The Hashemite University
Faculty of Engineering
Electrical Engineering Department

(Electrical Machines Lab)

Laboratory (110409470)
Credit hours (1)

Experiments:

1. **Introduction to the Electrical Machines Lab**.

2. **Single Phase Transformer I.**

3. **Single Phase Transformer II.**

4. **DC-Shunt Motor.**

5. **DC-Series Motor.**

6. **Separately Excited DC-Generator.**

7. **DC-Shunt Generator.**

8. **Induction Motor I.**

9. **Induction Motor II.**

10. **Synchronous Generator.**

GENERAL LABORATORY RULES
AND SAFETY RULES

- Be **PUNCTUAL** for your laboratory session.

- Foods, Drinks and smoking are not allowed.

- Open- toed shoes are not allowed.

- The lab timetable must be strictly followed. Prior permission from the lab supervisor must be obtained if any change is to be made.

- Respect the laboratory and its other user. Noise must be kept to a minimum.

- Workspace must be kept clean and tidy at all time. Points might be taken off on student / group who fails to follow this.

- Handle all apparatus with care.

- All students are liable for any damage to equipment due to their own negligence.

- Students are strictly **PROHIBITED** from taken out any items from the laboratory without permission from the lab Supervisor.

- Do not work alone.

- Report any injuries to your instructor immediately.

- Know where the main lab power switch is located and how to turn off the power.

- In the event of a fire:
  - ✓ De-energize the circuit.
  - ✓ Notify the instructor immediately (he or she may use an appropriate fire extinguisher).
  - ✓ Remove all fuels (such as paper), if possible.
  - ✓ Administer first aid.
  - ✓ Call Campus Public Safety Dept. if necessary. (Pull the fire alarm, evacuate the building and call from outside the building, if appropriate).

- Make connections to a de-energized circuit only. When in doubt, do not power-up without the instructor's inspection.

- Do not change the circuit with the power on. This can damage the components and create a safety hazard.

- Do not rely on fuses, relays, circuit breakers, interlock devices or other protective devices to protect you or your circuit.

- Turn off power to all equipment when finished.

- Many electrical components are hot when functioning – be careful.

- Do not bypass the protective third prong on an electrical plug. Use a properly grounded adapter when plugging into a two-prong outlet (check the outlet for proper grounding).

- Report defective equipment or components to your instructor immediately. Please do not return defective components to the Technical Support Center. (Your instructor will tag defective equipment with the nature of the problem along with the date).

- Pay particular attention to the polarity of polarized capacitors.

- If a component burns, avoid breathing the fumes. They could be toxic.

- Use only one hand at a time in any high-voltage circuit – prevent putting your body in the circuit.

- Avoid wearing loose or floppy clothing around moving machinery. Wear safety glasses.
- Do not attempt to pull someone from a "live" circuit. Turn the power off if possible. Otherwise, remove the person with a nonconducting object.

GRADING POLICY

The total marks for this lab is distributed as follows:

Lab Report + Prelab + Performance	40%
Mid-term Exam	20%
Final	40%

Laboratory Report Guidelines

Effective technical communication and documentation are essential skills for an engineer. Technical documentation can take on different forms depending on the needs of the audience. However, some common principles can be applied to all forms of technical documentation. Consideration of these principles is essential to ensure effective communication of the information that the audience needs. A few guidelines will be considered here to write effective lab reports.

The following guidelines are suggested for preparing to write:

- Define the audience and it's needs
- Establish a purpose for writing
- Determine the type of documentation to be written
- Follow an acceptable format
- Use Proper spelling, grammar, and technique

Defining the Audience

The audience for your report is a professor or technical assistant. They are familiar with the lab material and need to make an assessment of your understanding of the work completed in preparation for and during the lab session.

Establish the Purpose

The purpose of writing for this lab is to provide an opportunity to develop technical writing skills, and demonstrate understanding of the lab material. As a student, this process of organizing and writing technical documentation is a valuable tool. Write the type of documentation that you can keep as a reference for future use.

Determining the Documentation Type

The type of documentation written for these labs will be lab reports. Depending on the nature of the lab, these reports can be formal reports, informal reports, or status reports.

Following the Proper Format

The overall structure of each type of report is shown below.

Formal Reports
- Title Page
- Objectives
- Introduction
- Methodology/Theory
- Analysis/Results
- Conclusion
- Attached Files (Outputs, Plots, Schematics, etc.)

Informal Reports
- Title Page
- Introduction
- Analysis/Summary
- Conclusion
- Attached Files (Outputs, Plots, Schematics, etc.)

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 partner names, 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 prelab, 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.

Using Proper Spelling, Grammar, and Technique

Lab reports should be proofread for proper spelling and grammar. Use the spell check features of the word processor, and proofread. You may also want to have someone else to proofread your work.

Proper technique is essential for documenting what was accomplished in the lab and for establishing the tone of the report. Several examples of poor technique, which should be avoided, are listed below.

- The lab report is not a personal experience. Do not discuss how you feel it about the experiment. Your grade will not be based on how interesting you found the experiment, how satisfied you were personally with the results, or how frustrated you became when things did not work properly or in a timely manner.

- The lab report should not document the procedure or specific steps followed in completing the experiment. For example, it is not necessary to explain how a circuit was wired and how components were placed on a breadboard, or how the equipment was plugged in and measurements were made, etc. The only exception would be when a specific procedure required to obtain the desired result is not intuitively obvious.

- Avoid using anthropomorphisms (applying human feelings or actions to inanimate objects).

- Do not talk about yourself in the third person. Document what was done without using "I," "we," "the student," etc.

Use good judgment when adding details to your reports. Do not include unnecessary or obvious information. If there is more than one way to do something (e.g. collecting data), then add details that describes your choice (e.g. what piece of equipment, or what measurement function, etc. was used in collecting the data).

Additional guidelines that should be followed are listed below.

- All reports must be typed, using easy to read fonts. Clip-art images, color backgrounds and borders are inappropriate for a technical report.

- Figures, schematics, plots, and equations should be labeled and numbered so that they can be referred to in the report. Inline equations are not acceptable. Equations should be separated from the text, and centered in the page. Plot axes should have appropriate labels that clearly identify what is being represented. When possible, equations, schematics, figures, etc. should be placed in the body of the report near the text that first refers to them. Only include items in the appendix if they are supplementary items or if they cannot be easily included in the body of the report.

- Data that is not presented in a graph format should be organized in tables and must be identified by appropriate title, row/column heading, and units.

- Each student must submit an individual report based on individual effort. Even though partners work together in the laboratory, each student must submit their own report.

Electrical Machine Notation		
B	susceptance	siemens, S
E	induced voltage	volts, V
f	frequency	hertz, Hz
G	conductance	siemens, S
I	current	amps, A
j	j-operator	$1\angle 90°$
k	coefficient	number
m	number of phases	number
N	number of turns	Number
n	rotational speed	revs/min
P	power	watts, W
p	pole pairs	number
R	Resistance	ohms, Ω
s	slip	per-unit
S	voltamperes	volt-amps, VA
T	Torque	newton-metres, Nm
V	terminal voltage	volts, V
X	Reactance	ohms, Ω
Y	Admittance	siemens, S
Z	Impedance	ohms, Ω
δ	loss angle	degrees, °
Φ	magnetic flux	webers, Wb
ϕ	phase angle	degrees, °
η	Efficiency	per-unit
θ	Temperature	centigrade, °C
ω	angular speed	radians/sec

Experiment 2
Single Phase Transformer- I

Open circuit test, turns ratio test, measuring the resistance of transformer windings and polarity test.

A) Open Circuit Test:-

Objectives
- To determine the magnetic branch circuit parameters.
- To determine the no load current.
- To determine the iron losses at various voltages.

Introduction:
In the transformer open circuit test, various voltage levels are applied to the primary with the secondary open-circuited. Because the secondary is open circuited, the amount of current drawn by the transformer during this test is very small relative to the rated current. The power factor ends up being is quite small as well because R_C is much greater then X_m. referring to the transformer equivalent circuit shown in Figure 2-1.

V_1: supply voltage (primary)
V_2: load voltage (secondary)
R_C: core loss resistance
X_m: magnetizing reactance
R_{eqp}: winding resistance
jX_{eqp}: winding leakage reactance
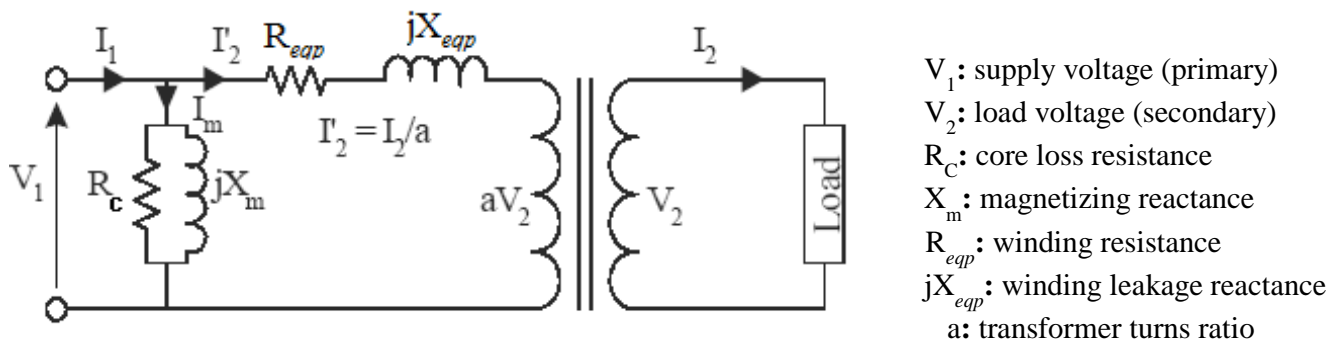a: transformer turns ratio

