_t V}. \quad , \quad \eta = \frac{P_{out}}{P_n}$$

9. Discussion

1- Plot N, T, P.F., and η against total current I_t

2- Comment

Three Phase Synchronous Generator Tests

1.Synchronous Machines No-Load Test

1.1. Objectives

To verify that the generated voltage in an alternator is proportional to the speed and excitation field current.

1.2. Introduction

This test is carried out with the alternator running on no-load and at rated speed. The field current and corresponding terminal voltage is recorded upto about 120% of rated terminal voltage. The characteristics showing the relationship between field current and the terminal voltage on no-load is called the open-circuit characteristic (O.C.C). The magnitude of induced emf per phase of an alternator is

$$E = 4.44\, f\, \Phi T_{ph}\, K_c\, K_d \qquad [V]$$

In the above formula

i) The frequency of the induced e.m.f can be expressed as:

$$f = \frac{P\,N}{120}$$

Where, P is the number of poles, and N is the speed of the rotor in rpm.

ii) Flux,Φ depends on the magnetude of the magnetizing current, i.e. the current following through the field winding. Thus, $\Phi \alpha\, I_f$ or $\Phi = K\, I_f$

The above relation is true up to the stage of saturation of the magnetic circuit of the machine. After saturation stage any further increase in I_f does not give rise to any appreciable increase in flux produced. Substituting the value of f and Φ in the emf equation,

$$E = 4.44 \frac{PN}{120} K\, I_f\, T_{ph}\, K_c\, K_d \qquad [\text{Volt / phase}]$$

in the above equation all terms except I_f and N are constant for a particulat machine.

Therefore, $E = K_1\, I_f\, N \qquad [V/phase]$

Therefore the induced emf of an-alternator varies in direct proportion to the field current and the speed. Further, if speed is kept constant, emf will vary in direct proportion to the field current and if field current is kept constant, emf will vary in direct proportion to the speed

The relation between the field current and the induced emf when plotted on a graph paper gives the magnetization characteristic or no-load characteristic of an alternator. A typical magnetization characteristic of an alternator is shown by the curve **A** in Fig. (8-1). Similar magnetization characteristics can be drawn at different rotor speeds. For example, if the speed is reduced by 50 per cent and kept constant at that value and the readings of induced emf are taken for various values of field current, another characteristic as shown by curve **B** of Fig. (1) can be plotted.

In Fig (1) it is seen that the characteristics do not start from the origin but a little above it. This shows that even when $I_f = 0$, the machine develops some induced emf. This is due to the residual magnetism of the field poles.

Note: To determine the effect of load on the terminal voltage, two sets of readings of terminal voltage corresponding to a particular value of field current are to be taken, one when there is no load and one when there is load connected across the output terminals, the speed of the rotor remaining constant in both the cases. For each set of readings the magnitude of load current is to be kept constant. The reasons for drop in terminal voltage of an alternator when loaded are voltage drop in the armature winding and armature reaction effect.

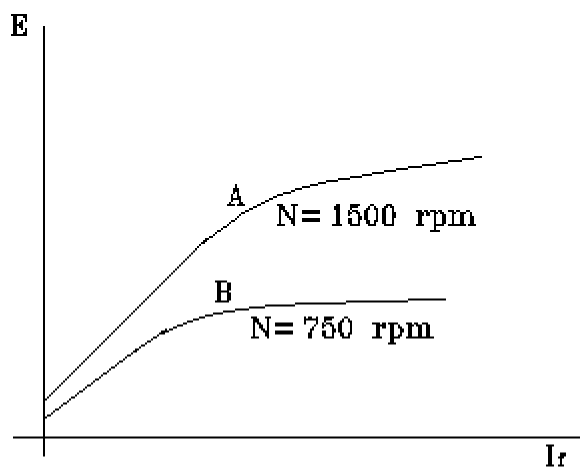


Fig.(1): Effect of speed on the magnetization characteristics of an alternator.

1.3. Experimental Procedure

Table (1): Name-plate table

DC Motor			
V_n 240 [V]	I_n 29-30 [A]	P_n 5.6 [kW]	N_n 750-2250 rpm
Excitation Separate			
V 26-120 [V]		I 0.49 - 2.3 [A]	
Three-Phase Synchronous Generator			
Rotor (is the armature); speed varies between 750-2250 rpm			
V_n 240/138 Y/Δ	I_n 12/20.8 [A]	S_n 5 [kW]	N_n 1500 rpm
F 50 c/sec		Cos φ 0.8	
Stator (is salient-pole)	V_n 120 [V]	I_n 2.4 [A]	P 4
Three- phase Tachogenerator			
V_n Y 30 [V]	I_n 0.115 [A]	P_n 6 [VA]	F 66 c/sec
At N 1000 rpm			

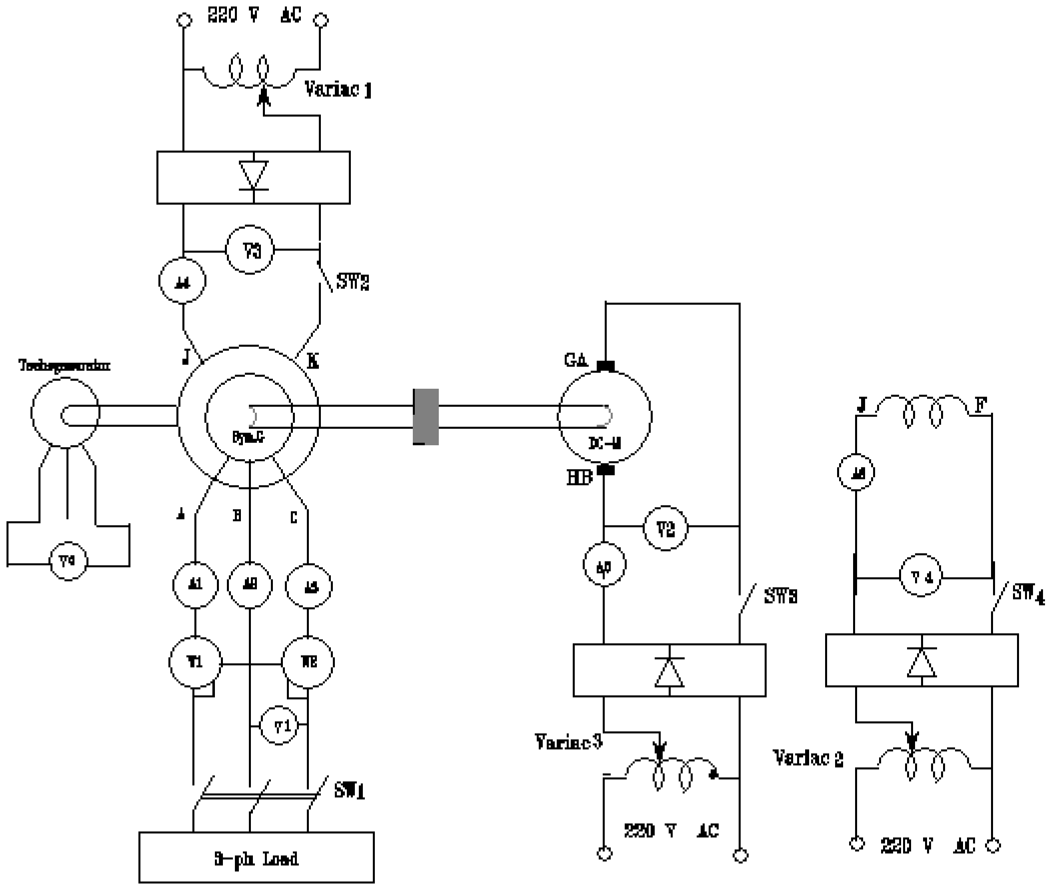


Fig.(2): Connection diagram of 3-ph Synchronous generator.

Table (2):Apparatus ratings

Variac1&2	240 V, 5A
Variac3	240 V, 20 A
A_1, A_2, A_3, A_5	0-15-30 A ≃ Ammeter
A_4, A_6	0-1-5 A = Ammeter
V_1	0-300 V ≃ Voltameter
V_2	0-300 V = Voltameter
V_3, V_4	0-150 V = Voltameter
V_5	0-50 V ≃ Voltameter
W_1, W_2	0-10-20 A / 0-60-120-240 V Wattmeters
3-ph Load	Resistive- inductive star connected

1- After making proper connection acording to Fig.(8-2) with SW_1 and SW_2open. Close SW_4 for the motor field to have proper field current then, close SW_3 of the motor armature consequently the motor rotares. Adjust the variac 3 to reach the rated speed 1500 rpm.the set up the rated speed. A little adjustment with the help of field variac 2, may be necessary. Measure the value of induced emf when If= 0. The lowest range of the voltmeter should be used as the value of induced emf will be a few volts only.

2- Close the field circuit of the alternator with the help of SW_2 with minimum value of variac1 output. Note the value of I_f and corresponding induced emf "E". Take a good number of readings up to 120% of the rated voltage of the alternator. In each case the speed should be kept constant. Take readings of E for increasing values of I_f only. Do not increase and then decrease.

3- starting from zero excitation, take another set of readings of I_f and E but at a lower speed. To reduce the speed of the set adjust the variac3 to a proper value.

5- Plot characteristics as follows:

a) E versus I_f at rated speed (1500 rpm). b) E versus I_f at half of the rated speed (750 rpm)

Table (3): Results for 1500 rpm

Rated Speed 1500 rpm																
I_f A																
E V																

Table (4): Results for 750 rpm

Half of Rated Speed 750 rpm																
I_f A																
E V																

1.4. Discution

Answer the following questions in your report:

1- Explain the shape of the magnetization characteristic of the alternator as drawn by you.

2- Explain why the magnitude of induced emf in an alternator is dependent upon

a) speed of the rotor, b) the magnitude of field current.

3. State the reasons for drop in terminal voltage of an alternator when loaded.

2. Synchronous Machines Short-CircuitTest

2.1. Objectives

To verify that the short-circuit current in an alternator is proportional excitation field current.

2.2. Introduction

Short-circuit test is performed when the alternator is running at rated synchronous speed. The armature terminals are short-circuited with a very low excitation field current. Armature short-circuit current upto rated value is recorded for various values of field current. A plot of field current versus armature short-circuit current is called short circuit chracteristic (S.C.C).

2.3. Experimental Procedure

1- Construct the wirring diagram as shown in Fig.(2), replacing the 3-phase load by symmetric short circuit.

2- Start DC motor and adjust the speed to the rated value 1500 rpm.

3- Gradually increase the excitation field current from its initial minimum value (zero field current) upto the armature short-circuit current reaches its rated value 12 A. Ensure the speed is constant at its rated value before recording.

Table (5): Results for 1500 rpm

Rated Speed 1500 rpm						
I_f A						
I_{sc} A						

2.4. Discution

Answer the following question in your report:

1- Explain why the relation between the armature short-circuit current and excitation fiel current is linear.

2- Is the machine in this test is loaded or not, if yes, which kind of loading ?

3. Synchronous Machines Voltage Regulation

3.1. Objectives

1- To determine the regulation of an alternator by two methods:

a) Synchronous Impedance Method b) Ampere-Turn Method c) Potier Method

2- To determine the efficiency of an alternator by measuring its losses through open circuit and short-circuit tests at different power factors and loads.

3.2. Introduction

The variation of the terminal voltage of an alternator between full- load and no-load, expressed as percentage of full-load voltage is called the percentage voltage of the alternator, i.e. V when loaded and E when the load is taken off. In actual practice it will be difficult to load a big alternator in the testing laboratory as the laboratory may not have such heavy loads. Moreover, during the testing period a considerable amount of electrical power will be wasted as tosses in the machine and in the load. That is why regulation of large alternators are not generally determined by direct loading method.

Regulation of an alternator can be determined from the results of the following two tests:

a) Open-circuit test, b) Short-circuit test.

3.2.1 Open-Circuit Test

This test is carried out with the alternator running on no-load and at rated speed. The field current and corresponding terminal voltage is recorded up to about 120 per cent of rated terminal voltage. The characteristic showing the relationship between field current and the terminal voltage on no-load is called the open-circuit characteristic (0. C. C).

3.2.2 Short-Circuit Test

Short-circuit test is performed when the alternator is running at rated rpm. The armature terminals are short-circuited with a very low excitation current. Armature current up to rated value is recorded for various values of field current. A plot of field current versus armature versus armature current is called short circuit characteristic (S. C. C). Since the emf generated on open circuit may be regarded as being responsible for circulating short-circuit current may be regarded as being responsible for circulating short-circuit current through the synchronous impedance, the value of synchronous impedance is taken as the ratio of the open-circuit voltage per phase to the short-circuit current per phase for a particular field current.

It may be noted that the value of the synchronous impedance calculated here is the unsaturated value (higher than the actual value), since the excitation under short-circuit condition is much lower than the normal value. The do resistance of the stator winding can be calculated by ammeter-voltmeter method. The ac resistance is higher than the do resistance. The value of do resistance calculated may be multiplied by a factor of 1.3 to calculated the ac resistance. The synchronous reactance can be, calculated as $X_s = \sqrt{Z_s^2 - R_a^2}$

That can be done by using the results of O.C.C and S.C.C. tests at same values of field current, as given Table (6), and shown in Fig.(3).

Table (6): Impedance calculation

I_f [A]						
O.C. Volt/ph						
S.C. Amps/ph						
Z_s [Ω]/ph						

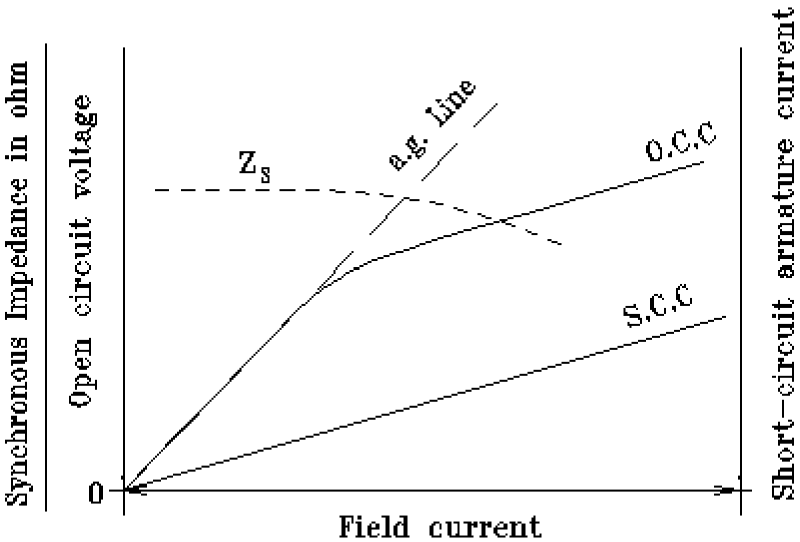


Fig.(3): Synchronous impedance calculation

3.2.3 Calculation of Voltage Regulation By Using Impedance Method

The relationship between terminal voltage and induced emf for a lagging/ leading power-factor load is given by the following expression:

$$E = \sqrt{(V\,Cos\varphi + mI_a\,R_a)^2 + (VSin\,\varphi \pm mI_a\,X_s)^2}$$

Where;

V:= the rated terminal voltage Volt/ph.

I_a:= the rated current of m/c Amp/ph

R_a:= the armature resistance of m/c Ω/ph

X_s:= the synchronous reactance of m/c Ω/ph, $X_s = \sqrt{Z_s^2 - R_a^2}$

Z_s:= the synchronous impedence of m/c Ω/ph, $Z_s = V_{rated}/I_{rated}$

φ:= the power factor angle

m:= load ratio (I_L/I_a)

± := +ve for lagging power factor , –ve for leading power factor and φ=0 for unity power factor

Table (7): Calculation of voltage regulation by impedance method

m (load ratio)	0	0.25	0.5	0.75	1.0	1.25
V.R at UPF						
V.R at 0.8 lag						
V.R at 0.8 lead						

Note: This method provides a higher values for voltage regulation because taking X_s is a constant value.