Figure 1-1: Transformer Equivalent Circuit referred to primary side

If I_2 equals zero (no load conditions), then I'_2 also equals zero. Therefore, I_1 equals I_m and the only power losses are core losses. So the new transformer equivalent model for the open circuit test can be drawn as follows:
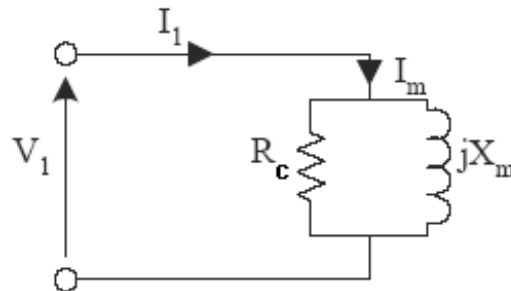

Figure 1-2: Open-Circuit Equivalent Circuit

Since the only power losses are core losses, we can calculate R_C from the equation:

Active power:
$$P_{1(oc)} = \frac{V_{1(oc)}^2}{R_C}$$

Z_m can be calculated using the open-circuit voltage, $V_{1\,(oc)}$, and current, $I_{1\,(oc)}$, from the following:

$$|Z_m| = \frac{V_{1(oc)}}{I_{1(oc)}}$$

Procedure:

We often apply voltage to the low voltage side, since: the open-circuit test requires the application of the rated voltage, it's easier to apply 115V, rather than 220V, a power supply of (L.V) is more readily available than a supply of (H.V).

1. The open circuit test of the transformer is generally done by supplying the low voltage side and keeping the high voltage side of transformer open.
2. **Note the rating specifications of the transformer**.
3. Connect the circuit shown in the practical diagram 2-A.
4. Vary the applied voltage to the low voltage side from **50** to **115V**.
5. Record the readings required inTable 2-A below.
6. Calculate the power factor at no load, I_{rc} and I_{xm}.

Table 2-A

Applied voltage (V_1)	No load current ($I_1 = I_m$)	Open side voltage (V_2)	No load input power (W_o)	Calculated $\cos\theta_o$	Calculated I_{rc}	Calculated I_{xm}
110V						
90V						
70V						
50V						

Where: $\cos\theta_o = \dfrac{W_o}{V_1 \times I_1}$, $I_{rc} = I_1 \times \cos\theta_o$, $I_{xm} = I_1 \times \sin\theta_o$.

Results:
1. Find the no load currents, I_{rc}, I_{xm}, $\cos\theta_o$, R_c and X_m **at the rated voltage**.
2. Plot the applied voltage V_1 against I_m .

Questions:
1. Why does the wattmeter in no load test read the iron losses only?
2. Why the no load test is usually done with supply given to the low voltage side?

B) Turns Ratio Test:-

Objectives:
To study the relation between the voltage on the primary and secondary sides of the single phase transformer.

Introduction:
The transformation ratio of a transformer is defined as the ratio exiting, in no load operation, between the **HV** winding voltage and the **LV** winding voltage.

Instead, the turns ratio of the transformer is defined as the ratio between the number of turns of the **HV** winding and the number of turns of the **LV** winding.

For an ideal two-winding transformer with primary voltage V_1 applied across primary turns N_1 , secondary voltage V_2 appears across the secondary turns N_2 :

$$\frac{V_1}{V_2} = \frac{N_1}{N_2}$$

The primary current I_1 and secondary current I_2 are related by:

$$\frac{I_2}{I_1} = \frac{N_1}{N_2} = \frac{V_1}{V_2} = a$$

Procedure:
Depending on the measured values of V_1 and V_2 in Table 2-A, calculate the ratio: V_1/V_2 .

Questions:
1. How does the transformer change the voltage from one value to the other?
2. What is the voltage ratio? Is it same for all condition?

C) Polarity Test:-

Objectives:
To find the polarity of the transformer windings and to study its importance.

Introduction:
The voltage induced in the secondary winding of a single-phase transformer is either in phase agreement or in opposition compared with the primary voltage. This depends on how the output terminals are considered. If the **HV** terminals are labeled **D & Q**, the **LV** terminals are labeled **d & q** and, when the voltage induced between **D & Q** is in phase agreement with the voltage induced between **d & q**, the polarity is said subtractive. Otherwise, the polarity is additive.

Procedure:

1. Connect the circuit shown in the practical diagram 2-B.
2. Turn on the power supply to set whatever voltage value under rated voltage.
3. Read the value of the voltage V from supply side and the voltage V_1 between the other open terminals of the windings.

$$V = \text{..............} \qquad\qquad V_1 = \text{...............}$$

If $V < V_1$ then, the polarity is additive.

If $V > V_1$ then, the polarity is subtractive.

The polarity of the tested transformer is ....

Questions:

1. What is meant by the additive polarity of transformer?
2. Explain the importance of polarity test on transformer?

D) Measuring the Resistances of the Transformer Windings:-

Objectives:

To determine the value of the winding resistances, which is required to determine the copper losses and the voltage drop.

Procedure:

1. Disconnect all connections on transformer.
2. Using an Ohmmeter, measure and record the DC resistance of each of the following windings.

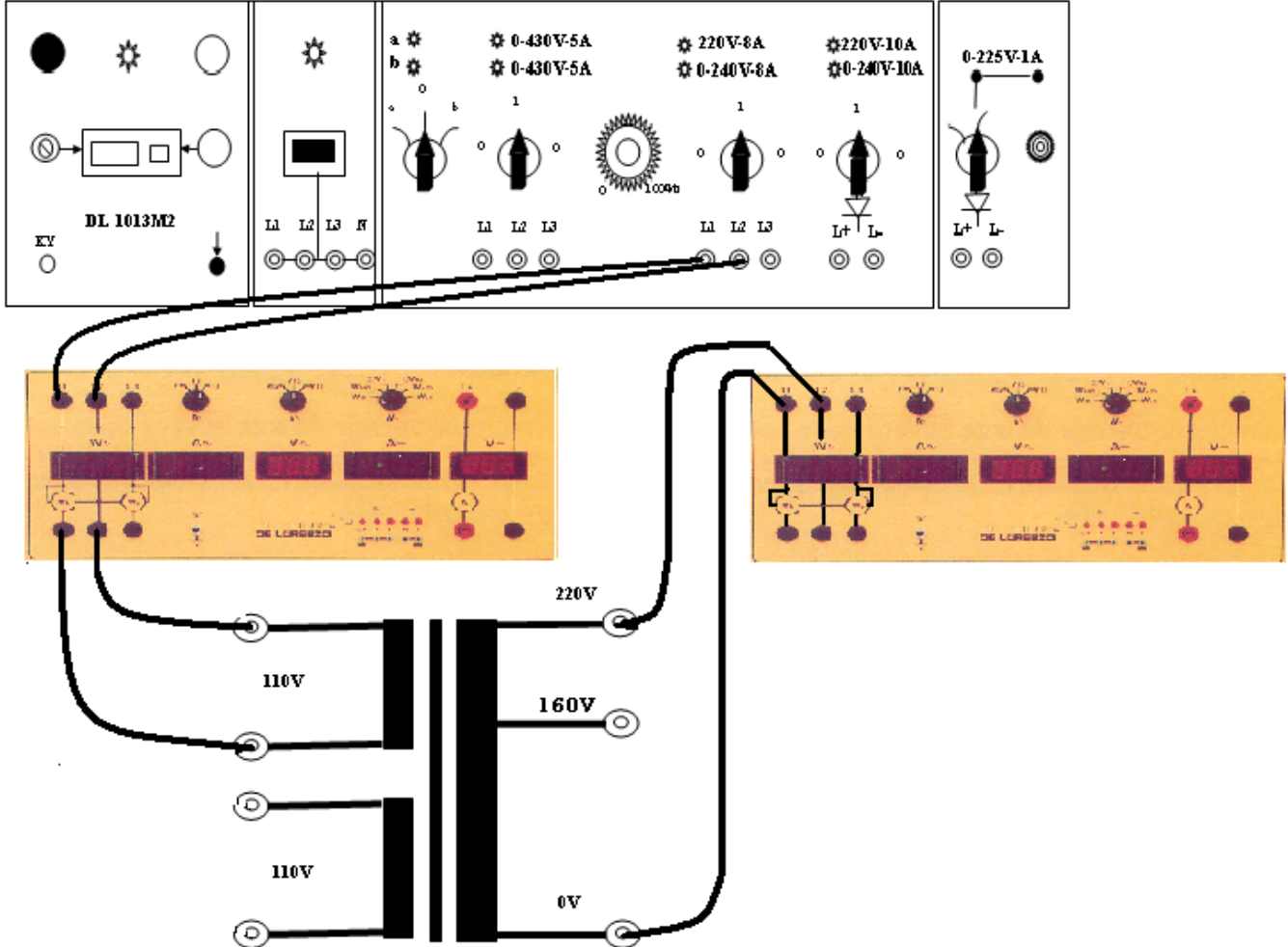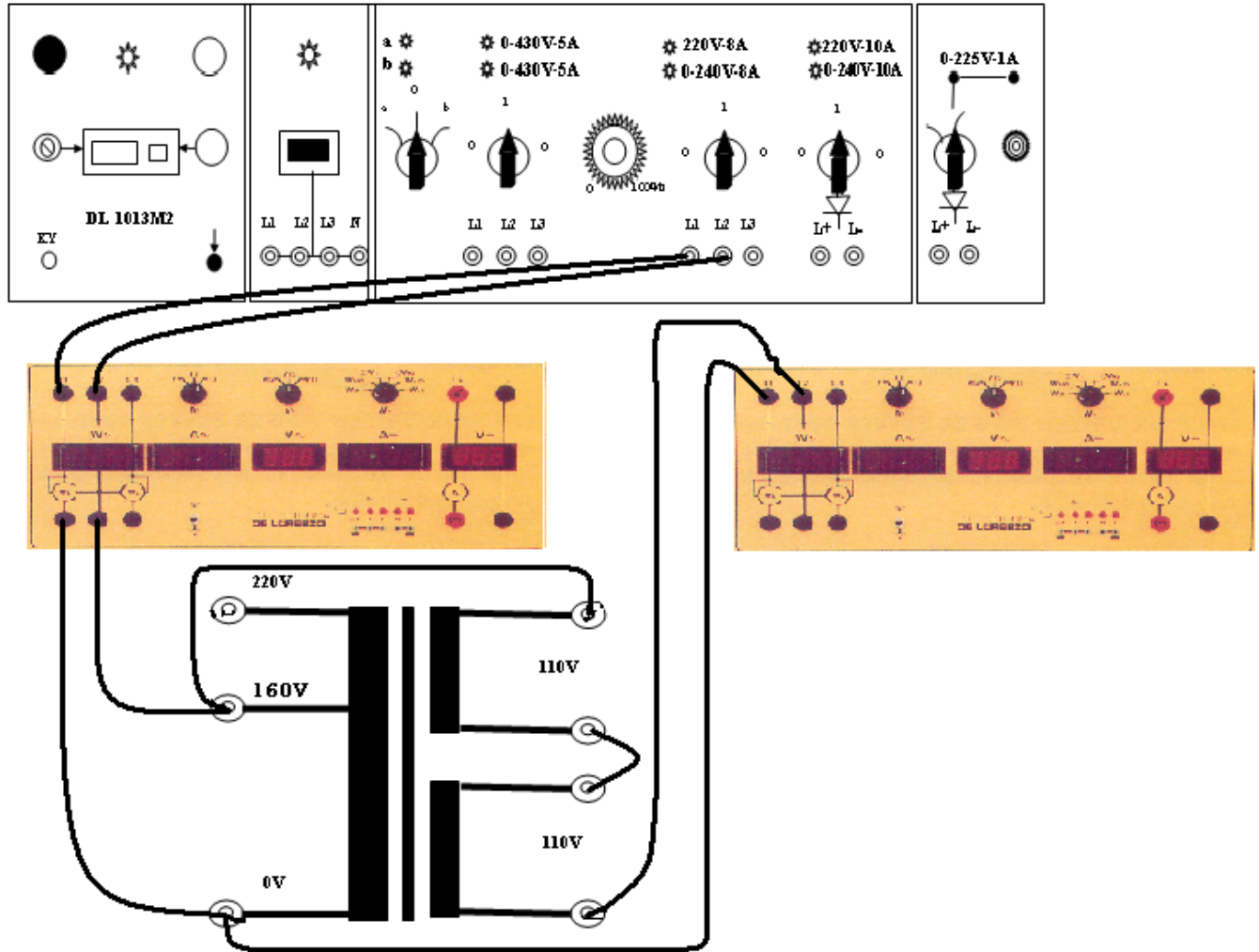| Table 2-B	
Winding	R_x
High voltage side 0V-220V	
High voltage side 0V-160V	
Low voltage side 110 V	