3.2.4 Calculation of Voltage Regulation By Using Ampere/ Turn Method

1- From O.C.C. find I_{f1} corresponding to the rated voltage.

2- From S.C.C. find I_{f2} corresponding to the rated current.

3- Calculate I_{ftot} from the following equation according to the vector diagram.

$$I_{ftot} = \sqrt{(I_{f1} \pm m\,I_{f2}Sin\varphi)^2 + (m\,I_{f2}Cos\varphi)^2} \quad \text{Amp}$$

4- Find the emf corresponding to I_{ftot} from O.C.C. and calculate the armature reaction voltage drop from the following equation $m\,I_a\,X_a = \sqrt{E^2 + V^2 - 2VE\,Cos\delta}$, where

$$\delta = \tan^{-1} \frac{m I_{f2} \cos\varphi}{I_{f1} \pm m I_{f2} \sin\varphi}.$$

Knowing I_a, X_a will be calculated

Note: This method neglect the leakage reactance of the machine and take X_s equals to X_a ,so it is not accurate method.

Table (8): Calculation of voltage regulation by Amper-Turn method for Cos φ= 1

I_{f1} = [Amp]		I_{f2} = [Amp]		Cos φ= 1	V=220 [V], Ia=12 [A]	
m	0	0.25	0.5	0.75	1.0	1.25
I_{ftot} [A]						
E [V]						
δ°						
%V.R.						
$m I_a X_a$						

Table (9): Calculation of voltage regulation by Amper-Turn method for Cos φ= 0.8 Lag

I_{f1} = [Amp]		I_{f2} = [Amp]		Cos φ= 0.8 Lag	V=220 [V], Ia=12 [A]	
m	0	0.25	0.5	0.75	1.0	1.25
I_{ftot} [A]						
E [V]						
δ°						
%V.R.						
$m I_a X_a$						

Table (10): Calculation of voltage regulation by Amper-Turn method for Cos φ= 0.8 lead

I_{f1} = [Amp]		I_{f2} = [Amp]		Cos φ= 0.8 lead	V=220 [V], Ia=12 [A]	
m	0	0.25	0.5	0.75	1.0	1.25
I_{ftot} [A]						
E [V]						
δ°						
%V.R.						
$m I_a X_a$						

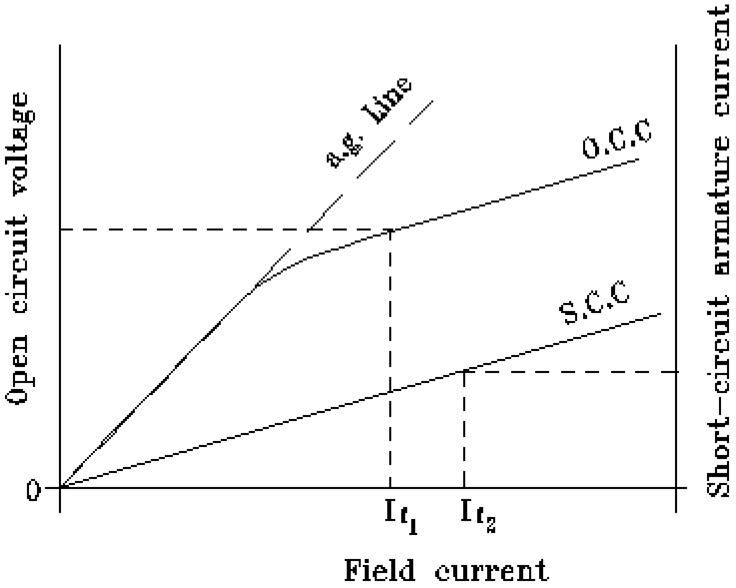


Fig.(4): Voltage regulation using Ampere-Turn method.

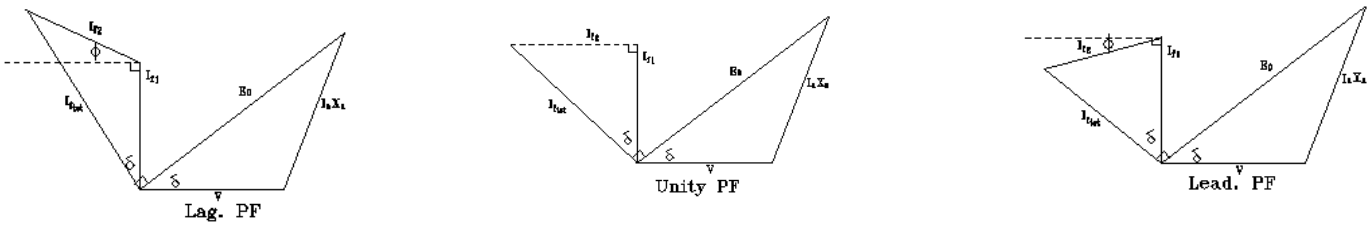


Fig.(5): Vector diagram for different power factors.

3.2.5 Calculation of Voltage Regulation By Potier Method

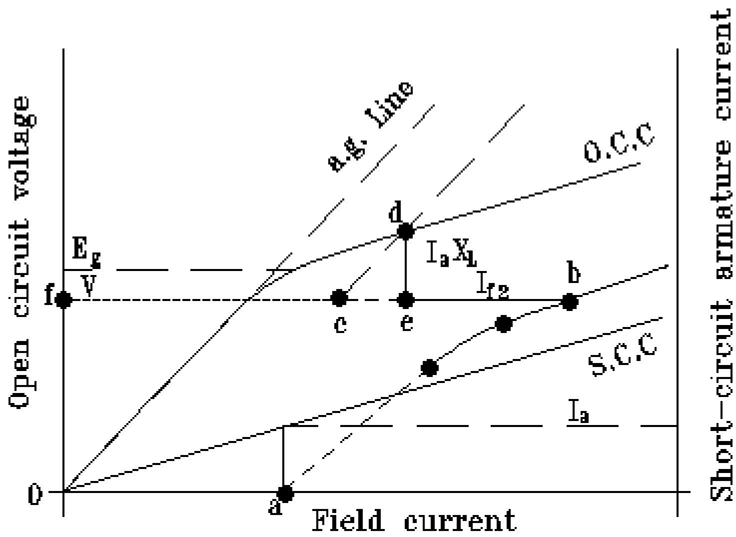


Fig.(6): Voltage regulation using Potier method

To calculate the voltage regulation by Potier method we need the O.C.C. , S.C.C. and Z.P.F. tests. The O.C.C. and S.C.C tests have been explained before. Z.P.F. tests will be explained as given below;

1- Conect the system according to the wirring diagram as shown in Fig.(2), using a pure variable 3-phase inductive load.

2- Start DC motor and adjust the speed to the rated value 1500 rpm, keep it constant.

3- Ensuring that the excitation field current is at minimum value.

4- Take different values of the terminal voltage and the field current at constant armature current(rated value 12 A) where the inductive load has variable values.

5- Rising the excitation field current causes the armature current increasing so the inductive load should be increased to keep the armature current constant at its rated value.

6- Find from S.C.C.test the field current corresponding to the rated armature current (12 A) this point will be one point of Z.P.F. test at V=0

<u>**Note**</u>**:**

a) The test results should be containing two imortant points, one at the rated voltage and the other from short-circuit test find the field current at zero voltage.

b) Plot this characteristics parallel to and in the same area of the no-load charcteristics c shown in Fig.(6) .

How to calculate the voltage regulation:

1- Draw a line at the rated terminal voltage intersecting the vertical axis at **f** and Z.P.F. at **b**.

2- From point **b** take a distance equal to **oa** will be **bc** and from point **c** draw a line parallel to the air-gap line intersecting the O.C.C at **d** . The Potier triangle will be **dcb**.

3- Draw a perpendecular line from **d** to the base line **cb** intersecting at **e**.

4- Line **de** is the leakage reactance voltage drop ($I_a X_L$)

5- Line **eb** represent the field current I_{f2}.

6- From the following equation we can calculate the air-gap voltage E_g

$$E_g = \sqrt{(V\,Cos\varphi + mI_a\,R_a)^2 + (VSin\,\varphi \pm mI_a\,X_L)^2}$$

where;

V:= the rated terminal voltage Volt/ph.

I_a:= the rated current of m/c Amp/ph

R_a:= the armature resistance of m/c Ω/ph

X_L:= the leakage reactance of m/c Ω/ph, $X_L = \dfrac{\overline{de} \text{ in volt}}{I_a}$

φ:= the power factor angle

m:= load ratio (I_L/I_a)

± := +ve for lagging power factor , –ve for leading power factor and φ=0 for unity power factor

7- Find the corresponding field current (I_{f1}) to the air-gap voltage E_g .

8- Draw the vector diagram represented the condition of operation as shown

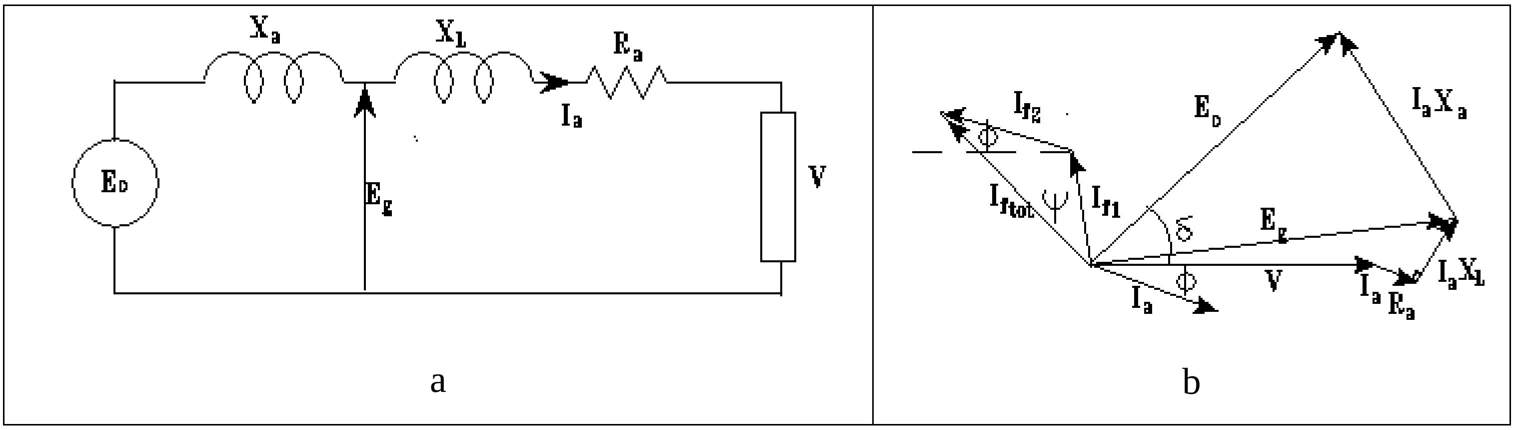


Fig.(7): The equivalent circuit and vector diagram for

Potier method at rated current and lagging power factor

Table (11): Calculation of voltage regulation by Potier method for Cos φ= 1

Ia=12 [A]		Cos φ= 1		V=220 [V],		
m	0	0.25	0.5	0.75	1.0	1.25
E_g [V]						
I_{f1} [A]						
I_{f2} [A]						
I_{ftot} [A]						
E_o [V]						
%V.R.						
$I_a X_a$						
δ°						

Table (12): Calculation of voltage regulation by Potier method for Cos φ= 0.8 Lag

Ia=12 [A]			Cos φ= 0.8 lag		V=220 [V],	
m	0	0.25	0.5	0.75	1.0	1.25
E_g [V]						
I_{f1} [A]						
I_{f2} [A]						
I_{ftot} [A]						
E_o [V]						
%V.R.						
$I_a X_a$						
δ°						

Table (13): Calculation of voltage regulation by Potier method for Cos φ= 0.8 lead

Ia=12 [A]			Cos φ= 0.8 lead		V=220 [V],	
m	0	0.25	0.5	0.75	1.0	1.25
E_g [V]						
I_{f1} [A]						
I_{f2} [A]						
I_{ftot} [A]						
E_o [V]						
%V.R.						
$I_a X_a$						
δ°						

Discussion

Compare between the voltage regulation methods stated above.Comment.

3.2.6. Calculation of Efficiency

In open-circuit test, the input to the alternator, i.e. the power required to drive the alternator is spent as, friction and windage loss and iron-loss. If the field of the alternator is kept unexcited, the input to the alternator will be equal to the friction; and windage loss of the alternator. Input to the alternator can be calculated by measuring the input to the motor driving the alternator and by knowing the efficiency of the driving motor thus: .

Input to the alternator = Input to the driving motor * Efciency of the driving motor

(Since output of the driving motor is equal to the input to the alternator.)

Note. The efficiency of the driving motor should be known or may be determined. For the purpose of calculation, the efficiency of the driving motor may be assumed suitably. Thus by measuring the input to the driving motor the friction and windage loss at rated speed and iron-loss at rated excitation voltage and speed can be

Calculated (two readings will have to be taken).

In short-circuit test the input to the alternator is spent as: $I_a^2 R_a$ (is the loss in the armature winding), friction and windage loss and a small amount of iron-loss. If the input power is recorded when full-load current is flowing through the short circuited armature, neglecting the small amount of iron- loss, $I_a^2 R_a$ loss can be calculated thus:

$I_a^2 R_a$ loss at full-load = Input to the alternator at full load short armature current circuit condition - Friction and windage loss at rated speed.

Thus from the open-circuit and short-circuit test data the following can be calculated:

a) Full-load $I_a^2 R_a$ loss (X),

b) Friction and windage loss at rated speed (Y),

c) Iron-loss at rated speed and rated voltage (Z).

The full-load efficiency of the alternator can be calculated thus:

Full-load efficiency =Output at full-load/ (Output at full-load +losses

one with no field excitation and one with rated excitation) *100

3.3. Experimental Procedure

1- Make connections as per circuit diagram shown in Fig. (2). Start the set with the help of a do motor and bring the speed of the set up to the rated speed of the alternator.

2- Excite the alternator with minimum field current and record the induced emf of the alternator for various values of field current at constant speed up to 120 % of the rated voltage of the alternator. Take at least ten readings at approximately equal increasing values of field current While taking readings, at no time decrease the field current of the alternator. Note down the readings of all the meters with rated excitation and also with no excitation.

3- With the field excitation of the alternator switched off, adjust the speed of the alternator to its rated speed.

4- Short circuit the armature terminals of the alternator with no field excitation.

5- Switch on the field excitation with minimum field current, then increase the field current till rated full-load current flows through the armature winding of the alternator. Record the data as per tables indicated and then switch off the set. Note the specifications of all the instruments and the set.

6. Measure the armature resistance of the alternator by ammeter-voltmeter method by applying very low do voltage, to its armature.

Table (14): Open-circuit test , Speed of the set = rated speed = ---------rpm

I_f Amp										
E V/ph										

Table (15): Short-circuit test , Speed of the set = rated speed = ---------rpm

I_f Amp										
I_{asc} Amp										

Losses test

At rated excitation and rated speed,
Input to do motor:
V=   volt
I =   Amp

p=   V.I .=   W

At rated speed with no excitation,
Input to do motor,
V=   volt
I =   Amp

p=   V.I .=   W

At rated speed and full-load current flowing through the alternator armature, Input to dc motor:
V=   volt
I =   Amp

p=   V.I .=   W

Note. Assuming a particular value of efficiency say 80 per cent for the d c motor, make calculations for various losses of the alternator and hence find its efficiency.

Table (16): Efficiency calculations at unity power factor

Friction losses = Y		Iron loss = Z		o/p = kVA*cos φ	
m load ratio	0.25	0.5	0.75	1.0	1.25
$m^2\ I_a^2 R_a$					
η %					

Table (17): Efficiency calculations at 0.8 lag. power factor

Friction losses = Y		Iron loss = Z		o/p = kVA*cos φ	
m load ratio	0.25	0.5	0.75	1.0	1.25
$m^2\ I_a^2 R_a$					
η %					

Where; $\eta = \dfrac{m * kVA * Cos\varphi}{m * kVA * Cos\varphi + \left(Y + Z + m^2 * X\right)} * 100$

3.4. Discussions

Answer the following questions in your report:

1. Draw the open-circuit and short-circuit characteristics of the alternator at rated speed on a common scale for field current on X-axis, and calculate the synchronous impedance and synchronous reactance. Explain why the value of synchronous reactance thus calculated is called the unsaturated value. Is the unsaturated value smaller than the saturated value?
2. Calculate the value of regulation of the alternator at full-load and at a) unity powerfactor, b) 0.8 lagging power-factor and c) 0.8 leading power-factor.
3. Write down the value of the following losses of the alternator under test: a) full-load armature $I_a^2 R_a$ loss b) friction and windage losses, c) iron-loss.
4. Calculate the fill-load efficiency of the alternator.
5. Mention the advantages and disadvantages (if any) of finding regulation of an alternator by synchronous impedance method (indirect method) than by direct loading method.
6. Mention why the speed of rotation of the alternator should remain constant at rated speed while performing the open-circuit test.
7. Explain the shape of the open-circuit characteristic of the alternator drawn by you.
8. Explain why the regulation of an alternator is more at 0.8 lagging power-factor than at unity power-factor.

4- THE EXTERNAL CHRACTERISTICS
OF THREE PHASE ALTERNATOR

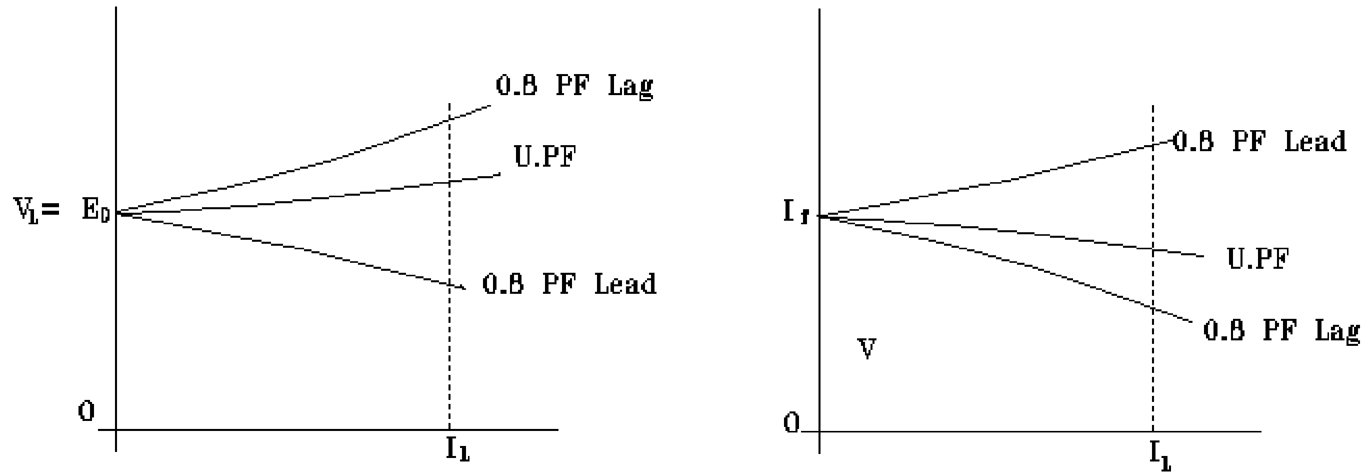
4.1. Objective

This test do to determine and plot the load characteristics of alternator for:

a) constant field current and b) constant terminal voltage.

4.2. Introduction

The alternator likes a dc generator, when loaded, its terminal voltage changes due to : a) voltage drop in armature windings and b) due to armature reaction effect. The effect of armature reaction on the terminal voltage is also depending upon the natural of load. That means the amount of variation of terminal voltage from full load to no-load depend upon the power factor of the load, that for constant excitation operation as shown in Fig.(8-a).



a- Constant field current . b- Constant terminal voltage.

Fig.(8): the external characteristics of 3-phade alternator.

Fig.(8-b) shows the amount of excitation required to maintain constant terminal voltage of an alternator at different load power factor.

4.3. Experimental Procedure

1- Construct the wirring diagram as shown in Fig.(2), using a pure variable 3-phase resistive load.

2- Start DC motor and adjust the speed to the rated value 1500 rpm, keep it constant.

3- Adjust the excitation field current to get the rated terminal voltage at no-load.

4- Take different values of the terminal voltage and the armature current at constant field current where the resistive load has variable values.

5- Reapet step 4, to take different values of the field current and the armature current at constant terminal voltage (the rated value at no-load).

Table (18): Constant Field Current Operation

Constant speed at 1500 rpm, I_f = [A]						
I_L Amps						
V Volts						

Table (19): Constant Terminal Voltage Operation

Constant speed at 1500 rpm, V= 220 [V]						
I_L Amps						
I_f Amps						

4.4. Discussion

Calculate the values of voltage regulation from the two charcteristics you have plotted using the no-load characteristics, if it needed. And plot the regulation against the armature current, comment.

Table (20): Constant Field Current Operation

Constant speed at 1500 rpm, I_f = [A], E= 220 [V]						
I_L Amps						
V Volts						
% V.R						

Table (21): Constant Terminal Voltage Operation

Constant speed at 1500 rpm, V= 220 [V]						
I_L Amps						
I_f Amps						
E [V]						
% V.R						

5. Synchronous Machines Parallel Operation

5. 1. Objectives

1- To synchronize a three-phase alternator with the bus-bar using

i) Three lamp method ii) Synchronoscope method

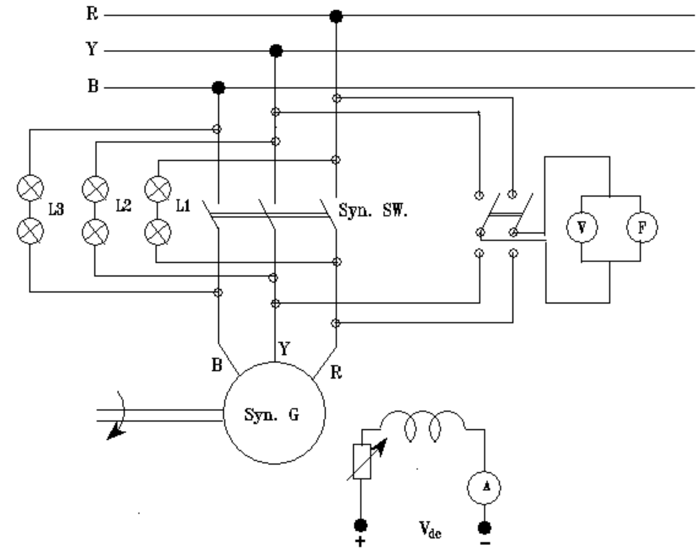
2- To study load sharing.

5.2.Introduction

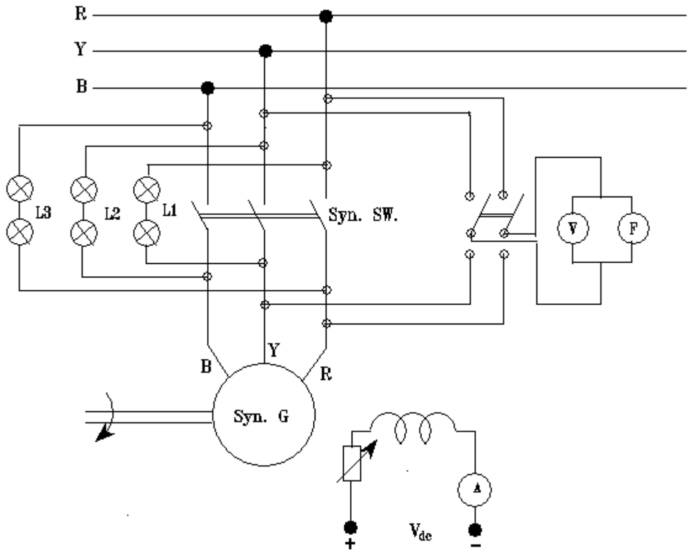
In power stations a number of alternators run in parallel. All the alternators are synchronized with a common bus-bar. The load is connected across the bus-bar. The alternators running in parallel share the total load proportionate to their ratings. In the event of increased demand of load' on a power station, additional generating sets are required to be connected in parallel with the bus bar. Before an alternator can be connected in parallel with the bus bar it should be synchronized with the lamp method. The following conditions are to be fulfilled before connecting an alternator in parallel with others: a) The voltages of the alternator should be the same as the bus-bar voltage. b) The frequency of voltage of the alternator should be the same as the bus-bar voltage frequency. c) The phase sequence of the voltages of the three-phase alternator to be connected in parallel should be the same as that of the bus bar, i.e. the other alternators. d) At the instant when the paralleling switch is closed, the voltages of the alternator should be in time-phase with the bus-bar voltage.

5.2.1 Three-lamp Method of synchronization

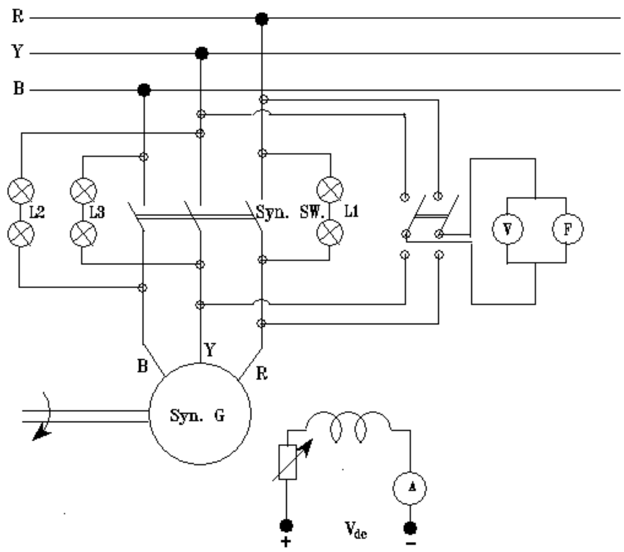
This method divided among three cases; Dark lamps, Light lamps and dark-light lamps as shown in Fig.(1). In the third method see, Fig. (1-c), note that one pair of lamps are connected between the R phase of the alternator, and the R phase of the bus bar. Other two pairs of lamps are connected between the Y phase of the alternator and The B phase of the bus bar and vice versa. Here two lamps are connected in series as the maximum voltage, which will appear across the lamps, will be the line voltage, i.e. 400V, (for a 400V machine). As lamps are generally **rated for 230V, for safety** reasons, we need to connect two lamps in series. When the alternator is brought to rated speed and provided with excitation, voltages



a) Dark Method



b) Light Method



c) Dark-Light Method

Fig.(1): Three-lamp Method of synchronization

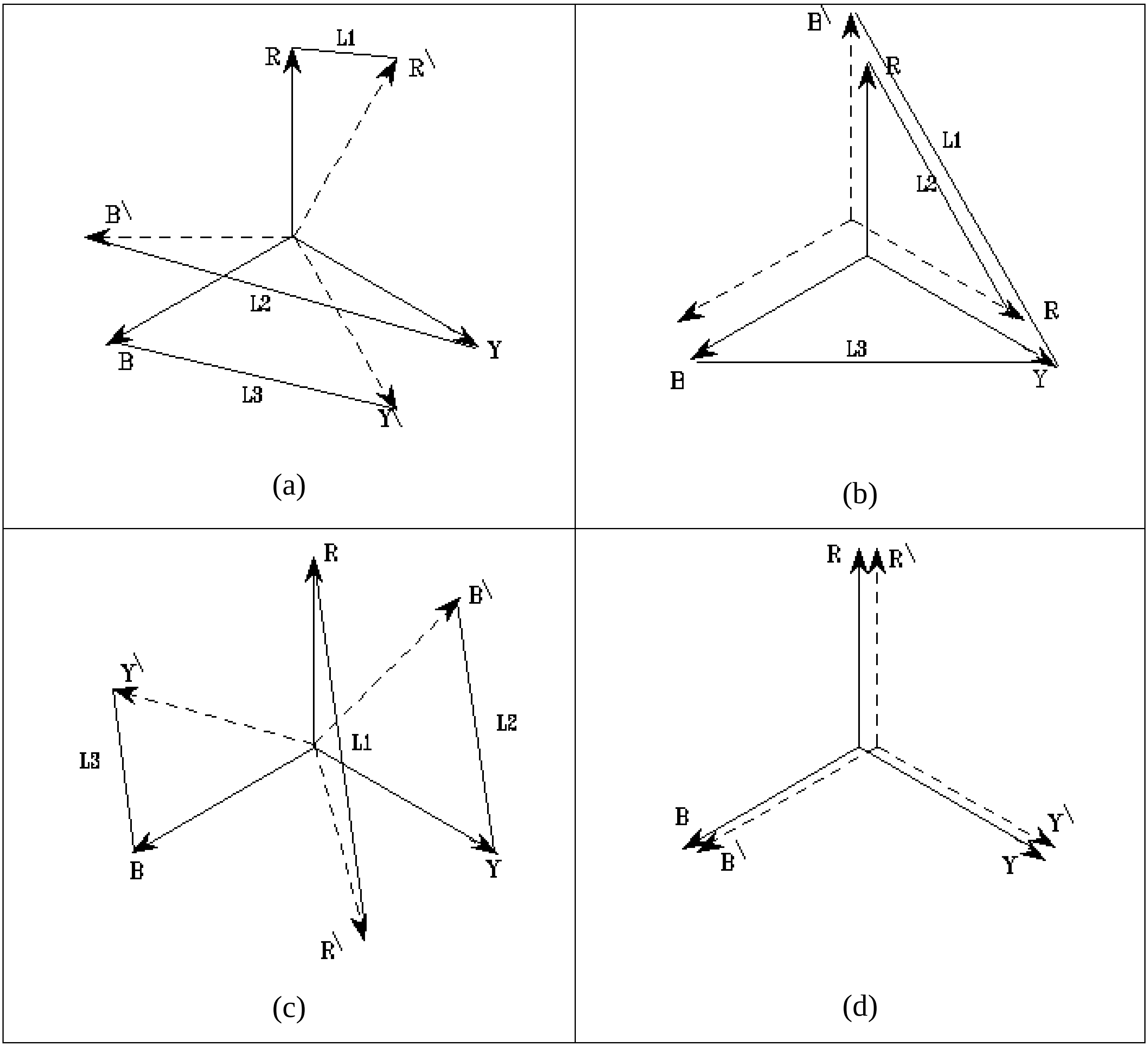


Fig.(2): Three voltages of the bus-bar and alternator during the synchronization as shown in time phase

At the correct instant of synchronization we find that;

a) For Dark Method   L1, L2, L3 are dark.

b) For Light Method L1, L2, L3 are have maximum light

c) For Dark-Light Method L1 is dark and L2, L3 are light.

will be induced across the alternator terminals which can be made equal to the bus-bar voltage by adjusting the field excitation of the alternator. Fig. (2) shows the different instants of the alternator voltages with respect to the bus-bar voltages. Phasors drawn in thick lines indicate the three voltages of the alternator. If all the conditions of synchronization are fulfilled, then the two sets of phasors at a particular instant of time will be in position as shown in Fig. (2-d). At that instant the switch Syn.SW can be closed and the alternator will run in parallel with the bus-bar.

In the Dark-Ligh method of synchronization, at the moment of synchronization the lamps connected in phases RR\ will be dark whereas other two pairs of lamps will be bright as full-line voltages will be appearing across them. If the frequency of the incoming alternator is more than the bus-bar frequency, the lamps will be darken in the sequence 132132…

This will indicate that the speed of the alternator should be reduced. On the other hand, if the frequency of the alternator is less than the bus-bar voltage frequency then the lamps will be darken in sequence 123123 .... This will indicate that the speed of the alternator should be increased. The above is explained through series of phasor diagrams as shown in Fig. (2).