Diagram 2-A

Diagram 2-B

Experiment 3
Single Phase Transformer- II

Short circuit test and load test on a single phase transformer

A) Short Circuit Test

Objectives:
- To carry out a short circuit test on a single phase transformer.
- To determine the parameters of the equivalent circuit.
- To determine the copper losses.
- To determine the impedance of the transformer.

Introduction:
In the short circuit test a very low voltage is applied to the transformer primary (V_{rated} = 220 V) while the secondary (parallel, V_{rated} = 110 V) is shorted. The current drawn by a short-circuited transformer can be very high with only a small primary voltage. The primary voltage is controlled to carefully adjust the current flowing into the transformer. The input voltage required to circulate rated short circuit current in the LV windings is quite small, (V_1 = 13V) therefore V_1^2/R_C and V_1^2/X_m are negligible. This condition results in very small core losses and a negligible magnetizing current. For practical purposes, $I_1 \approx I'_2$. The winding impedance referred to the primary side is:

$$Z_{eq(sc)} = \frac{V_{1(sc)}}{I_{1(sc)}}$$

The winding resistance (R_{eq}) referred to the primary side is:
$$R_{eq} = Z_{eq} \times \cos\theta_o$$
The winding leakage reactance (X_{eq}) referred to the primary side is:
$$X_{eq} = Z_{eq} \times \sin\theta_o$$
Where $V_{1(sc)}$, $P_{1(sc)}$ and $I_{1(sc)}$ are the measured input values of the short circuit test.

Procedure:
We often apply voltage to the high voltage side, since:
        a) We don't need applied high voltage.   **b) The rated current on this side is low**.
1. Connect the circuit shown in the practical diagram (3-A).
2. Increase the supply voltage gradually from zero to a value which will cause current through the winding equal to the rated full load current with the secondary or low voltage side of the transformer short circuited.
3. Read the instruments ammeter $I_{1\ (sc)}$, voltmeter $V_{1\ (sc)}$, and wattmeter $W_{1\ (sc)}$, and then complete the Table (3 – A).
4. Calculate the power factor under short circuit conditions $\cos\theta_o$.
5. Calculate the impedance Z_{eq}, the resistance R_{eq}, and reactance X_{eq} referred to the input side HV. **at the rated current.**

Table 3 - A

$I_{1(sc)\ (A)}$	$V_{1(sc)\ (V)}$	$W_{1(sc)\ (W)}$	Calculated $\cos\theta_o$	Z_{eq}	R_{eq}	X_{eq}
1.2						
1.0						
0.8						
0.6						

Questions:

1. Why a short circuit test is done on the transformer with LV winding shorted and supply given to the HV winding side?
2. Draw the equivalent circuit of the transformer indicating the values of the parameters?

B) Load Test

Objectives:

- To carry out the load test on a single phase transformer by direct loading.
- To find transformer efficiency and regulation.

Introduction:

In the transformer load test the primary winding is connected to the supply voltage and various load levels are applied to the secondary. The actual transformer on-load efficiency (η_{actual}) can be determined from experimental readings and is defined by the following equation:

$$\eta_{actual} \% = \frac{P_{out}}{P_{in}} \times 100\%$$

Where: $P_{out} = \text{Re}\{V \times I^*\}$ if the load is purely resistive, then: $P_{out} = V_2 \times I_2$

Note: In practice the output power would be measured.

The theoretical on-load transformer efficiency can be predicted from the transformer equivalent circuit using the following equation:

$$\eta_{predicted} = \frac{P_{out}}{P_{out} + P_{iron} + P_{cu}} \times 100\%$$

Transformer core or iron losses are defined as: $P_{iron} = \frac{|V_1|^2}{R_m}$

Transformer copper losses P_{Cu} are defined as: $P_{cu} = |I_2|^2 \times R_{eq}$

Note: The maximum transformer efficiency occurs when the variable losses (dependent upon the current drawn) equal the fixed losses (independent of the current drawn):

$$P_{cu} = P_{iron}$$

The output current (I_2) associated with the maximum efficiency is defined as:

$$I_2 = \frac{a \cdot V_1}{\sqrt{R_1 \cdot R_C}}$$

Voltage Regulation (VR) is a measure of the voltage drop for the transformer under load (i.e., the change in the secondary voltage form (no-load) conditions to (on-load) conditions). The transformer voltage regulation expressed as a percentage of the on load secondary voltage is defined by the following equation:

$$VR_{actual} = \frac{\left|V_{2(no-load)}\right| - \left|V_{2(on-load)}\right|}{\left|V_{2(on-load)}\right|} \cdot 100\%$$

In the load test experiment, a=1. $V_{2\ (no\text{-}load)}$ and $V_{2\ (on\text{-}load)}$ are the measured voltage levels.
The theoretical voltage drop in the transformer output voltage (on-load) can be approximated from the equivalent circuit parameters by assuming the transformer load is purely resistive. The transformer's voltage drop is largely due to the voltage drop across the transformer winding resistance R_1 Since the turns ratio a=1 the estimated or predicted voltage regulation is:

$$VR_{predicted} \approx \frac{\left|I_2\right| \cdot R_1}{\left|V_{2(on-load)}\right|} \cdot 100\%$$

Procedure:
1. Connect a resistive load to the (110V) terminals of the tested transformer. As the circuit shown in the practical diagram 3-B.
2. Set the protector resistance value to avoid rated current pass limit. When the load resistance approach from zero. $R_{protection} = \dfrac{V_n^2}{S_n}$ $V_n = 110\ V$ $S_n = 300\ VA$
3. Adjust the primary voltage to 220V, and keep it during test.
4. Slowly increase the load current by decreasing the ohmic value of the load, and then complete the Table (3– B).
5. Plot the load voltage against the load current.
6. Plot the efficiency against the load current

Table 3 – B

I_1 (primary current)	P_1 (input power)	V_2 (load voltage)	I_2 (load current)	P_2 (output power)	η %
1.2					
1.0					
0.8					
0.6					

Questions:

1. Is the active power P_1 less than the active power P_2? What is the function of the no load current?
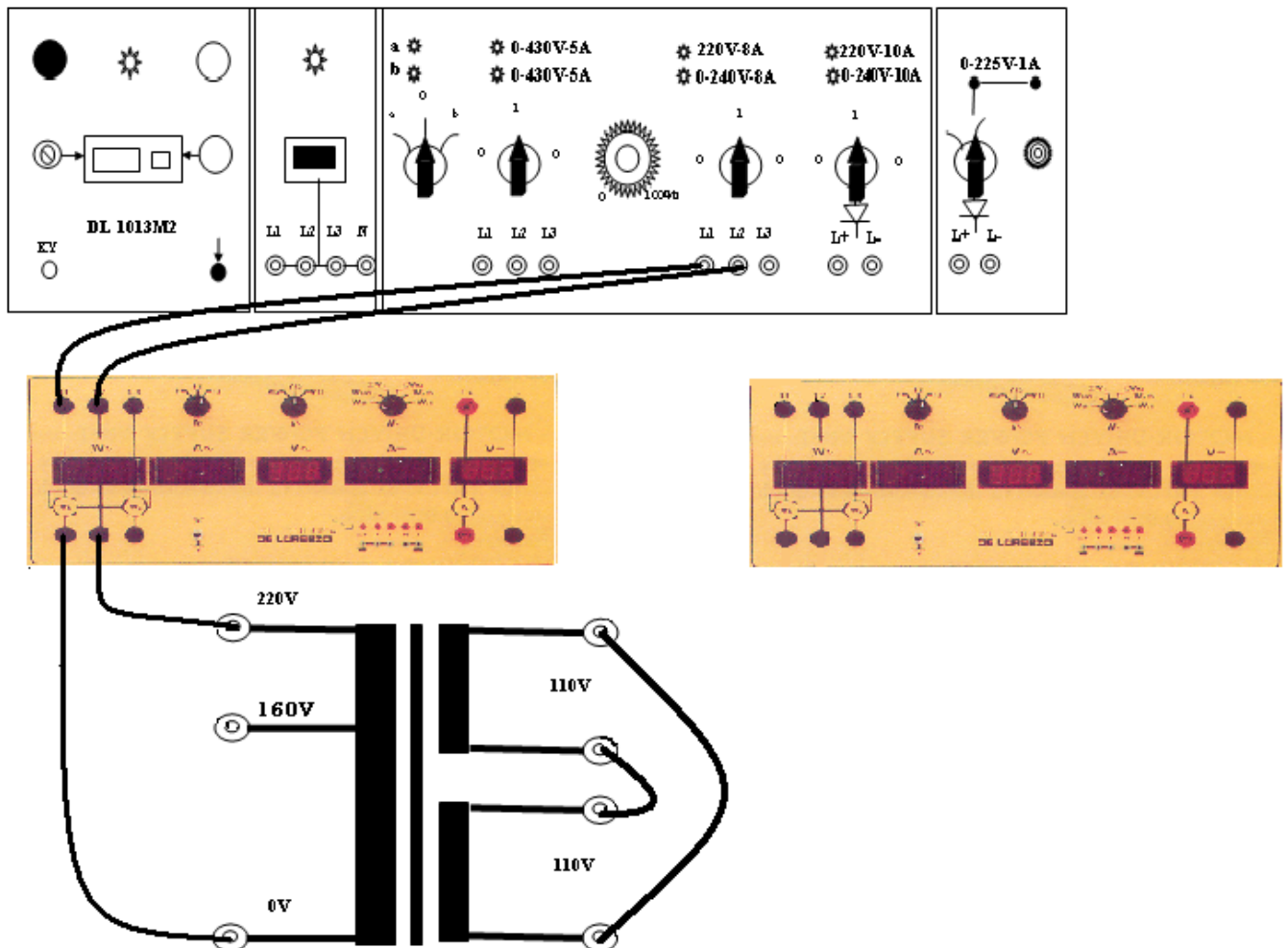2. Why will the transformer consume more current when it is loaded?
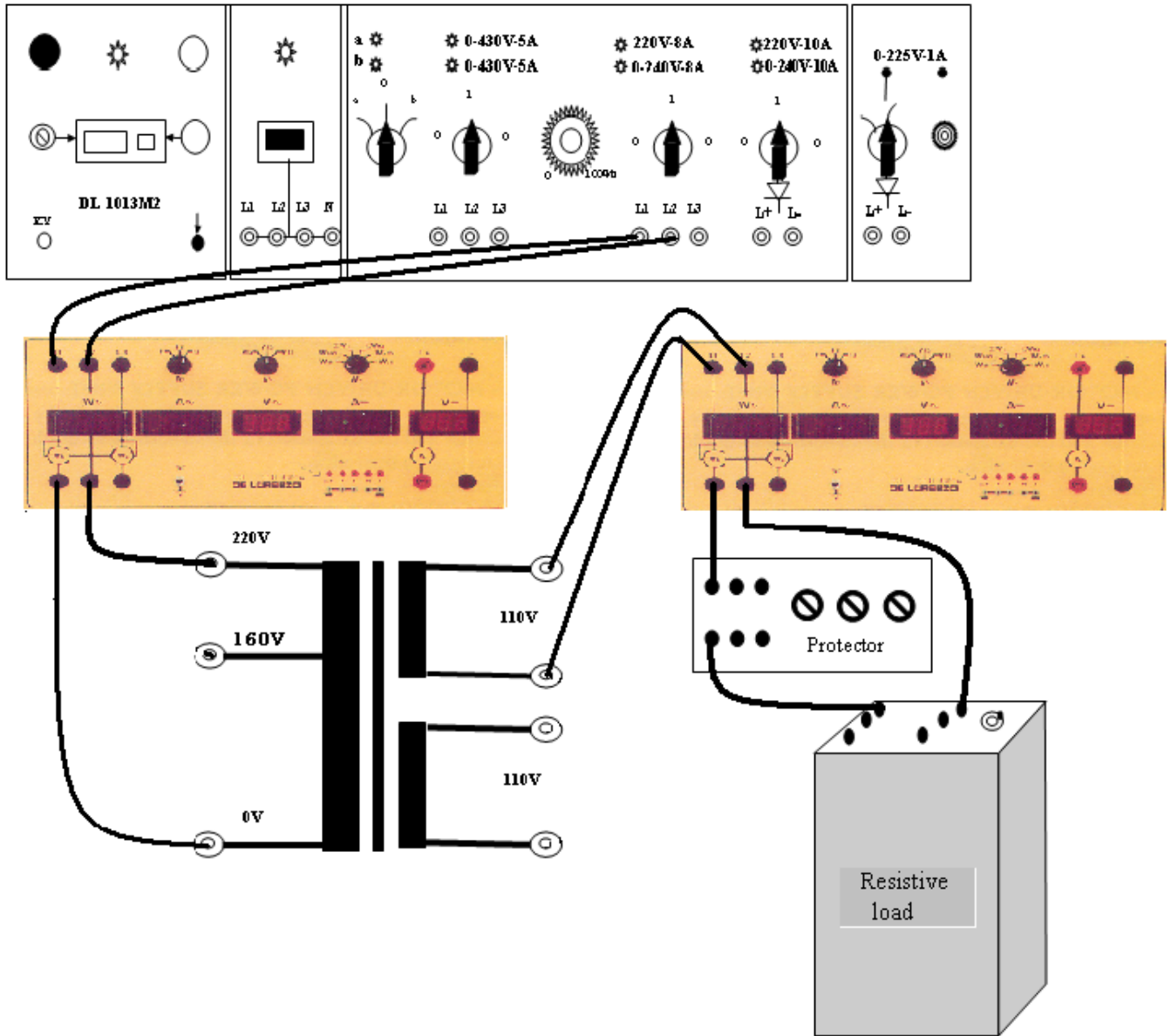
Diagram 3-A

Diagram 3-B

Experiment 4
DC-Shunt Motor

Objectives:
- To determine the variation of speed in an unloaded and a loaded shunt wound dc motor using both armature voltage control and field rheostat control.
- To determine the torque characteristic and the efficiency characteristic.
- To find out how the direction of the rotation of a DC Shunt motor can be reversed.

Introduction:
A shunt motor is essentially the same as a separately excited motor. The only difference is that a separately excited DC motor has its field circuit connected to an independent voltage supply (see Figure 4-1) while the shunt DC motor has its field circuit connected to the armature terminals of the motor (see Figure 4-2). If we assume that the supply voltage of the motor is constant, the principles of operation for the separately excited and shunt DC motors are the same.
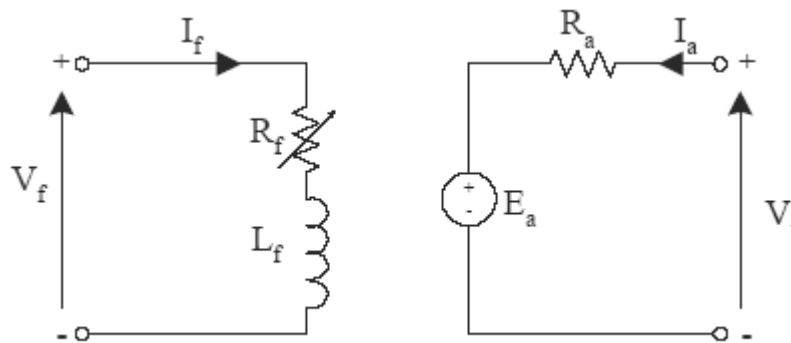

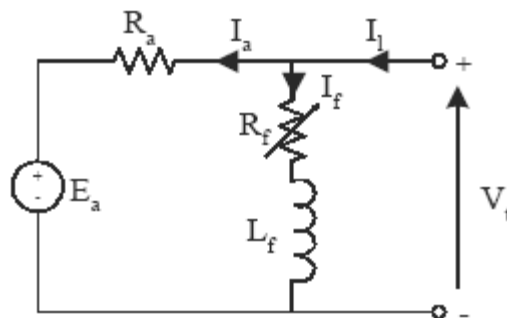Figure 4-1 : Equivalent Circuit of Separately Excited DC

Figure 4-2 : Equivalent Circuit of Shunt DC Motor

The torque-speed relationship of a shunt DC motor is defined by:

$$n = \frac{V_t}{K_E \cdot \Phi} - \frac{R_a}{K_M \cdot K_E \cdot \Phi^2} \cdot \tau$$

Where:

n : angular velocity of the machine.

Φ : magnetic flux.

Vt : terminal voltage.