5.2.2 Synchrocsope Method

One of the instruments to indicate accurately the point of synchronization is the *synchronoscope.* In its common form it utilises a split-phase arrangement to give a rotating field which is excited by the other generator which is to be synchronized. If the frequency of the income allternator differ from the Frequency of the bus-bar, the reaction of the two fields is to produce rotation. A pointer connected to the rotor moves over the dial face and indicates the relative phase positions of the system. The direction of rotation, clockwise or anticlockwise, indicates whether the incoming alternator is running too fast or too slaw. Sometimes it is not possible to use lamps or a synchronoscope on higher voltages of the bus-bars ; hence small transformers are introduced to reduce the voltage applied to the synchronism indicator. The dial face, showing the marking shown in Fig. (3).

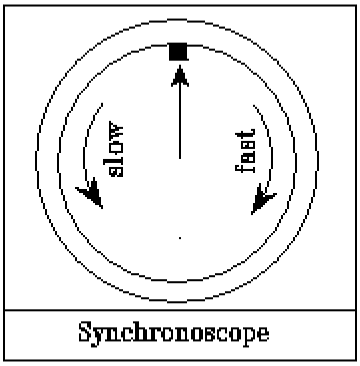


Fig.(3): Synchronoscope device

When the pointer stops in the vertical the frequencies are equal, and the voltages are in phase, and when this is so, the paralleling switch may be closed.

5.3. The Analysis of Operation Modes of Synchronous Machine

When the synchronous machine is connected to the bus-bars after the synchronization instant the machine is floating i.e. the operation mode not defined. It can be operated with or without the prime-mover as follows;

a) without the prime-mover the machine drawn from the bus-bars the active power needed to recover the no-load losses for no-load operation. If the excitation regulated without loading the shaft it can be operate as condenser, hence supplies the bus-bars with reactive power. If the shaft loaded by a mechanical load ,it operates as a motor and drawn the reactive power needed to the load from the bus-bar.

b) with the prime-mover the machine will supply the bus-bars with active power according to the mechanical power on the shaft.

5.3.1. Operation as synchronous condenser

The main advantage of the synchronous condenser is its ability to take leading current, thus it increases the power factor of the plants that employ inductive apparatus. If a plant or a factory has too many induction machines, it’s more economical to remove some induction motors by synchronous motors.

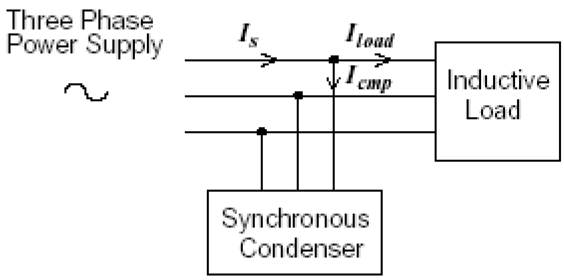


Fig.(4): Power factor compensation for an inductive load using a synchronous condenser

The leading currents of synchronous motor may rise the over-all power factor of the plant in this way the reactive power is supplied locally; the power factor of the load is improved. A synchronous motor used in this way is some times called **a synchronous capacitor,** since by drawing a leading component of the current from the line, it acts like a capacitance see Fig.(4).

5.3.2. Operation as synchronous motor

Electromagnetic Power and Torque

When a synchronous machine is operated as a motor to drive a mechanical load, in steady state, the mechanical torque of the motor should balance the load torque and the mechanical loss torque due to friction and windage, that is $T = T_{load} + T_{loss}$

Multiplying the synchronous speed to both sides of the torque equation, we have the power balance equation as $P_{em} = P_{load} + P_{loss}$

where $P_{em} = T\omega_{syn}$ the electromagnetic power of the motor, $P_{load} = T_{load}\,\omega_{syn}$ is the mechanical

power delivered to the mechanical load, and $P_{loss} = T_{loss}\,\omega_{syn}$ the mechanical power loss of the system. Similar to the case of a generator, the electromagnetic power is the amount of power being converted from the electrical into the mechanical power. That is

$P_{em}=3\,E_a\,I_a\,\text{Cos}\,\varphi_{Ea\,Ia} = T\omega_{syn}$

where $\varphi_{Ea\,Ia}$ is the angle between phasors $\mathbf{E}_a$ and $\mathbf{I}_a$.

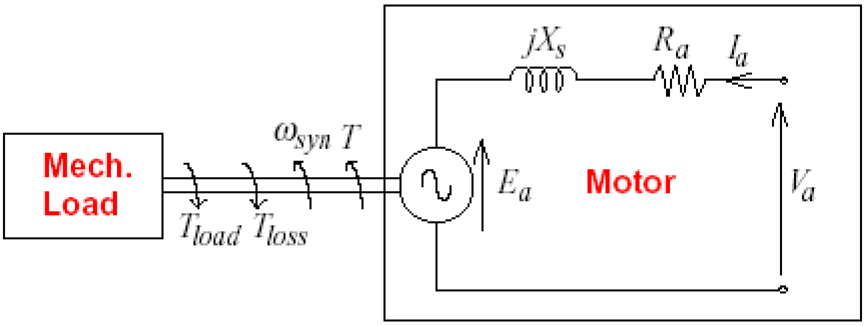


Fig.(6): A synchronous machine operated as motor

When the stator winding resistance is ignored, the per phase circuit equation can be approximately written as $V_a = E_a + j X_s I_a$

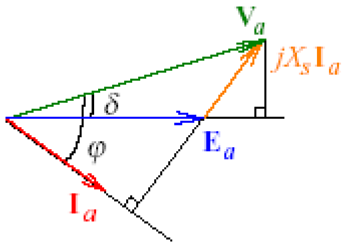


Fig.(6): Motor phasor diagram

The corresponding phasor diagram is shown in Fig.(6). From the phasor diagram, we can readily obtain

$V_a \sin\delta = X_s I_a \cos\varphi_{Ea\,Ia}$ Where; $\varphi_{Ea\,Ia} = \varphi - \delta$

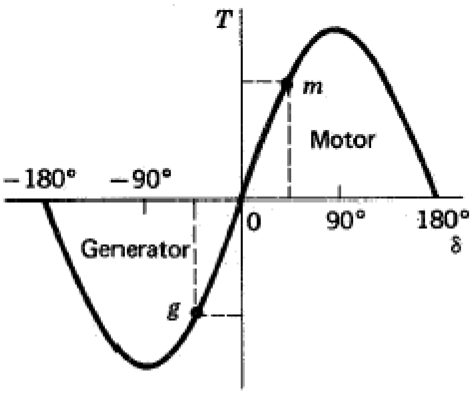


Fig.(7): Electromagnetic torque vs. load angle

Therefore,

$$P_{em} = \frac{3 V_a E_a}{X_s} \sin\delta \qquad \text{and} \qquad T = \frac{P_{em}}{\omega_{syn}} = \frac{3 V_a E_a}{\omega_{syn} X_s} \sin\delta$$

where δ is the ***load angle***. When the stator winding resistance is ignored, δ can also be regarded as the angle between the rotor and stator rotating magnetic fields. In motor mode, the stator field is ahead of the rotor. The electromagnetic torque of a synchronous machine is proportional to the sine function of the load angle, as plotted in Fig.(7), where the curve in the third quadrant is for the situation when the machine is operated as a generator, where the electromagnetic torque is negative because the armature current direction is reversed.

Synchronous Motor Power Factor

Assume that a synchronous motor is driving a constant torque load. The active power converted by the machine is constant, no matter what the value of the field current is, since the motor speed is a constant. Thus,

$$T = \frac{3 V_a E_a}{\omega_{syn} X_s} \sin\delta = \text{Constant} \qquad \text{or} \qquad E_a \sin\delta = \text{Constant}$$

$$\& \quad P_{em} = 3 V_a I_a \cos\varphi = \text{Constant} \qquad \text{or} \qquad I_a \cos\varphi = \text{Constant}$$

Using the phasor diagram below, we analyze the variation of the power factor angle of a synchronous motor when the rotor field excitation is varied. For a small rotor field current the induced *emf* in the stator winding is also small, as shown by the phasor $\mathbf{E}_{a1}$. This yields a lagging power factor angle $\varphi_1 > 0$. As the excitation current increases, the lagging power factor angle is reduced. At a certain rotor current, the induced emf phasor $\mathbf{E}_{a2}$ is perpendicular to the terminal voltage phasor, and hence the stator current phasor is aligned with the terminal voltage, that is a zero power factor angle $\varphi_2 = 0$. When the rotor current further increases, the stator current leads the terminal voltage, or a leading power factor angle $\varphi_3 < 0$. In the phasor diagram Fig.(8), the above two conditions on E_a and I_a mean that they will only be able to vary along the horizontal and the vertical lines, respectively, as shown below.

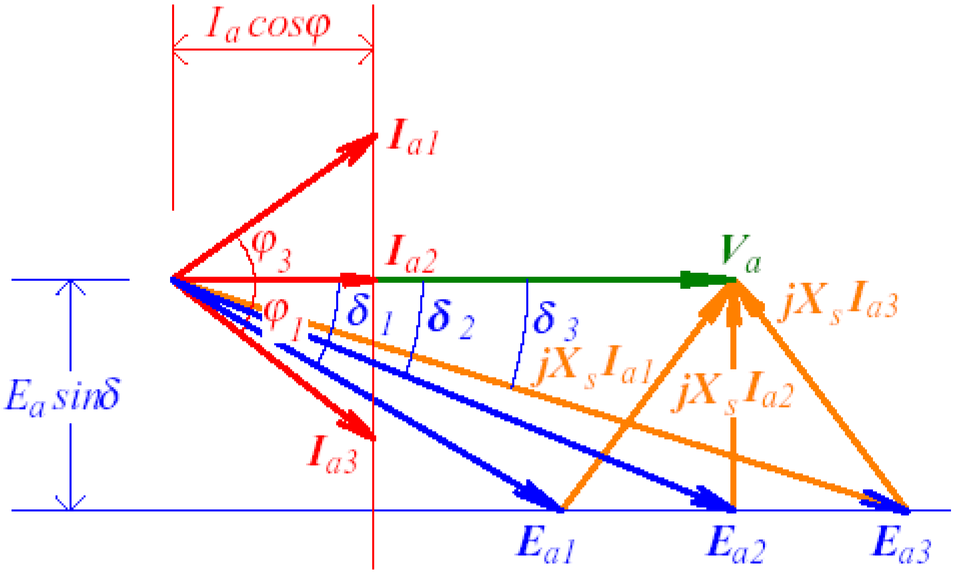


Fig.(8): Phasor diagram of a synchronous motor in under excitation, unit power factor, and over excitation mode

For conversion of a certain amount of active electrical power into mechanical power, a certain amount of magnetic flux is required. In the case of a lagging power factor, the rotor field current is so small that some reactive power is required from the stator power supply, and hence the stator current lags the terminal voltage. This state is known as ***under excitation***. When the rotor field current is just enough to produce the required magnetic flux, a unit power factor is obtained. If the rotor field current is more than required the spurious reactive power is to be exported to the power lines of the power supply. This state is known as ***over excitation***.

In practice, because of this feature, synchronous motors are often run at no active load as ***synchronous condensers*** for the purpose of power factor correction. The diagram underneath the phasor diagram illustrates schematically the power factor compensation for an inductive load, which is common for factories using large induction motor drives, using a synchronous condenser. By controlling the rotor excitation current such that the synchronous condenser draws a line current of leading phase angle, whose imaginary component cancels that of the load current, the total line current would have a minimum imaginary component. Therefore, the overall power factor of the inductive load and the synchronous condenser would be close to one and the magnitude of the overall line current would be the minimum. It can also be seen that only when the power factor is unit or the stator current is aligned with the terminal voltage, the magnitude of the stator current is minimum. By plotting the magnitude of the stator current against the rotor excitation current, a family of “V” curves can be obtained. It is shown that a larger rotor field current is required for a larger active load to operate at unit power factor.

5.3.3. Operation as synchronous generator

Electromagnetic Power and Torque

When a synchronous machine is operated as a generator, a prime mover is required to drive the generator. In steady state, the mechanical torque of the prime mover should balance with the electromagnetic torque produced by the generator and the mechanical loss torque due to friction and windage, or $T_{pm} = T + T_{loss}$

Multiplying the synchronous speed to both sides of the torque equation, we have the power balance equation as

$P_{pm} = P_{em} + P_{loss}$

where $P_{pm} = T_{pm}\omega_{syn}$ is the mechanical power supplied by the prime mover, $P_{em} = T\omega_{syn}$ the electromagnetic power of the generator, and $P_{loss} = T_{loss}\omega_{syn}$ the mechanical power loss of the system. The electromagnetic power is the power being converted into the electrical power in the three phase stator windings. That is $P_{em} = T\,\omega_{syn} = 3\,E_a\,I_a\,\mathrm{Cos}\,\varphi_{Ea\,Ia}$,

where $\varphi_{Ea\,Ia}$ is the angle between phasors $\mathbf{E}_a$ and $\mathbf{I}_a$.

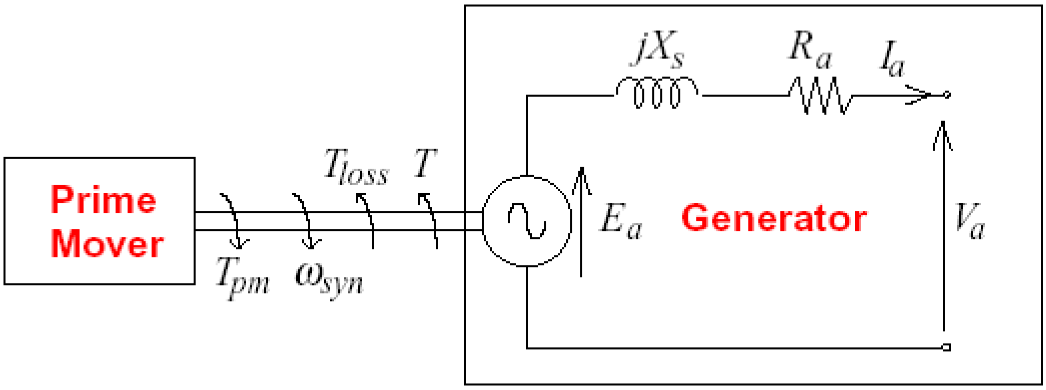


Fig.(9): A synchronous machine operated as generator

For larger synchronous generators, the winding resistance is generally much smaller than the synchronous reactance, and thus the per phase circuit equation can be approximately written as $V_a = E_a - j\,X_s\,I_a$

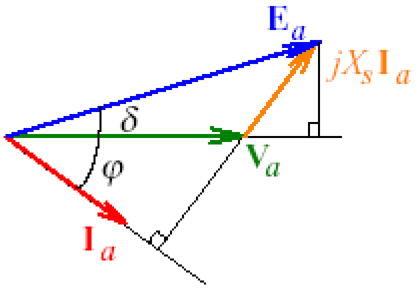


Fig.(10): Generator phasor diagram

The corresponding phasor diagram is shown in Fig.(10) From the phasor diagram, we can readily obtain $E_a \sin\delta = X_s I_a \cos\varphi$

When the phase winding resistance is ignored, the output electrical power equals the electromagnetic power, or $P_{em}=P_{out}= 3 V_a I_a \cos\varphi$

Therefore

$$P_{em} = \frac{3E_a V_a}{X_s}\sin\delta \qquad \text{and} \quad T = \frac{P_{em}}{\omega_{syn}} = \frac{3E_a V_a}{\omega_{syn} X_s}\sin\delta$$

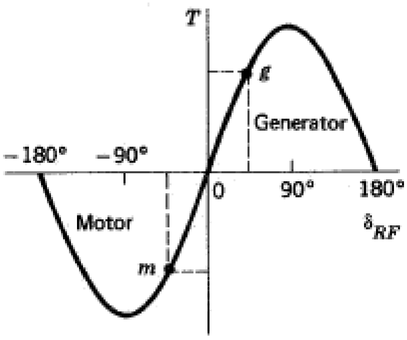


Fig.(11): Electromagnetic torque vs. load angle

where δ is the angle between the phasors of the voltage and the emf, known as the ***load angle***. When the stator winding resistance is ignored, δ can also be regarded as the angle between the rotor and stator rotating magnetic fields. The electromagnetic torque of a synchronous machine is proportional to the sine function of the load angle, as in Fig.(11) above, where the curve in the third quadrant is for the situation when the machine is operated as a motor, where the electromagnetic torque is negative because the armature current direction is reversed.