Ra : armature resistance.

KE, KM : constants depending on design features of the given motor.

This equation is a linear regression. As the torque increases, the speed decreases. The equation becomes non-linear if either V_t,R_a, or flux changes. If armature reaction occurs, the flux is reduced, causing the torque-speed characteristic to be altered. Sometimes compensating windings are introduced to counteract any armature reaction.

There are three ways via which the speed of a shunt DC motor can be controlled:

1. By altering the field resistance, causing the field flux to change.
1. By altering the terminal voltage.
2. By inserting a resistor in series with the armature.

The first two are commonly used, but the third is less common because it reduces the efficiency of the motor. In this lab we will be looking at the properties of the shunt motor by increasing the load using an electromagnetic brake to achieve pre-specified currents. Some useful formulas for describing the characteristics of a shunt excited DC motor are:

$$V_t = I_a \cdot R_a + E_a \quad \circledcirc \quad E_a = K_E \cdot \Phi \cdot n \quad \circledcirc \quad n = \frac{V_t - I_a \times R_a}{K_E \times \Phi} \quad \circledcirc \quad \tau = K_M \cdot \Phi \cdot I_a$$

$$P_{input} = V_t (I_a + I_f) \quad \circledcirc \quad \Phi = K_F \cdot I_F \quad \circledcirc \quad P_{output} = \frac{2\pi n}{60} \times \tau \quad \circledcirc$$

A) Measuring some Characteristics of DC Shunt Motor.

Procedure:

1. Connect the circuit shown in the practical diagram (4-5).
2. Make a note of the DC motor shown on the rating plate; these ratings must not be exceeded at any time during the laboratory exercises.
3. Set the excitation resistance on mid-position and the starting resistance on maximum.
4. Switch on the variable DC voltage. Turn up the variable DC voltage to 220 V.
5. Slowly turn off the starting rheostat and observe that the speed increases.
6. Turn on 0-225 DCV source, arrange the voltage to read armature current in steps up to full load, and then complete the Table(4-1).

	Table 4-1							
$I_f(A)$ constant	$I_a(A)$	$V_t(v)$ constant	P_{in} (W)	$n(rpm)$	$\tau(Nm)$	$P_{out}(W)$	$\eta\%$
0.28		220			0		
0.28	1.5	220					
0.28	3.0	220					
0.28	4.5	220					
0.28	6.0	220					
0.28	6.7	220					

Questions:
1. Plot speed versus torque curve.
2. Plot speed versus armature current curve.
3. Plot efficiency versus output power curve.
4. Explain the nature of the curves in questions 1,2 and 3.

B) Speed control of a DC Shunt Motor.

1 - By Altering the Terminal Voltage.

Procedure:
1. After finishing the Table (4-1). Decrease the load till armature current equals 3A,
2. Vary the terminal voltage as shown in the Table(4-2).
3. **Be carefully don't accede rated armature current 6.7A   when arrived to 50V.**

	Table 4-2						
$I_f(A)$	$I_a(A)$	$V_t(v)$	P_{in} (W)	$n(rpm)$	$\tau(Nm)$	$P_{out}(W)$	$\eta\%$
0.28	3.0	220					
		200					
		150					
		100					
		50					

Questions:
1. Plot speed versus voltage curve.
2. Plot efficiency versus speed curve.
3. Why the armature current is increasing when the terminal voltage is decreasing?

2 - By Altering the Field Resistance.

Procedure:
1. Same connection as before.
2. Start the DC motor with the starting rheostat, and increase terminal voltage to 220V then turn off the starting rheostat.
3. Adjust the current field from excitation rheostat to (0.28A).
4. Increase the load to read 2 Nm
5. Vary the excitation rheostat to decrease the current field to (0.22A), with a step of .03A
6. Record the data in Table (4-4).

Table 4-4

$I_f(A)$	$I_a(A)$	$V_t(v)$ constant	$n(rpm)$	$\tau(Nm)$ $\approx$constant	$\eta\%$
0.28		220		2	
0.25		220		2	
0.22		220		2	

Questions:
1. Plot the curve of speed versus field current, and explain the nature of the curve.
2. Plot the curve of armature current versus field current, and explain the nature of the curve.
3. Plot the efficiency versus speed curve.
4. What happens to speed when the excitation rheostat is increased?
5. Can the speed of shunt motor be reduced by varying field resistance? Why?

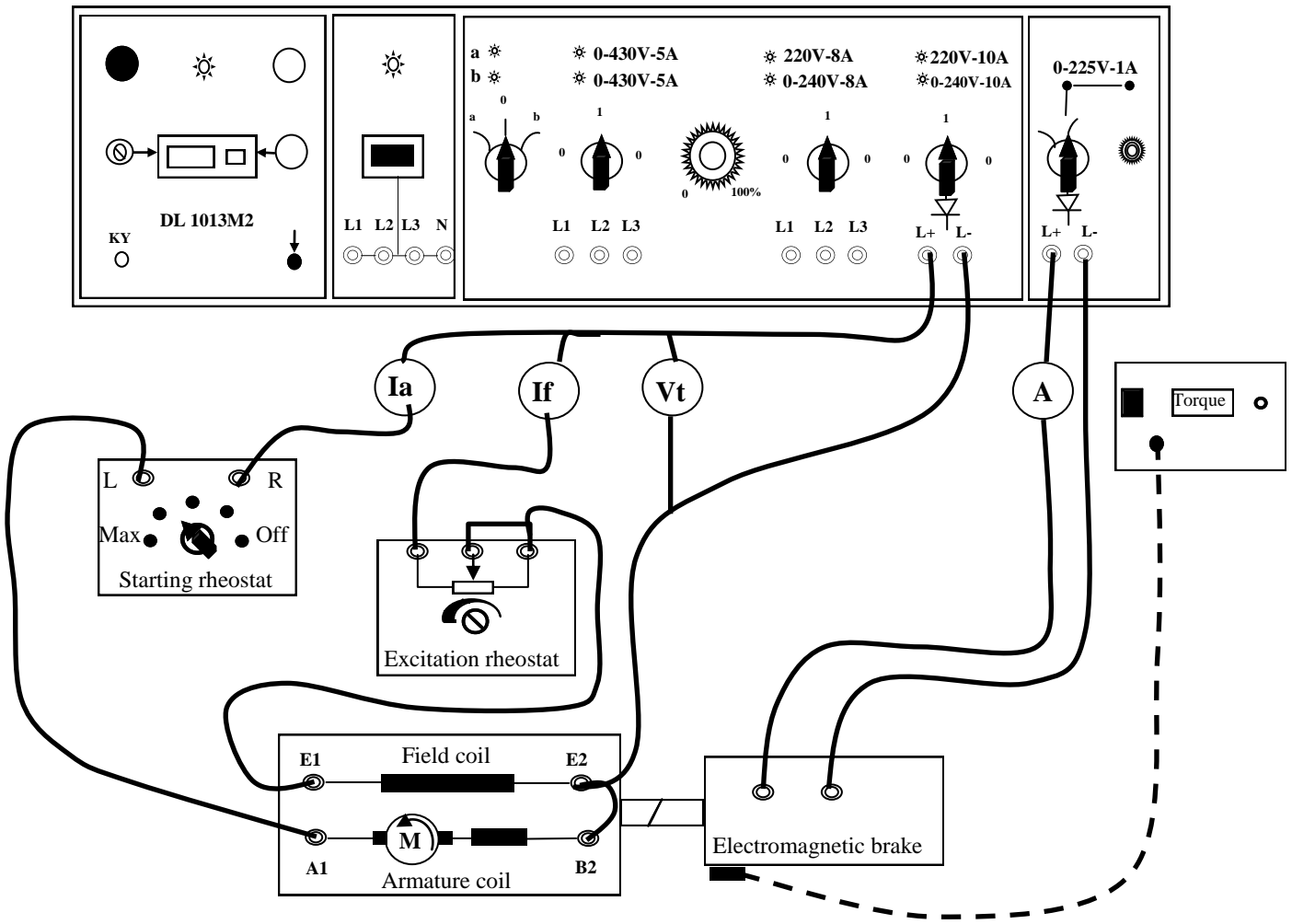## C) Reversing the Direction of Rotation of DC shunt Motor.

Procedure:
1. For the same connection before, try to find out how the direction of a DC shunt motor can be reversed?
2. By the help of your supervisor prepare the connection to reverse the direction of rotation

Questions:
1. If the direction of the current through the field is changed, what happens?
2. If the direction of the current through the armature is changed, what happens?
3. If the direction of the current through both the armature and field is changed, what happens? Explain why?

Diagram 4-5

DL 1013M2

KY

L1 L2 L3 N

a
b

0-430V-5A
0-430V-5A

220V-8A
0-240V-8A

220V-10A
0-240V-10A

0-225V-1A

a   b
0   0   1   0   0   100%   1   0   0   1   0

L1 L2 L3

L1 L2 L3

L+   L-

L+   L-

Ia

If

Vt

A

Torque

L   R
Max   Off
Starting rheostat

Excitation rheostat

E1   Field coil   E2

M

A1   Armature coil   B2

Electromagnetic brake

Experiment 5
DC-Series Motor

Objectives:
- To determine the variation of speed in an unloaded and a loaded series wound DC motor using armature voltage control.
- To determine the torque characteristic and the efficiency characteristic.
- To find out how the direction of the rotation of a DC series motor can be reversed.

Introduction:
A series DC motor has relatively few field turns connected in series with the armature. The equivalent circuit is shown in Figure (5-1):
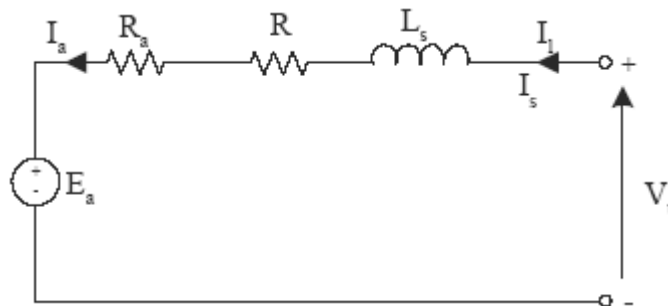

Figure 5-1 Equivalent Circuit of Series Connected DC Motor

The torque-speed relationship for a series motor is much different than that of a shunt motor. As torque increases in the series motor, the speed decays as described by the equation:

$$n = \frac{V_t}{K_E \times \sqrt{\frac{K_\varphi}{K_M}} \times \tau} - \frac{R}{K_E \times K_\varphi}$$

There are three ways via which the speed of a **Series DC Motor** can be controlled:

1. by altering the terminal voltage.
2. by inserting a resistor in parallel with the field coil, causing the field flux to change.
3. by inserting a resistor in parallel with the armature. To change armature current

The series motor's behavior described by this equation is due to the fact that the flux in the motor is directly proportional to the armature current (at least until saturation is reached). Another quality of the series motor is that it delivers more torque per ampere than any other DC motor; therefore, it is the best choice for high torque applications.

One thing to note about the series connected DC motor is that as the torque goes to zero (no load is applied) the machine's speed goes up to infinity. Fortunately, there are mechanical, stray and core losses that prevent this, but the motor can still accelerate itself to speeds that can seriously damage its components. It is therefore very important to only connect a load to a series motor with a belt that is in good condition, for a broken belt would have serious consequences.

The speed of a series connected DC motor can be controlled by altering the terminal voltage. In this lab we will be looking at the properties of the series motor by increasing the load using an electromagnetic brake to achieve pre-specified currents. Some useful formulas for describing the characteristics of a series DC motor are:

$$V_t = I_a \cdot (R_a + R_f) + E_a \quad , \qquad \Phi = K_F \cdot I_a \quad , \qquad \tau = K_M \times \Phi \times I_a = K_M \times K_F \times I_a^2$$

A) Measuring some characteristics of DC series motor.

Procedure:
AT NO TIME ALLOW THE LOAD TO GO TO ZERO ON A SERIES MOTOR!

1. Connect the circuit shown in the practical diagram (5-2).
2. Take a look to the rating plate of DC motor; these ratings must not be exceeded at any time during the laboratory exercises.
3. Set the starting resistance on maximum.
4. Apply the load by connecting it with the supply and increasing the voltage to reads 0.15 A on ampermeter (this means the load) and put the starting resistance to maximum.
5. Switch on the variable DC voltage. Turn up the variable DC voltage to 220 V.
6. Slowly turn off the starting rheostat and observe that the speed increases.
7. Arrange the load in steps from **2Nm** to full load, and then complete the Table (5-3).
8. Don't go down with the load to less than 2Nm.
9. Complete the next part B-1.

	Table 5-1						
I_a(A)	V_t (V) constant	P_{in}(W)	n(rpm)	τ(Nm)	P_{out}(W)	η%
4	220					
5	220					
6	220					
7	220					
7.3	220					

Questions:
1. Plot speed versus torque curve.
2. Plot efficiency versus output power curve.
3. Explain the nature of curve 1and 2.

B) Speed Control of a DC series motor.

By altering the terminal voltage.

Procedure:
1. After the armature current reaches the rated value of 7.3A, vary the terminal voltage as Table 5-2

Table 5-2

I_a(A)	V_t (V)	P_{in}(W)	n(rpm)	τ(Nm)	P_{out}(W)	$\eta\%$
	200					
	150					
	100					
	50					
	0					

Questions:
1. Plot the speed versus V_t curve and versus efficiency in the same graph. (Table 5-2)

C) Reversing the Direction of Rotation of DC Series Motor.

Procedure:
1. For the same connection, try to find out how the direction of a DC series motor can be reversed?
2. By the help of your supervisor prepare the connection to reverse the direction of rotation.

Questions:
1. If the direction of the current through the field is changed, what will happen?
2. If the direction of the current through the armature is changed, what will happen?
3. If the direction of the current through both the armature and field is changed, what will happen? Explain why?

Diagram 5-1
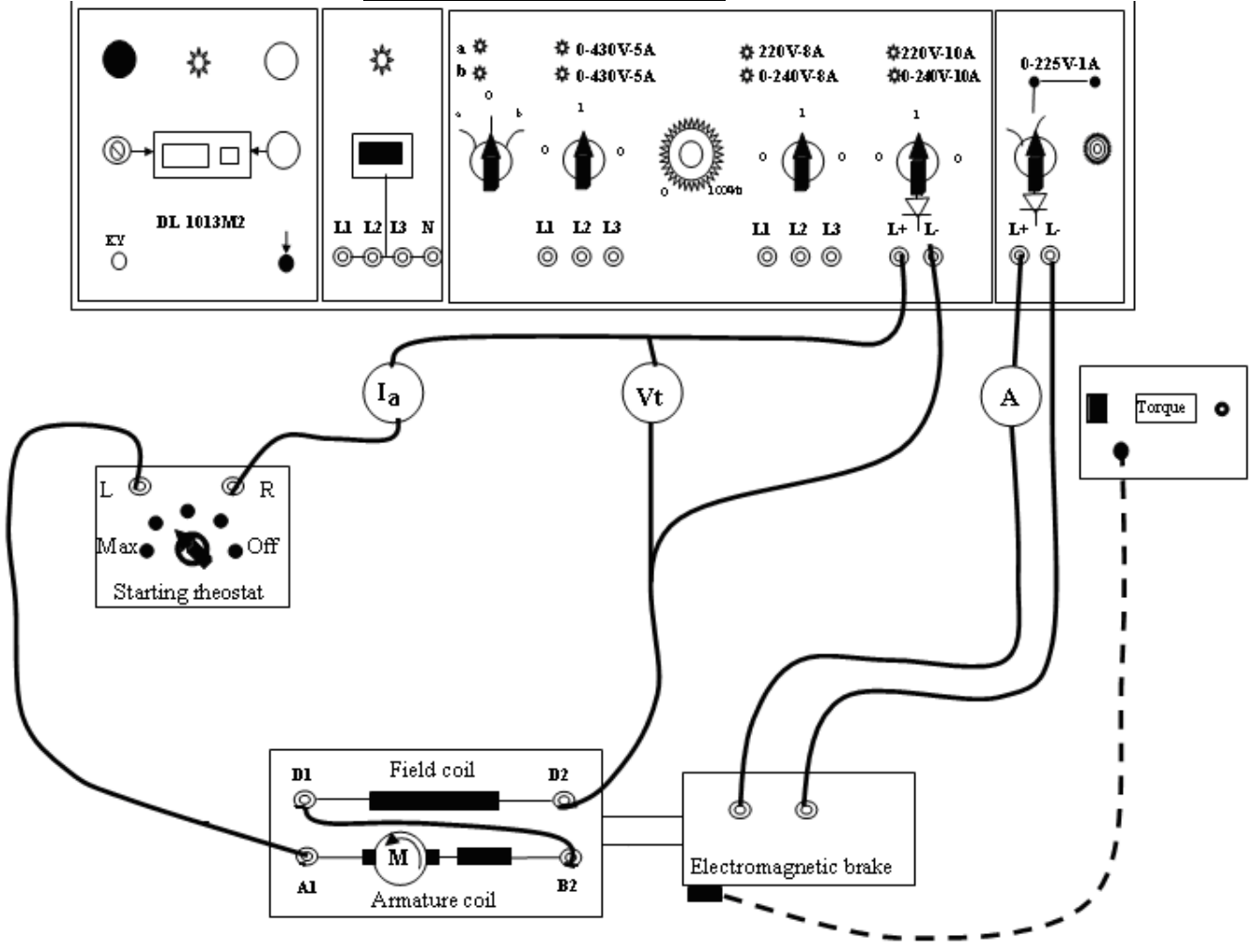
Experiment 6
DC-Separately Excited Generator

Objective:
- To determine the no-load characteristic.
- To determine the load characteristic.
- To determine the external voltage characteristic and the control characteristic.

Introduction:

If a coil is rotated through a magnetic field as shown in Figure (6-1), an alternating voltage will be produced. To make this voltage available to a stationary external circuit, two slip rings and brushes must be provided. For the external circuit to produce DC voltage, it is necessary to reverse the polarity of the external leads at the same time the voltage in the coil is reversed. This is accomplished by segmenting a slip ring to form what is called a commutator. An elementary two segment commutator is illustrated in Figure (6-2). This single coil, two piece commutators will yield a unidirectional but pulsating voltage as shown in Figure (6-3). However, when a large number of commutator segments or bars is used, the resulting voltage will be more uniform as shown in Figure (6- 4).
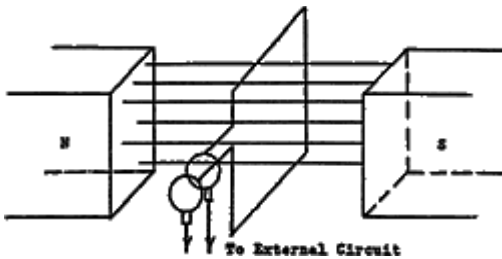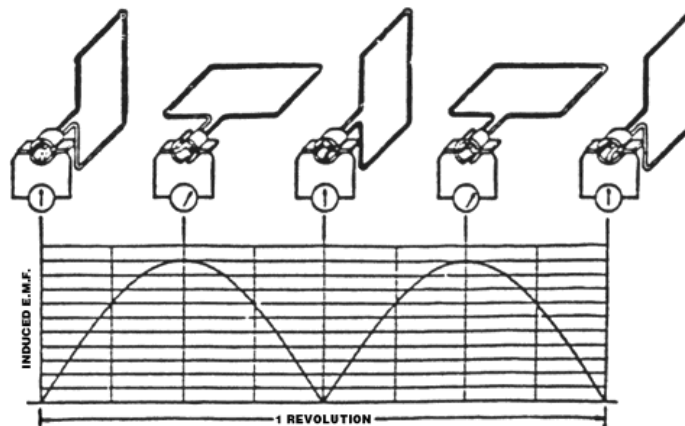