Voltage Regulation

The terminal voltage at constant field current varies with the armature current, or load current; that is, the generator has regulation that becomes more marked as the load circuit becomes more inductive and the operating power factor falls. This regulation is defined as

$$VR = \frac{V_{a(NL)} - V_{a(rated)}}{V_{a(rated)}}$$

where $V_{a(NL)}$ is the ***magnitude*** of the no load terminal voltage, and $V_{a(rated)}$ the magnitude of the rated terminal voltage. When a generator is supplying a full load, the required terminal must be the rated voltage. The normalized difference between the magnitudes of the no load voltage and the full load voltage by the rated voltage is defined as the ***voltage regulation***.

This value may be readily determined from the phasor diagram for full load operation. If the regulation is excessive, automatic control of field current may be employed to maintain a nearly constant terminal voltage as load varies.

5.4. Connection diagram

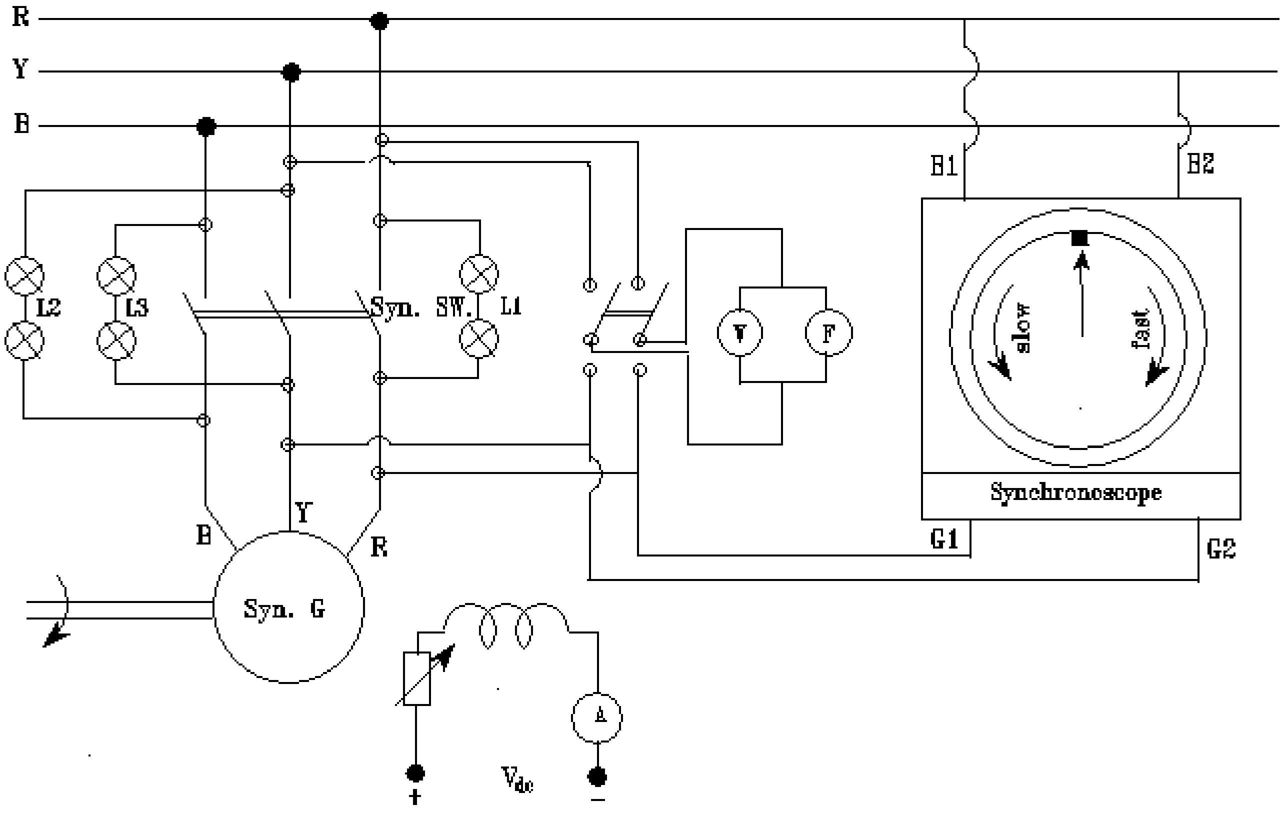


Fig.(12):The connection diagram of the alternator, when sychronized with busbar

As explained before the corret instant of synchronization when the lamps L1 dark, L2,L3 light and the pointer of synchoronoscope in the vertical position. Then close the synchronizing switch(Syn.SW). The machine now is floating on the bus-bars and can be operate in three modes; compensator, motor, and generator.

5.5. Equipment Required

- alternator 240V driven by a prime mover,
- Six 230V filament lamps,
- Double pole 2-way switch,
- Field regulating rheostat,
- Speed- meter,
- Ammeter dc (one), ac (one),
- Voltmeter ac,
- Ammeter, moving- iron type (three),
- Phase sequence indicator.

5.6. Experimental Procedure

1. Check the phase sequences of the bus-bars and alternator voltages with the help of the phase sequence indicator. Make connections as shown in Fig.(12).
2. Run the alternator at rated speed. Adjust the field excitation of the alternator such that the induced emf is equal to the bus-bar voltage. This can be checked by connecting a voltmeter and frequency meter across the bus-bar and across the alternator terminals by turn, with the help of double-way swith.
3. By adjusting the speed of the prime-mover, bring the alternator to a speed that the per of lamps to the identical phases will be dark and the other pairs of lamps will be bright and the pointer synchronoscope device in the vertical position. At that time chech the bus-bar and the alternator voltage and frequency also. If the two voltages and frequencies are the same, connect rhe alternator across the bus-bar with the help of synchronizing switch. The alternator is now synchronized and is floating on the bus-bar.
4. For the alternator to share any load, the input to the prime-mover will have to be increased. In case the prime-mover is a dc machine, its excitation may be increased slowly. Note the ammeter reading connected to the bus-bar.

5.7. Discusion

1. Explain the need for parallel operation of alternators.
2. Explain the effect of change of :

    a) excitation of an alternator synchronized with the bus-bar

b) Prime-mover input to an alternator synchronized with the bus-bar

3. Explain why an alternator should be synchronized before it can share load while running in parallel with other alternator connected to the bus-bar.

6. Synchronous Machines Motor Operation (V-Curves)

6.1.Objectives

To determine how armature current and power factor of a synchronous motor varies with change of excitation at different loads, supply voltage remaining constant.

6.2.Introduction

Similar to a dc motor, in a synchronous motor also the applied voltage V is opposed by an induced emf, E. The resultant voltage causes a current to flow through the armature winding which has an impedance of Z_s. When a synchronous motor is loaded, its speed does not change. Therefore, the magnitude of induced emf also does
not change. To supply the additional output power requirement, the induced emf fafils back by a certain angle 'δ', which is called the load angle. See Fig.(1-a). In a synchronous motor the rotor field rotates at the same speed as the rotating magnetic field produced by the polyphase stator current. When load on the rotor increases, its field axis makes a comparatively bigger angle with the axis of the rotating field and thereby supply the additional load. In case of a dc motor, however, the torque or load angle is kept fixed at 90 deg., i.e. to its maximum value and does not change). The effect of change of excitation of a synchronous motor at a particular load is shown in Fig.(1). Load angle δ will remain constant. Angle between *ER* and Ia will also remain constant at about 90 deg. since it is fixed by the ratio of reactance to resistance of the armature circuit (as the value of reactance is much higher than the value of armature resistance, the value of φ is usually about 90 deg.).

$$\text{Input power to the motor} = \sqrt{3}\ V\ Ia \cos\varphi$$

Where $\cos\varphi$ is the power factor. If V is constant and load is constant, input should remain constant and hence I_a cosh should remain constant. ($I_a \cos\varphi$ is the cos component of I_a on the voltage axis. In Fig. (1) OX represent $Ia\cos\varphi$). Assuming the supply voltage and load on the motor to remain constant, any change of excitation, I_f will simply increase or decrease the magnitude of E.

From the phasor diagram in Fig. (1), it is seen that increase in field current causes leading power-factor current, while decrease in field current causes Lagging power-factor current drawn by the motor.

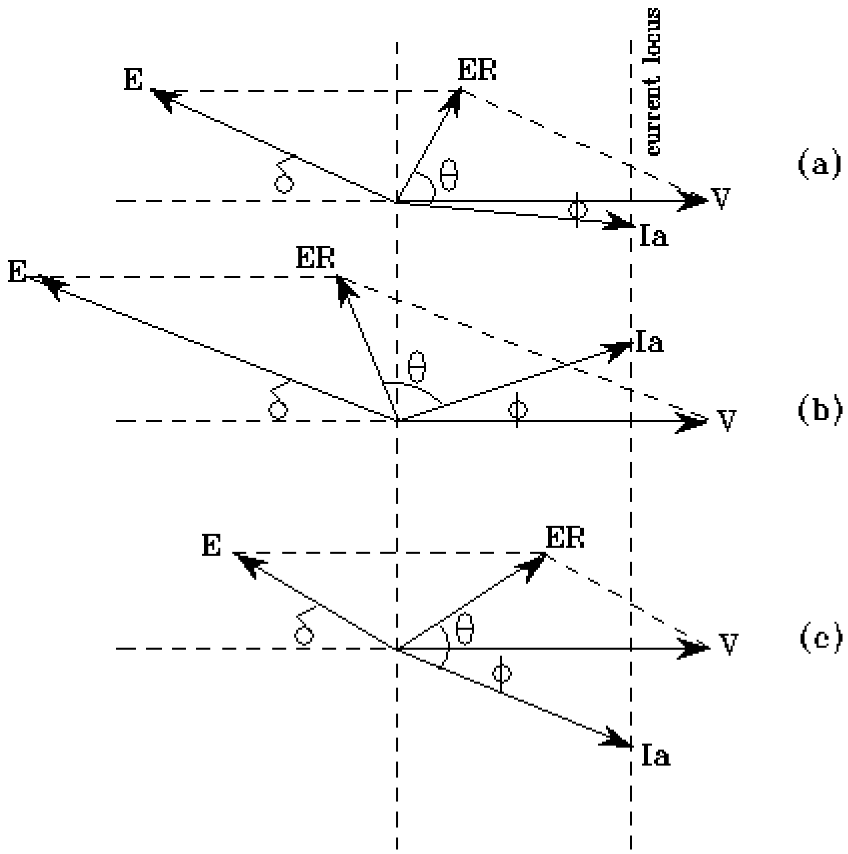


Fig. (1): Phasor Representation of the effect of change of excitation of a synchronous motor:

a) with initial excitation, b) when excitation is increased, c) when excitation is decreased.

There will be some excitation, which will cause unity power-factor current drawn by the motor. The magnitude of armature current at that excitatiolr would be the minimum excitation corresponding to unity power-factor current drawn by the motor is called normal excitation. Excitation more than the normal excitation (also called over excitation) causes leading power factor current and excitation less than the normal excitation (also called under excitation) causes lagging power-factor current.

A typical characteristic showing the relationship between field current If and armature current Ia of a synchronous motor for a particular load is shown in Fig. (2). Normal excitation (i.e. minimum armature current) corresponds to unity power -factor. Excitation below normal gives rise to lagging power-factor current whereas excitation more than normal gives rise to leading power-factor current drawn by the motor.

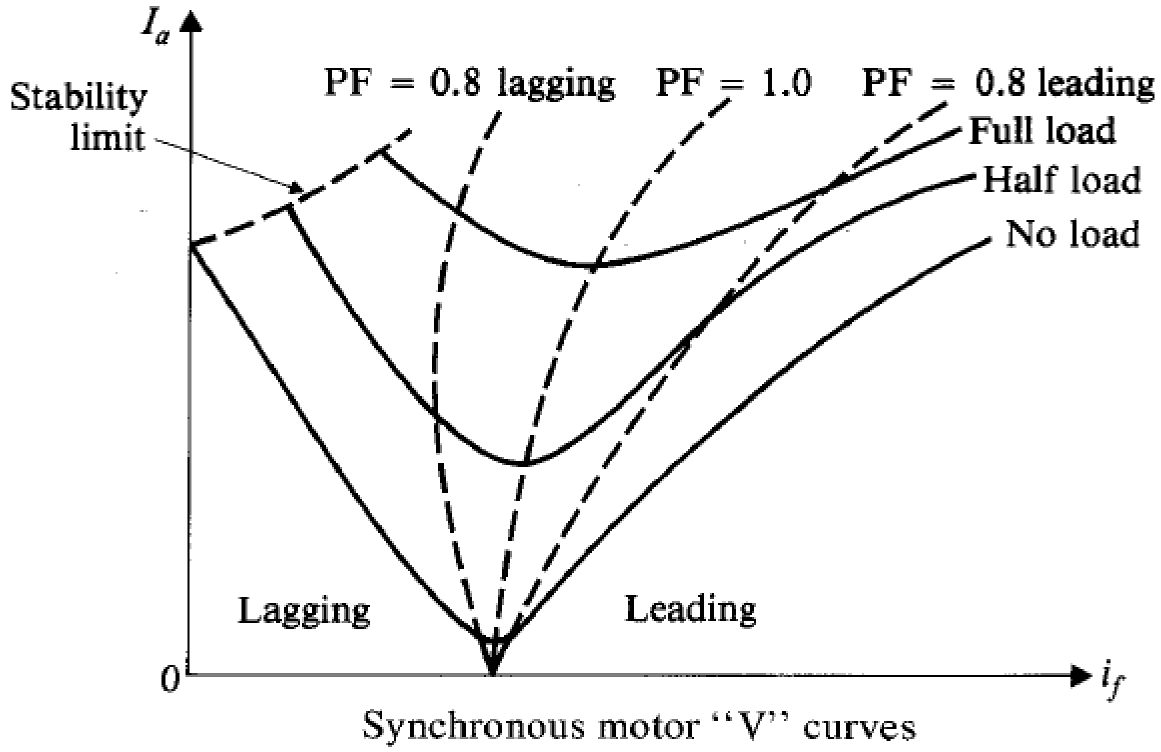


Fig. (2): Graphical representation of the effect of change of excitation on armature current of a synchronous motor at various shaft loads.

Therefore, by varying the excitation of a synchronous motor, it can be made to behave either like an inductive load (when under excited) or a capacitive load (when overexcited).

An overexcited synchronous motor is, therefore, also called a synchronous condenser. The shape of the If versus IQ characteristics shown in Fig. (2) are often referred to as synchronous motor V curves. If by changing loads on the synchronous motor effects of If on Ia is studied, a series of V curves will be obtained as shown in the figure.