Figure (6-1).
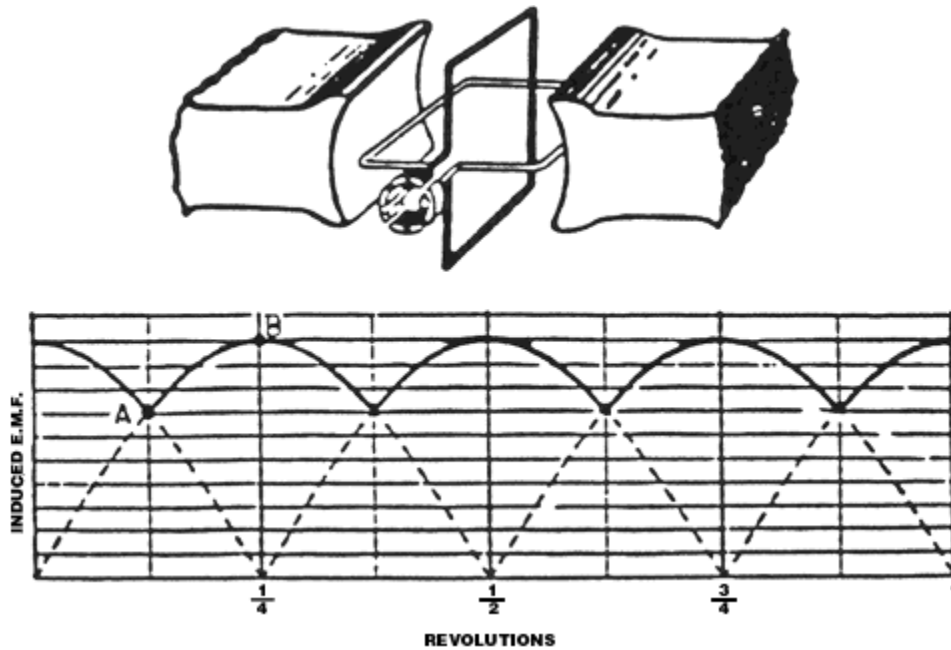Brushes and slip rings provide AC voltage
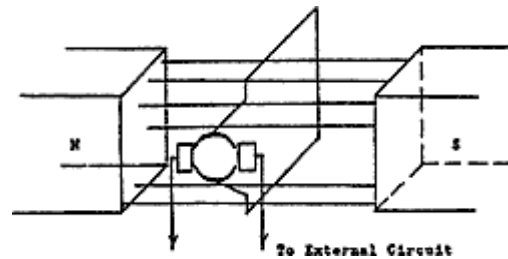
Figure(6- 2).
Brushes and Commutator provides DC voltage

Figure (6-3).
Unidirectional, Pulsating Voltage

Figure (6-4).
Uniform DC Voltage

The generated voltage in real DC machine is:

$$E_A = \frac{ZP}{2\pi a}\phi\omega$$

Where:
Z = Total number of conductors.
P = Poles
a = No, of parallel paths.
ω = Rotational speed rad/s .
Φ = Flux per pole. In meter.

For a given machine:

$$E_A = V_T + I_A R_A$$

$$\frac{ZP}{2\pi a}\phi\omega = V_T + I_A R_A$$

Where:
V_T = terminal voltage.
I_A = current of armature.
R_A = resistance of armature.

DC-Separately Excited Generator:

The separately excited DC generator has its field circuit connected to an independent voltage supply see Figure (6-5).
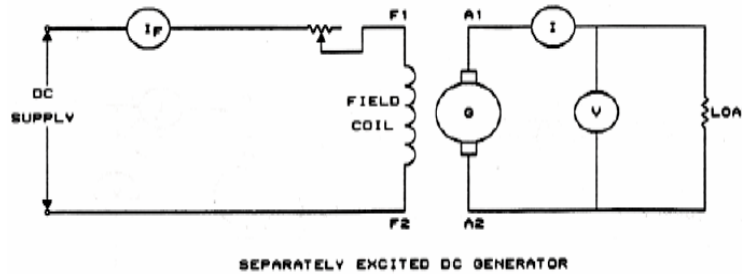

Figure (6-5)

The no-load characteristic

Procedure:
1. Connect the circuit shown in the practical diagram (6-6).
2. Make a note of the DC generator shown on the rating plate; these ratings must not be exceeded at any time during the laboratory exercises.
3. The supervisor should now check the connections.
4. The DC- generator is fed with fixed DC voltage from the power pack. Adjust the shunt rheostat to obtain minimum excitation current. Turn on the fixed DC voltage switch.
5. From the torque measuring unit. Adjust the potentiometer to obtain maximum excitation current for DC motor.
6. Set the variable DC voltage control to zero and turn on the variable voltage switch. Then turn up the rotor voltage to bring the speed to 1400rpm. *This speed must be maintained constant through out the experiment* and must therefore be checked from time to time. *The switch S must be off*.
7. Vary the excitation current from zero to maximum in steps 0.1A, and record the data as the table (6-7).Increasing.
8. Vary the excitation current from maximum to zero in steps 0.1A, and record the data as the Table (6-7).Decreasing.
9. Repeat the steps from 6 to 8 steps and record data in table (6-8).

Table (6-7)

1400rpm			
Increasing		Decreasing	
E_A (V)	I_F (A)	E_A (V)	I_F (A)
	0		0
	0.1		0.1
	0.2		0.2
	0.3		0.3
	0.4		0.4
	0.5		0.5
	0.6		0.6
	0.7		0.7
	0.8		0.8

Table (6-8)

1200rpm			
Increasing		Decreasing	
E_A (V)	I_F (A)	E_A (V)	I_F (A)
	0		0
	0.1		0.1
	0.2		0.2
	0.3		0.3
	0.4		0.4
	0.5		0.5
	0.6		0.6
	0.7		0.7
	0.8		0.8

The load characteristic

Procedure:

1. Adjust the speed of the motor to 1400rpm. *This speed must be maintained constant through out the experiment* and must therefore be checked from time to time.
2. Adjust the excitation rheostat **R$_{my}$** of the DC generator to bring rated current (I_F = 0.8A). *This current must be maintained constant through out the experiment* and must therefore be checked from time to time. *The switch S must still be off*.
3. Adjust the load resistor (**R$_L$**) to high resistance(**clockwise to stop**), turn on switch **S.**
4. Vary the load resistor to bring current (I_A) a steps of 1A to the rated current.
5. Record the data of terminal voltage and load current in the Table (6-9)

Table (6-9)

I_F (A)	N(rpm)	I_A (A)	V_T (V)
0.8	1400		
0.8	1400	2	
0.8	1400	3	
0.8	1400	4	
0.8	1400	5	
0.8	1400	6	
0.8	1400	7	
0.8	1400	8	
0.8	1400	9	

Questions:

1. Draw the no load characteristic for increasing and decreasing I_F on (x) axis at 1400 and 1200 rpm on the same graph?
2. Draw the external voltage characteristic with I_A on (x) axis?
3. Why does the no load characteristic differ for increasing and decreasing excitation current?
4. Why does V_T increase with decrease I_A ?

The practical diagram (6-6)
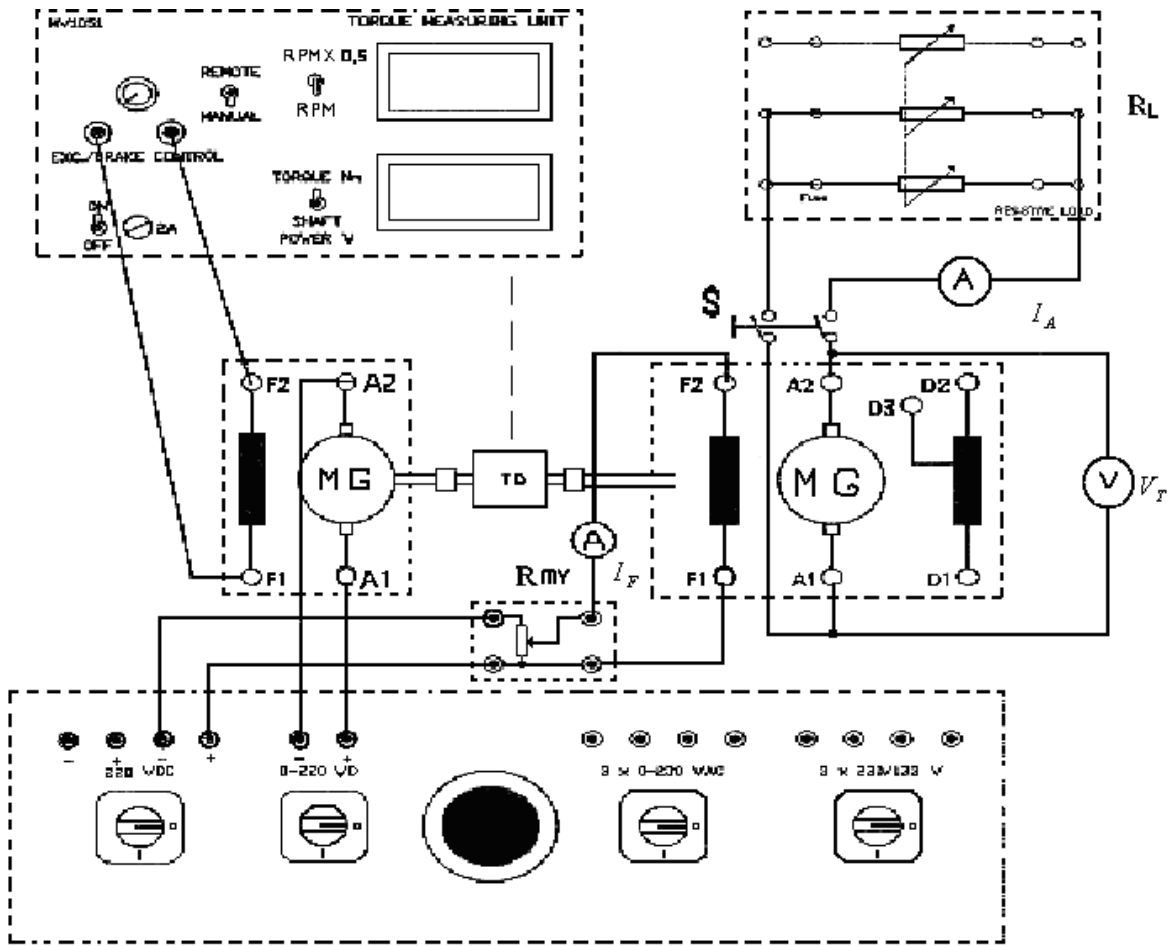
Experiment 7
DC-Shunt Excited Generator