6.3. Connection Diagram

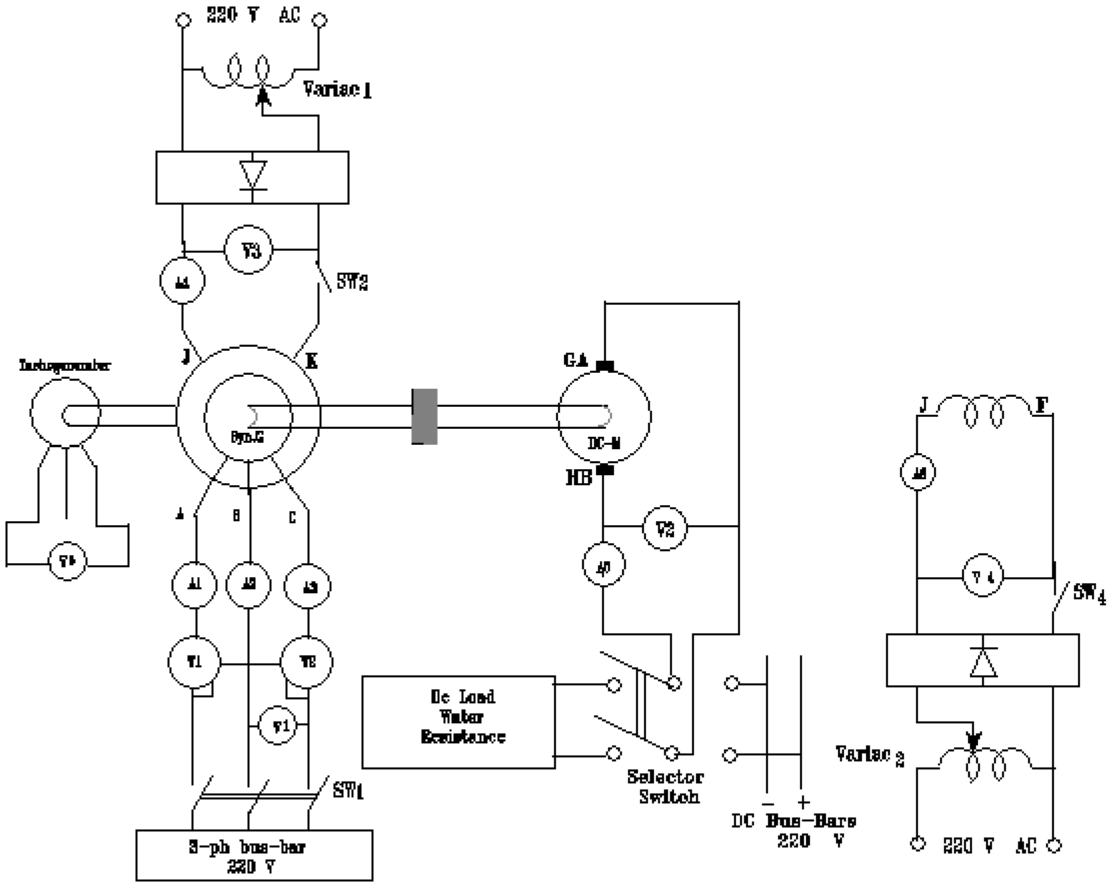


Fig. (3): Connection diagram for studying the effect of variation of excitation on armature current and power factor of a synchronous motor.

6.4. Equipment Required

- Synchronous motor coupled with a dc machine having any water resistance load,
- Wattmeter (two),
- Ammeter ac,
- Voltmeter ac,
- Ammeter dc,
- Voltmeter dc,
- Water resistance load

6.5. Experimental Procedure

1. Make connections as per circuit diagram shown in Fig. (3). Start the synchronous motor as generator and synchronied it to bus-bars as stated in the previous experiment. and keeping the field current at its minimum value. Disconnect the selector switch from the dc bus-bars. The motor will now be running at synchronous speed.

   Increase the field current to its maximum permissible value .

2. ***Run 1 (no-load).*** Reduce the field current, I_f step by step and record values of I_f, I_a,V,W_1, W_2, in a tabular form. While reducing I_f current I_a, will be decreasing to a minimum value and then again increasing. The range of variation of excitation current should be such that it does not cause excessive current (more than rated full-load current) to flow through the armature circuit of the motor.

3. ***Run II(half-load)***. Increase the excitation of the-field to its permissible maximum value again. Turn on the selector switch to the water resistanece to load the dc generator and increase the dc armature current upto the synchronous motor half loaded.

   Reduce excitation and record at each step values of I_f, I_a, V, W1, W_2, V_G and I_G. Both in RUN II and I take at least ten readings. Record data in a tabular form.

4. ***Run III (full-load)***. As in run II but increase the synchronous motor armature current upto the its full load using the water resistance load.

6. 6. Results

Run I (no-load)	Synchronous Motor	I_f [A]							
		I_a [A]							
		V [V]							
		W_1 [W]							
		W_2 [W]							
		P.F.							
	DC Gen	V_G [V]							
		I_G [A]							
Run II (half-load)	Synchronous Motor	I_f [A]							
		I_a [A]							
		V [V]							
		W_1 [W]							
		W_2 [W]							
		P.F.							
	DC Gen	V_G [V]							
		I_G [A]							
Run III (full-load)	Synchronous Motor	I_f [A]							
		I_a [A]							
		V [V]							
		W_1 [W]							
		W_2 [W]							
		P.F.							
	DC Gen	V_G [V]							
		I_G [A]							

I. Sample Calculation and Results. Calculate the values of values of power-factor corresponding to each reading. Show one sample calculation.

2. Draw graph showing the effect of If on Ia, and power factor at (a) no-load, (b) at a particular load.

6.7. Discussions

Answer the following qauestions in your report:

1. From the experimental results, suggest an important application of a synchronous motor.
2. Explain why power factor of synchronous motor changes with change of excitation
3. Explain why with the change of excitation of a synchronous motor, the magnitude of armature current decreases and then again increases.

7. SLIP TEST

7.1.Objective

To determine the direct and quadrature reactances of synchronous machine under steady state conditions

7.2.Introduction

The values of X_d and X_q are determined by applying a balanced reduced external voltage (say, V volts) to an unexcited alternator running at speed a little less than the synchronous speed due to the voltage V applied to the stator terminals a current I will flow causing a stator mmf. This stator mmf moves slowly to the poles and induces an emf in the field circuit in a similar fashion to that the rotor in an induction motor at slip frequency. The effect will be that the stator mmf will move slowly relative to the poles. The physical poles and the armature reaction mmf are alternately in face and out, the change occurring at slip frequency. When the axis of the pole and the axis of the armature reaction mmf wave coincided the armature mmf acts through the field magnetic circuit. The voltage applied to the armature is then equal to drop caused by the direct component of armature reaction and leakage reactance. When the armature reaction mmf is in quadrature with the field poles, the applied voltage is equal to the leakage reactance drop plus the equivalent voltage drop of the cross magnetizing field component.

7.3 Connection Diagram

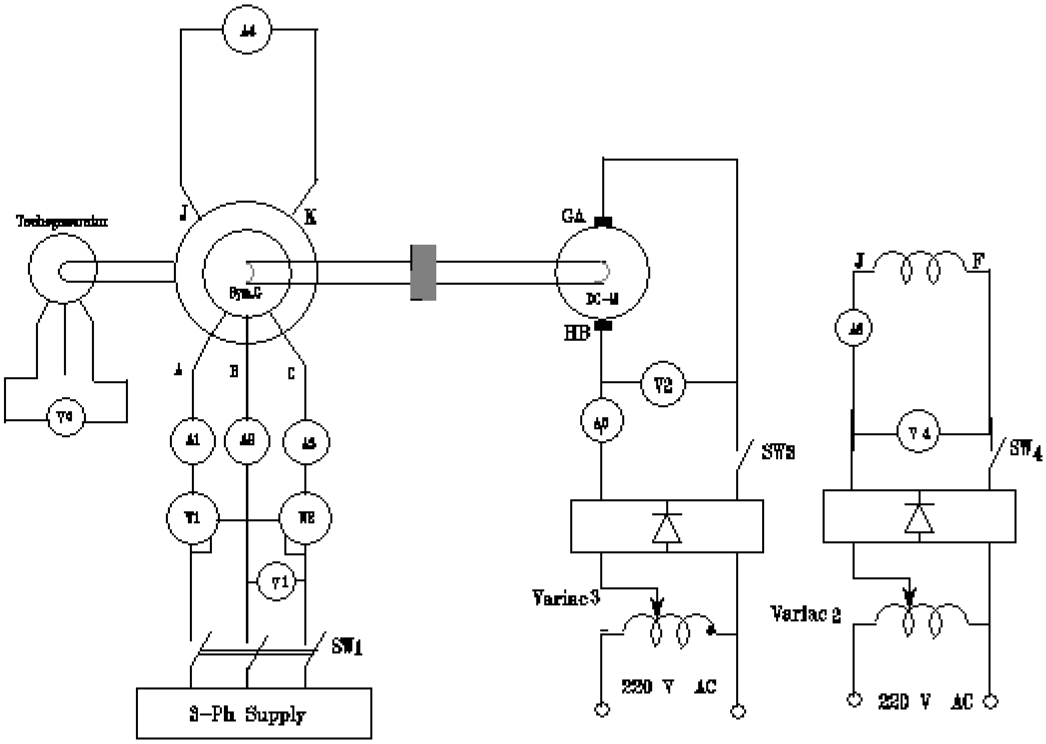


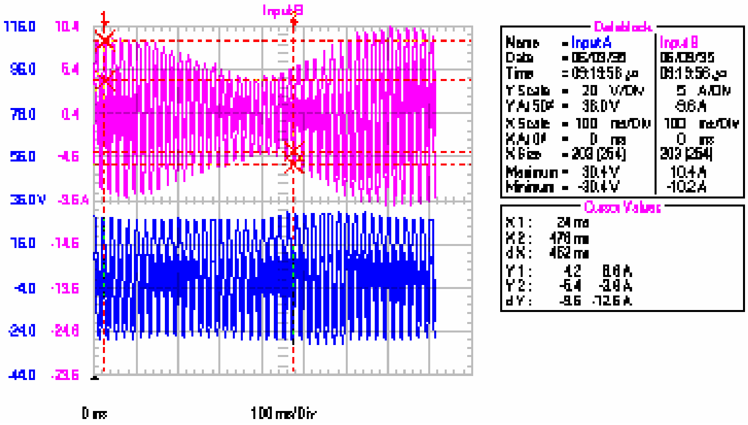
Fig.(1): Slip-test wiring diagram

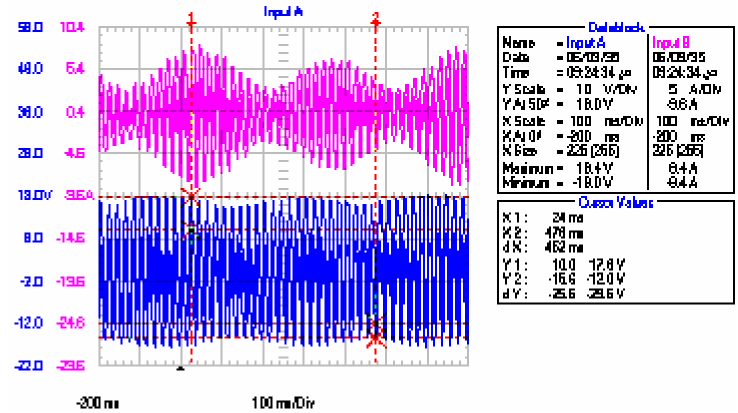
7.4 Experiment Procedure

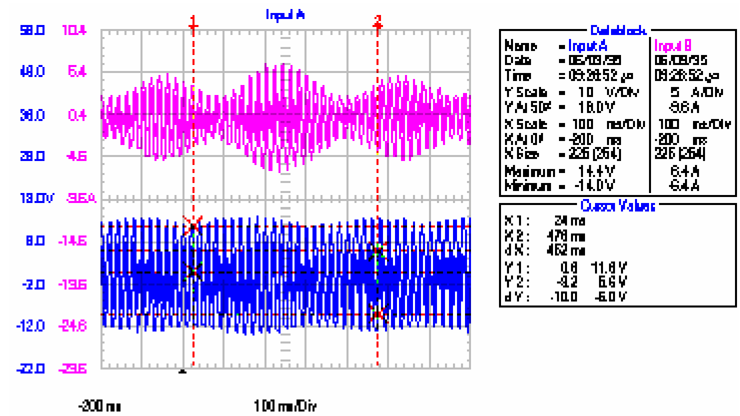
1- Start the DC motor at speed a little less than the synchronous speed in the same direction of the rotating magnetic field.
2- Make short circuit on the field winding of the synchronous machine.
3- Excite the terminals of the synchronous machine from 3-phase supply with reduced voltage, to provide maximum current.
4- Regulate the speed of the DC motor to have slowly variation for the waveforms of the armature current and voltage in order to record the values of armature current and voltage. It is prefer to use a storage oscilloscope .
5- From oscillograph record calculate the reactances of direct and quadrature from the following equations

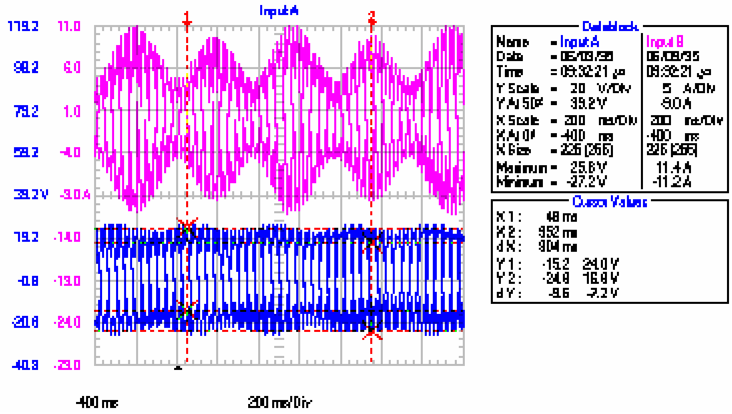
$$X_d = \frac{\max.\text{voltage}}{\min.\text{current}} \quad , \quad X_q = \frac{\min.\text{voltage}}{\max.\text{current}}$$

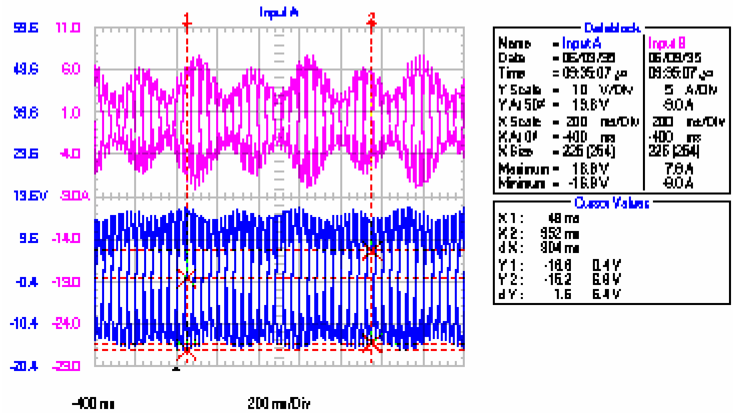
7.5 Results

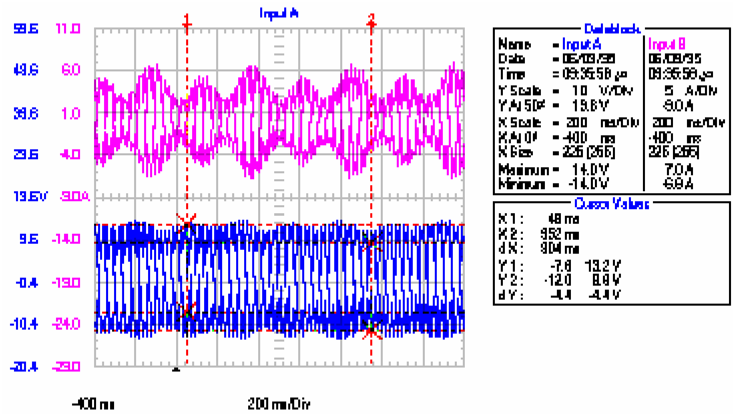

Input B
0 ms
100 ms/Div


Input A
-200 ms
100 ms/Div


Input A
-200 ms
100 ms/Div







7.6 Discussion

From the above oscillograhp calculate X_d and X_q of each case.

8. **Sudden symmetrical short-circuit of Synchronous Generator**

8.1 Objective

Determine transient and sub-transient reactances and time constants for the synchronous machine.

8.2 Introduction

A sudden short circuit in the stator windings of synchronous machine. Though of relatively short duration, is very difficult process for both the machine itself and the all apparatus connected to it, since the current surges occurring at sudden short-circuit may exceed the rated current values 10 to 15 times.

The process of sudden short circuit differs greatly from that of a sustained short-circuit. Any a symmetrical sustained short-circuit, the armature reaction mmf has an amplitude constant in relation to time and, since it runs in synchronism with the rotor, does not induce current in the rotor windings. With a sudden short circuit, however, the stator current varies in magnitude and results in the armature reaction flux also varying and inducing currents in the rotor windings which, in turn, influence the stator currents.

8.3 Connection Diagram

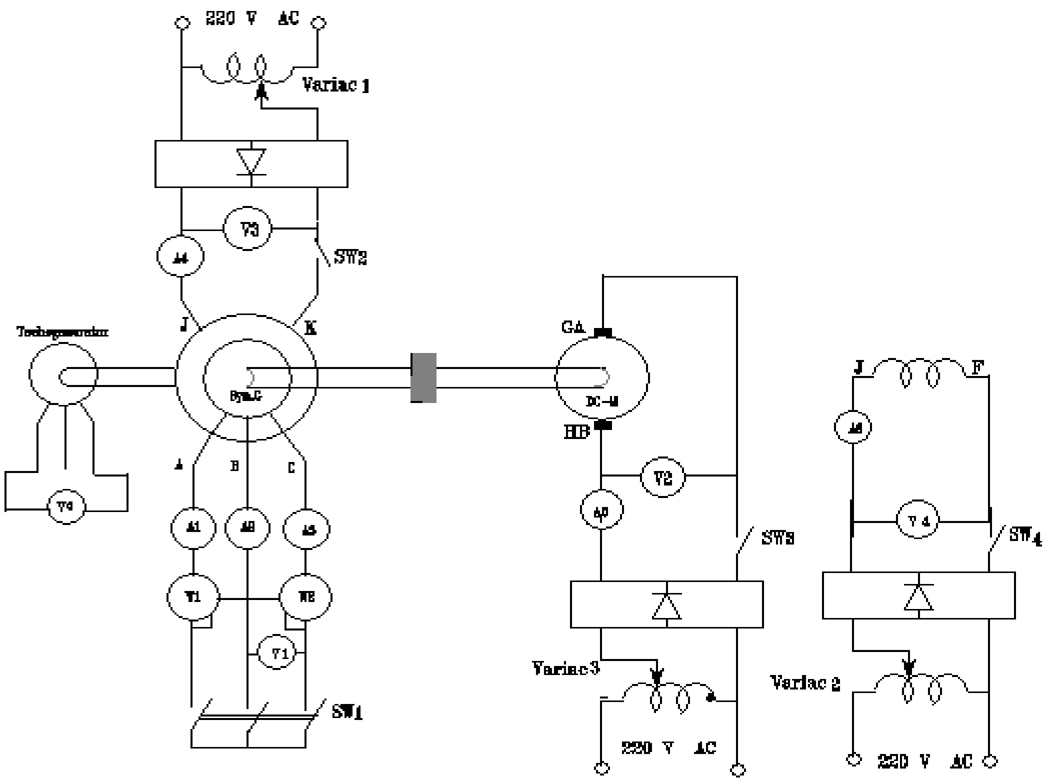


Fig.(1): Wiring diagram of sudden short-circuit of synchronous

8.4 Experimental procedure

1- Start the DC motor at the synchronous speed .

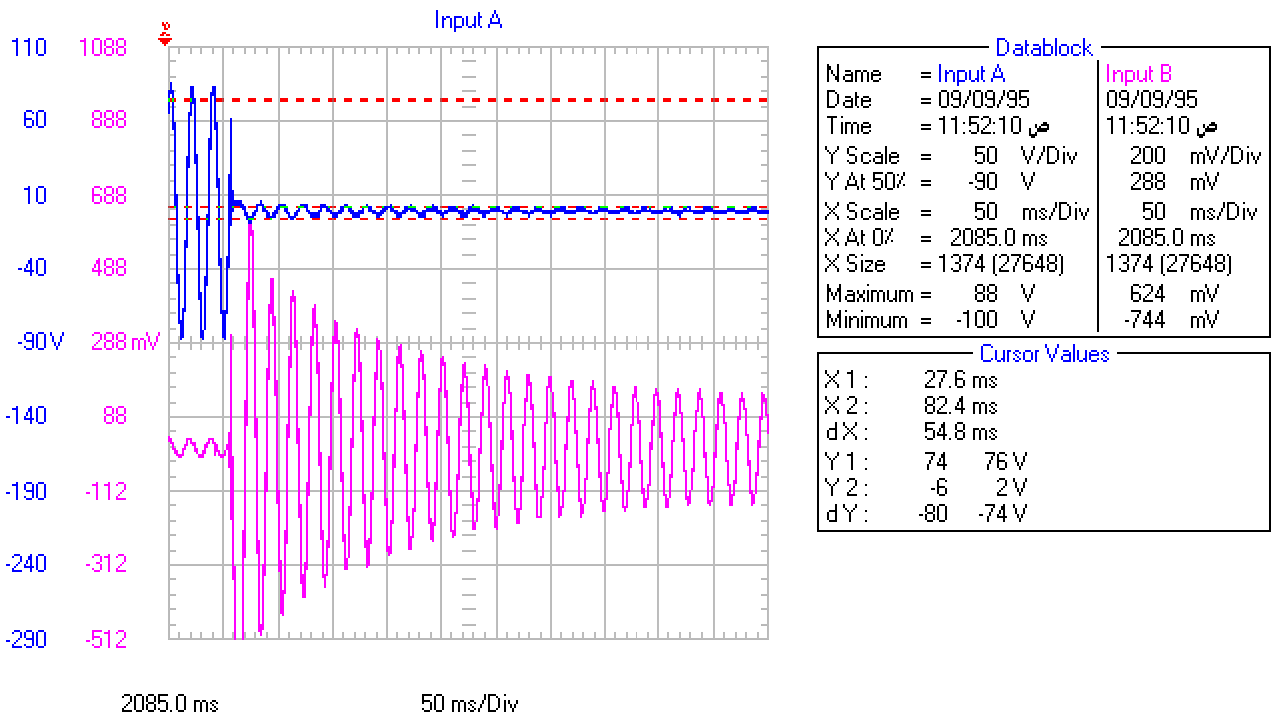
2- Excite the field winding of the synchronous machine while the armature terminals are shorted (close switch SW_1) till the rated current reaches. Keep the corresponding field current value constant and then open switch SW_1 .

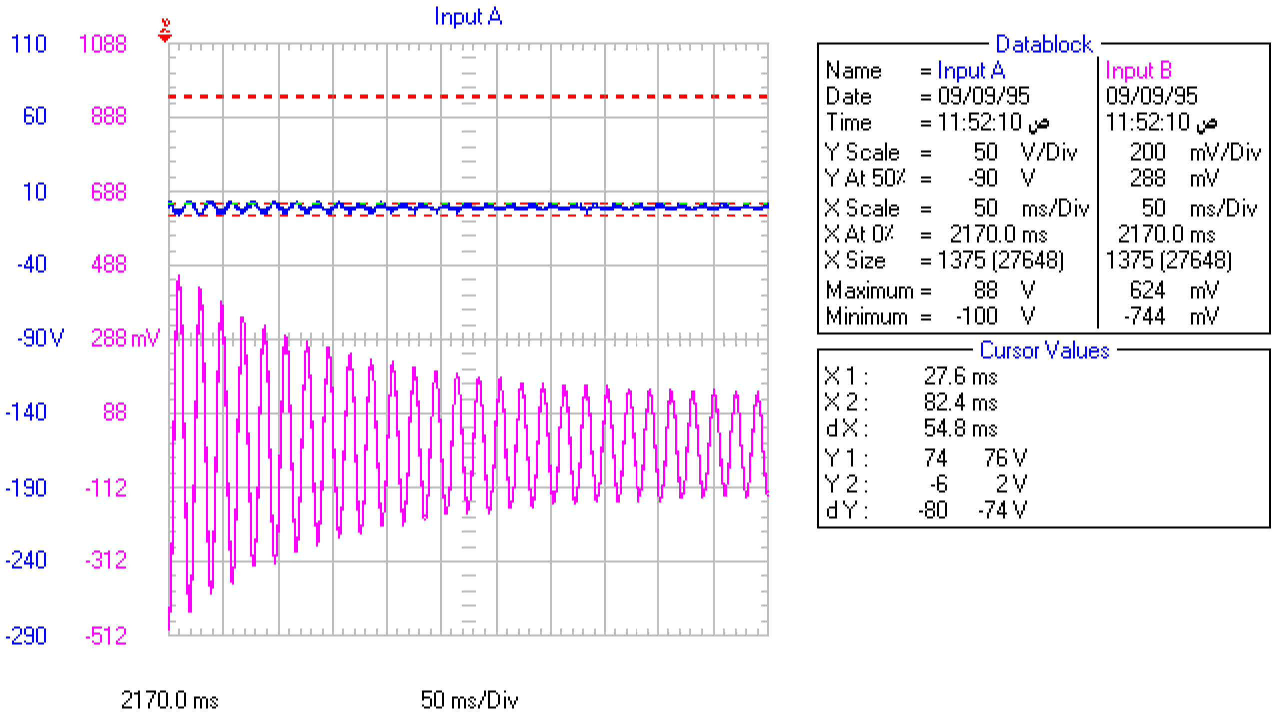
3- Connect a storage oscilloscope to record the waveforms of the armature currents, the terminal voltage and the field current.

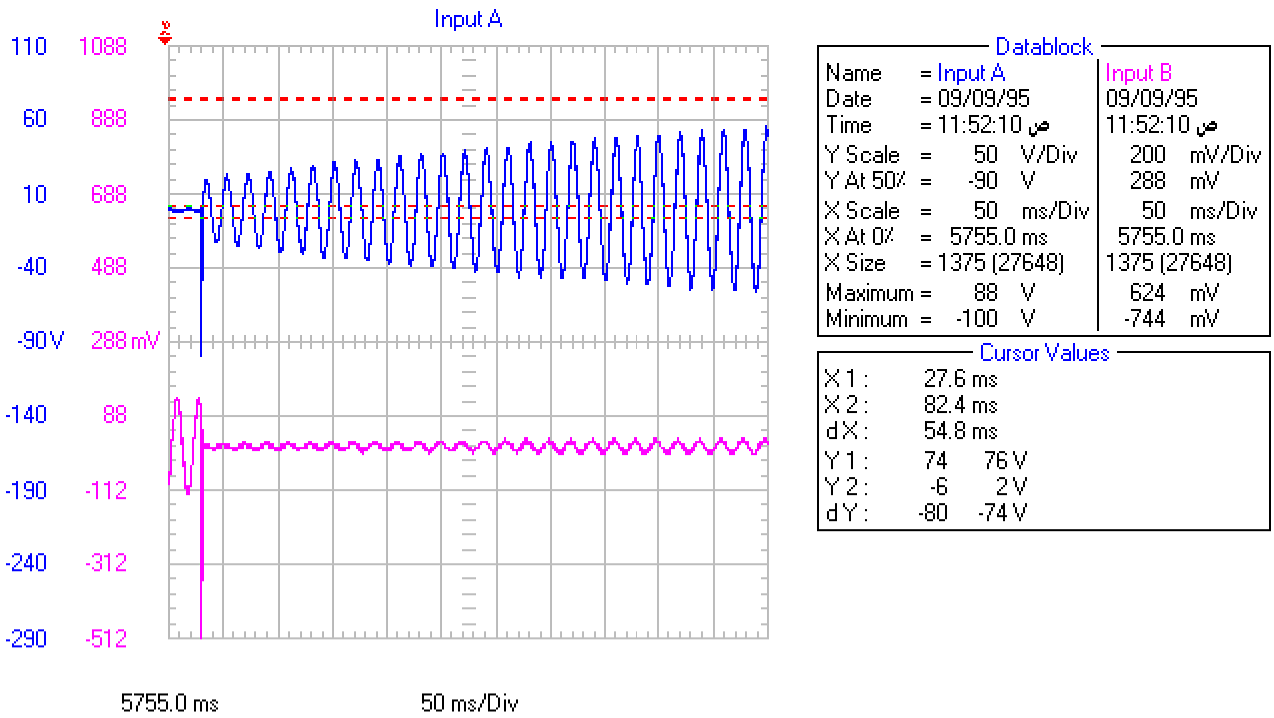
4- Apply a sudden short-circuit to the synchronous machine terminals (closing switch SW_1) and store the waves mentioned before and finally clear the short circuit (opening the switch SW_1) and store the same waves again.

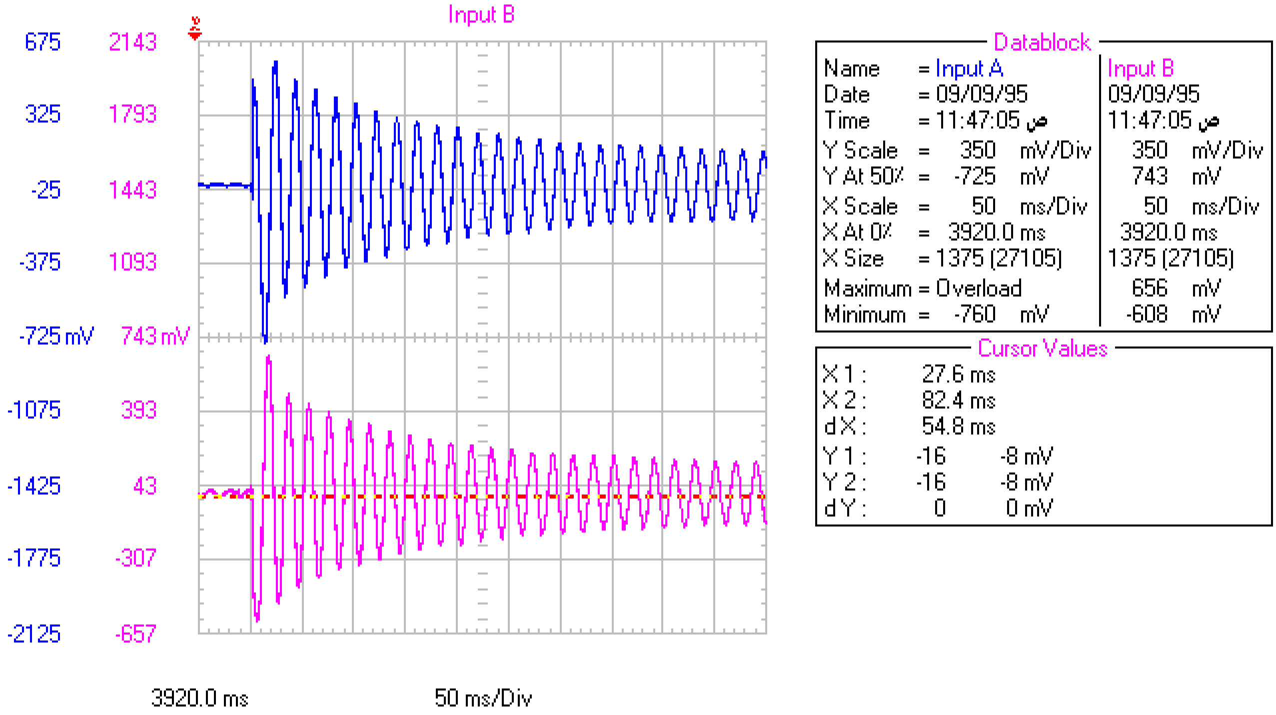
5- Repeat step 4 at different instance.

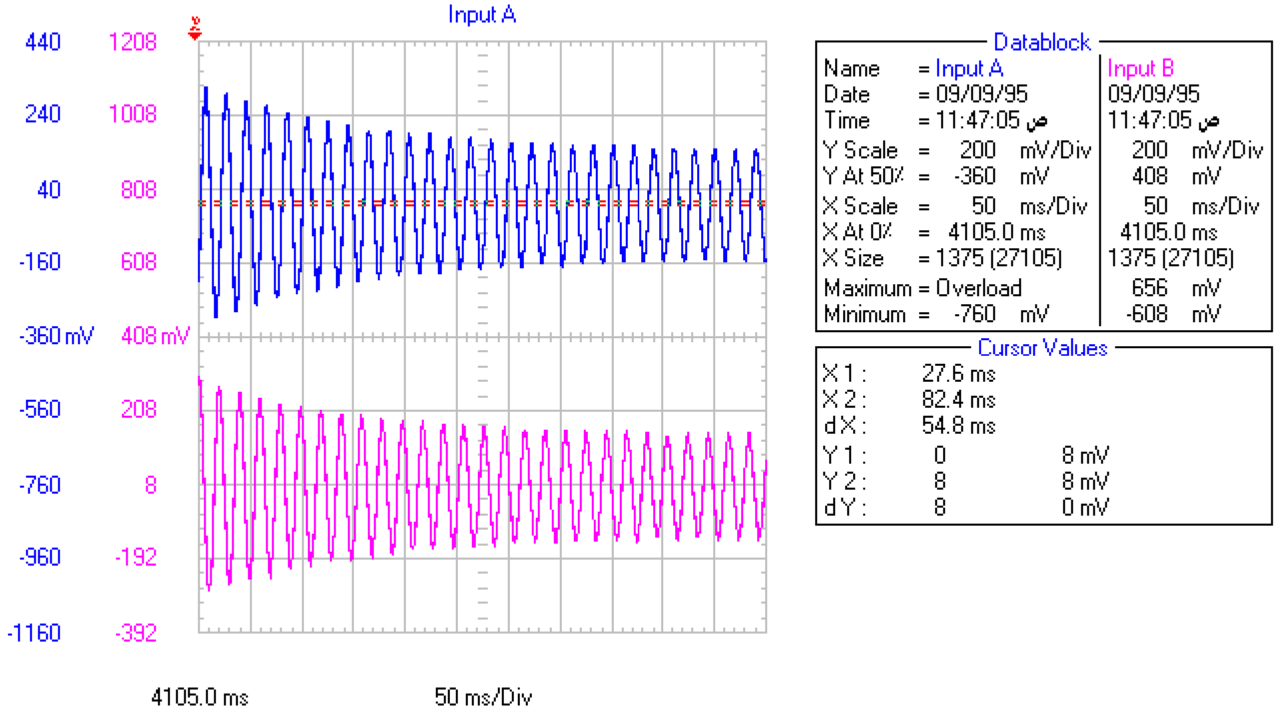
8.5 Results

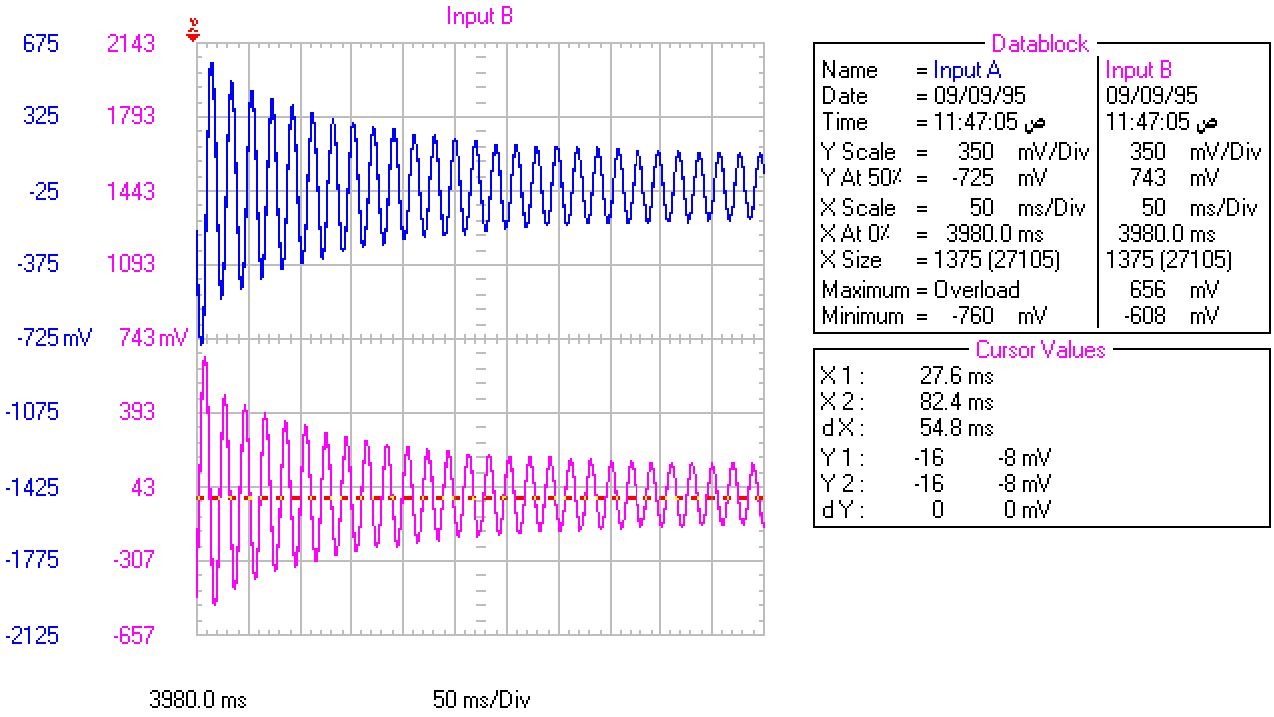


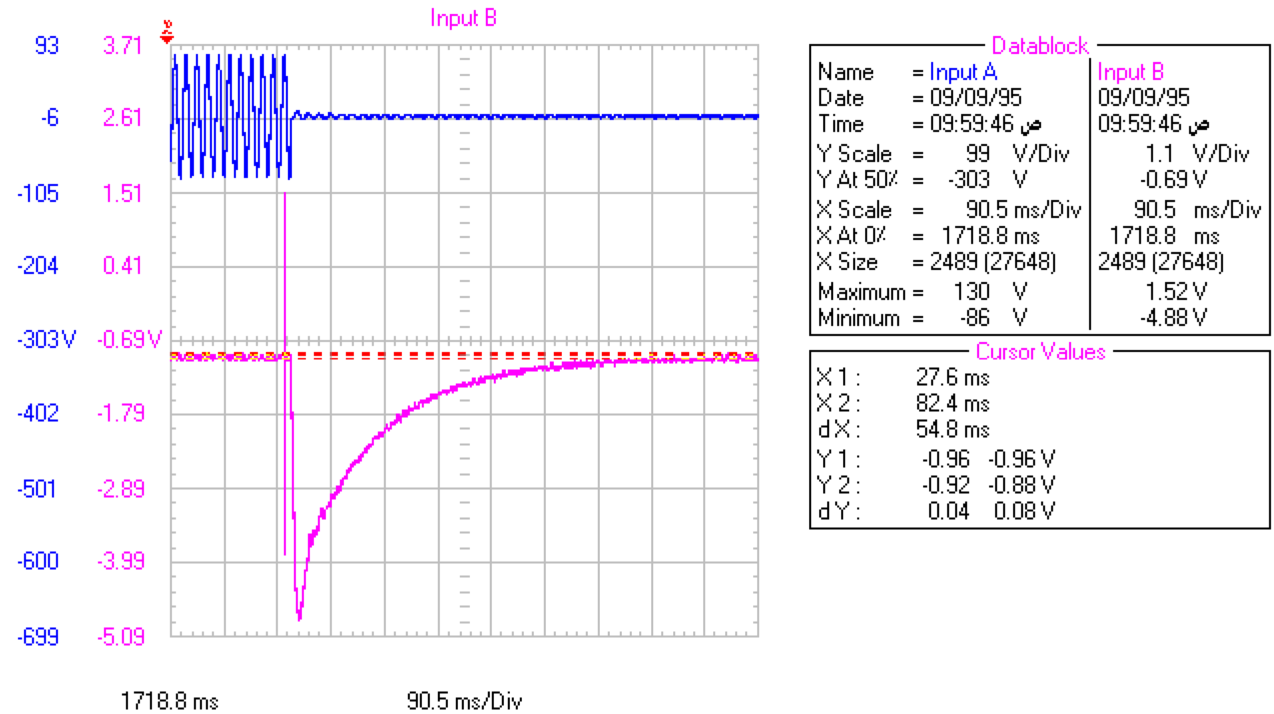

Input A
110 1088
60 888
10 688
-40 488
-90 V 288 mV
-140 88
-190 -112
-240 -312
-290 -512
2170.0 ms
50 ms/Div
Datablock
Name = Input A
Date = 09/09/95
Time = 11:52:10 ص
Y Scale = 50 V/Div
Y At 50% = -90 V
X Scale = 50 ms/Div
X At 0% = 2170.0 ms
X Size = 1375 (27648)
Maximum = 88 V
Minimum = -100 V
Input B
09/09/95
11:52:10 ص
200 mV/Div
288 mV
50 ms/Div
2170.0 ms
1375 (27648)
624 mV
-744 mV
Cursor Values
X 1 : 27.6 ms
X 2 : 82.4 ms
d X : 54.8 ms
Y 1 : 74 76 V
Y 2 : -6 2 V
d Y : -80 -74 V

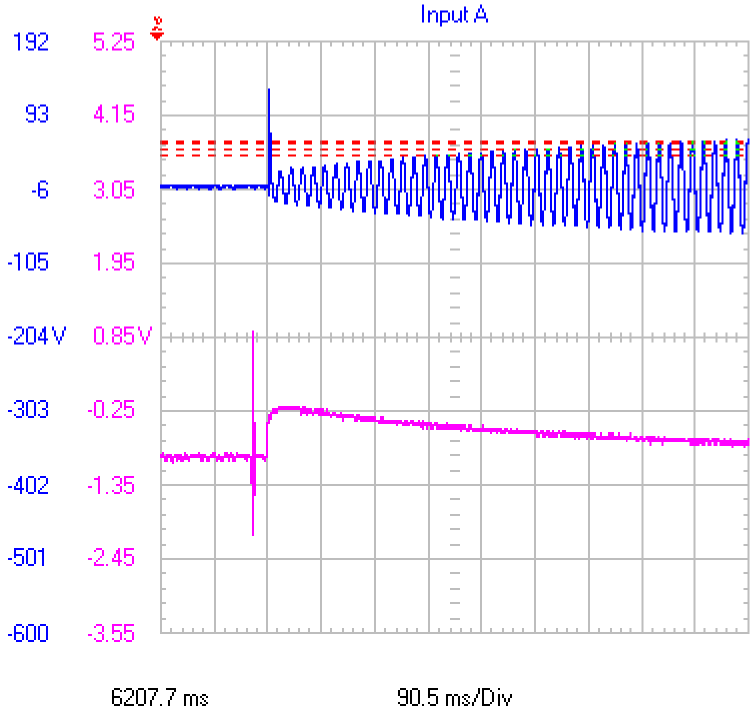

Input A
110 1088
60 888
10 688
-40 488
-90 V 288 mV
-140 88
-190 -112
-240 -312
-290 -512
5755.0 ms
50 ms/Div
Datablock
Name = Input A
Date = 09/09/95
Time = 11:52:10 ص
Y Scale = 50 V/Div
Y At 50% = -90 V
X Scale = 50 ms/Div
X At 0% = 5755.0 ms
X Size = 1375 (27648)
Maximum = 88 V
Minimum = -100 V
Input B
09/09/95
11:52:10 ص
200 mV/Div
288 mV
50 ms/Div
5755.0 ms
1375 (27648)
624 mV
-744 mV
Cursor Values
X 1 : 27.6 ms
X 2 : 82.4 ms
d X : 54.8 ms
Y 1 : 74 76 V
Y 2 : -6 2 V
d Y : -80 -74 V


Input B
675
325
-25
-375
-725 mV
-1075
-1425
-1775
-2125
2143
1793
1443
1093
743 mV
393
43
-307
-657
3920.0 ms
50 ms/Div
Datablock
Name = Input A
Date = 09/09/95
Time = 11:47:05 ص
Y Scale = 350 mV/Div
Y At 50% = -725 mV
X Scale = 50 ms/Div
X At 0% = 3920.0 ms
X Size = 1375 (27105)
Maximum = Overload
Minimum = -760 mV
Input B
09/09/95
11:47:05 ص
350 mV/Div
743 mV
50 ms/Div
3920.0 ms
1375 (27105)
656 mV
-608 mV
Cursor Values
X 1 : 27.6 ms
X 2 : 82.4 ms
d X : 54.8 ms
Y 1 : -16 -8 mV
Y 2 : -16 -8 mV
d Y : 0 0 mV


Input A
440
240
40
-160
-360 mV
-560
-760
-960
-1160
1208
1008
808
608
408 mV
208
8
-192
-392
4105.0 ms
50 ms/Div
Datablock
Name = Input A
Date = 09/09/95
Time = 11:47:05 ص
Y Scale = 200 mV/Div
Y At 50% = -360 mV
X Scale = 50 ms/Div
X At 0% = 4105.0 ms
X Size = 1375 (27105)
Maximum = Overload
Minimum = -760 mV
Input B
09/09/95
11:47:05 ص
200 mV/Div
408 mV
50 ms/Div
4105.0 ms
1375 (27105)
656 mV
-608 mV
Cursor Values
X 1 : 27.6 ms
X 2 : 82.4 ms
d X : 54.8 ms
Y 1 : 0 8 mV
Y 2 : 8 8 mV
d Y : 8 0 mV


Input B
675 2143
325 1793
-25 1443
-375 1093
-725 mV 743 mV
-1075 393
-1425 43
-1775 -307
-2125 -657
3980.0 ms
50 ms/Div
Datablock
Name = Input A | Input B
Date = 09/09/95 | 09/09/95
Time = 11:47:05 ص | 11:47:05 ص
Y Scale = 350 mV/Div | 350 mV/Div
Y At 50% = -725 mV | 743 mV
X Scale = 50 ms/Div | 50 ms/Div
X At 0% = 3980.0 ms | 3980.0 ms
X Size = 1375 (27105) | 1375 (27105)
Maximum = Overload | 656 mV
Minimum = -760 mV | -608 mV
Cursor Values
X 1 : 27.6 ms
X 2 : 82.4 ms
d X : 54.8 ms
Y 1 : -16 -8 mV
Y 2 : -16 -8 mV
d Y : 0 0 mV


Input B
93 3.71
-6 2.61
-105 1.51
-204 0.41
-303 V -0.69 V
-402 -1.79
-501 -2.89
-600 -3.99
-699 -5.09
1718.8 ms
90.5 ms/Div
Datablock
Name = Input A | Input B
Date = 09/09/95 | 09/09/95
Time = 09:59:46 ص | 09:59:46 ص
Y Scale = 99 V/Div | 1.1 V/Div
Y At 50% = -303 V | -0.69 V
X Scale = 90.5 ms/Div | 90.5 ms/Div
X At 0% = 1718.8 ms | 1718.8 ms
X Size = 2489 (27648) | 2489 (27648)
Maximum = 130 V | 1.52 V
Minimum = -86 V | -4.88 V
Cursor Values
X 1 : 27.6 ms
X 2 : 82.4 ms
d X : 54.8 ms
Y 1 : -0.96 -0.96 V
Y 2 : -0.92 -0.88 V
d Y : 0.04 0.08 V



Datablock

	Input A	Input B
Name	= Input A	Input B
Date	= 09/09/95	09/09/95
Time	= 09:59:46 ص	09:59:46 ص
Y Scale	= 99 V/Div	1.1 V/Div
Y At 50%	= -204 V	0.85 V
X Scale	= 90.5 ms/Div	90.5 ms/Div
X At 0%	= 6207.7 ms	6207.7 ms
X Size	= 2489 (27648)	2489 (27648)
Maximum	= 130 V	1.52 V
Minimum	= -86 V	-4.88 V

Cursor Values

X 1 :	27.6 ms	
X 2 :	82.4 ms	
d X :	54.8 ms	
Y 1 :	42	48 V
Y 2 :	56	60 V
d Y :	14	12 V