Objective:

- To determine the no-load characteristic.
- To determine the load characteristic.
- To determine the external voltage characteristic and the control characteristic.
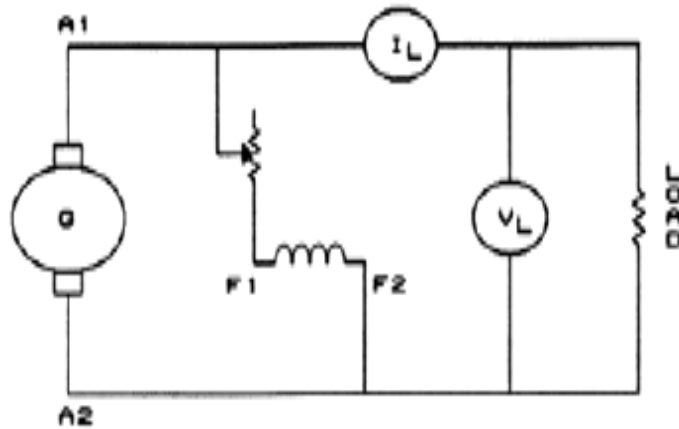
Introduction:

Figure (7-1)
A self-excited shunt generator

A self-excited shunt generator has the advantage that its field is energized by the voltage produced by its own armature see Figure (7-1), which is initially built up by residual magnetism. Hence, the field current is not constant, but depends upon the terminal voltage, which drops off as the load current is increased. The terminal voltage will decrease with the increase in load current because of three factors:

- A. Internal $I_A R_A$ drop in the armature resistance.
- B. Reduction in effective flux due to armature reaction.
- C. Reduction in field flux resulting from drop in terminal voltage for reasons **A** and **B**.

The No-Load Characteristic

Procedure:

1. Connect the circuit shown in the practical diagram (7-5).
2. Make a note of the DC generator shown on the rating plate; these ratings must not be exceeded at any time during the laboratory exercises.
3. The supervisor should now check the connections.
4. From the torque measuring unit. Adjust the potentiometer to obtain maximum excitation current for DC motor.
5. Set the variable DC voltage control to zero and turn on the variable voltage switch. Then turn up the rotor voltage to bring the speed to 1400rpm. ***This speed must be maintained constant through out the experiment*** and must therefore be checked from time to time. ***The switch S must be off***.

6. Vary the excitation current from zero to maximum in steps 0.1A, and record the data as the table (7-2).Increasing.
7. Vary the excitation current from maximum to zero in steps 0.1A, and record the data as the Table (7-2).Decreasing.
8. Repeat the steps from 6 to 8 steps and record data in table (7-3)

Table (7-2)

1400rpm			
Increasing		Decreasing	
E_A (V)	I_F (A)	E_A (V)	I_F (A)
	0		0
	0.1		0.1
	0.2		0.2
	0.3		0.3
	0.4		0.4
	0.5		0.5
	0.6		0.6
	0.7		0.7

Table (7-3)

1200rpm			
Increasing		Decreasing	
E_A (V)	I_F (A)	E_A (V)	I_F (A)
	0		0
	0.1		0.1
	0.2		0.2
	0.3		0.3
	0.4		0.4
	0.5		0.5
	0.6		0.6
	0.7		0.7

The Load Characteristic

Procedure:

1. Adjust the speed of the motor to 1400rpm. ***This speed must be maintained constant through out the experiment*** and must therefore be checked from time to time.
2. Adjust the excitation rheostat **R_{my}** of the DC generator to bring rated current (I_F = 0.8A).***The setting of the excitation rheostat R_{my} must thereafter not be changed during the experiment***. ***The switch S must still be off***.
3. Adjust the load resistor (**R_L**) to high resistance (**clockwise to stop**), turn on switch **S.**
4. Vary the load resistor to bring current (I_A) in steps 1A to rated current.
5. Record the data of terminal voltage and load current in the Table (7-4)

Table (7-4)

I_m (A)	RPM	I_L (A)	V_t(V)
0.8	1400	0	
	1400	2	
	1400	4	
	1400	6	
	1400	8	

Questions:

5. Draw the no load characteristic for increasing and decreasing I_F on (x) axis at 1400 and 1200rpm on the same graph?

1.

2. Draw the external voltage characteristic separately and shunt excitation in the same diagram with I_A on (x) axis?

3. Why does V_T decrease with increase I_A ?

4. Why does V_T decrease more with shunt than with separately excitation?

5. Why does the generator not take up voltage in measurement if the field is wrongly connected?

The practical diagram (7-5)
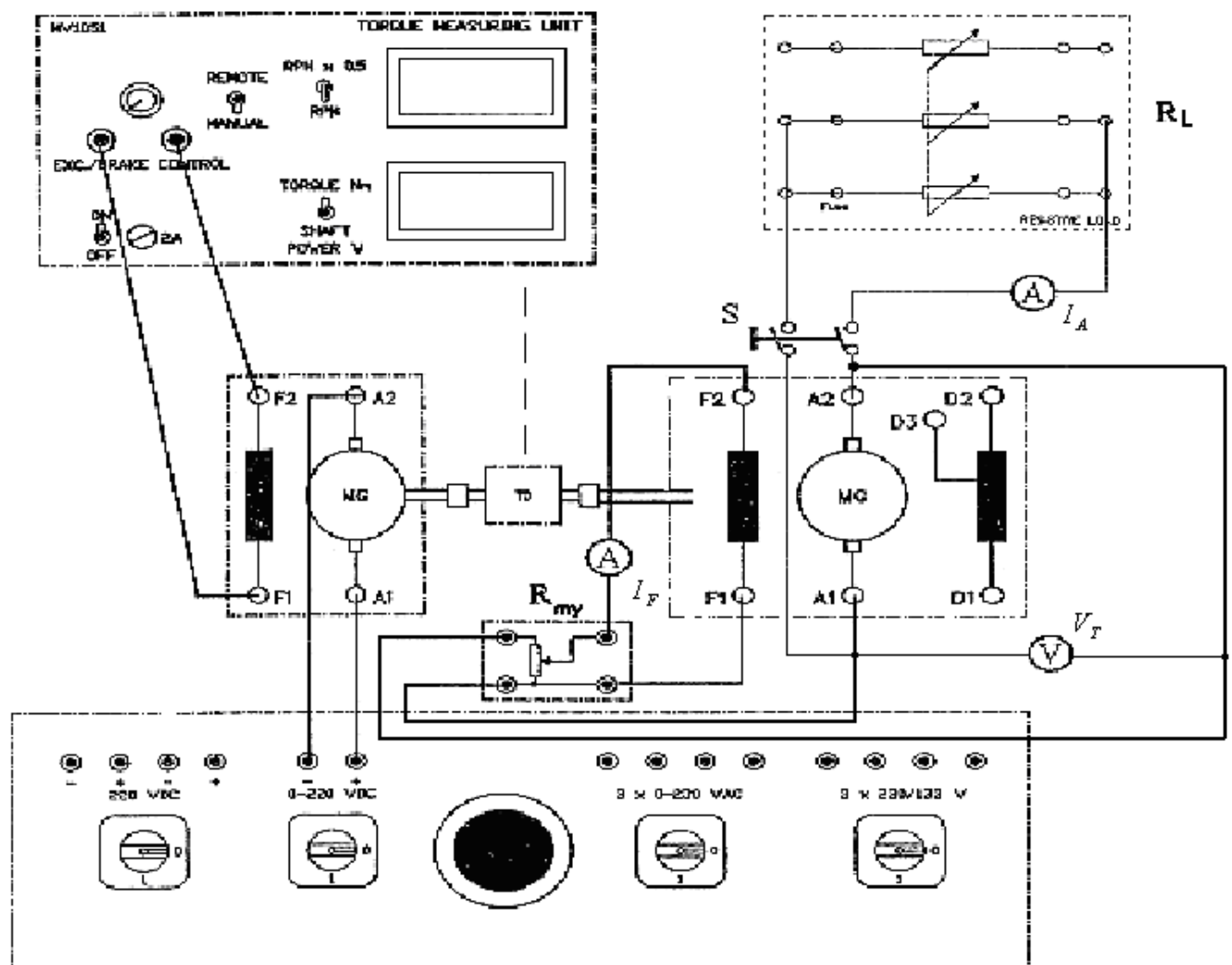
Experiment (8)
Induction Motor (1)

Objective

The purpose of this experiment is to illustrate the operating characteristics of a three-phase squirrel cage induction motor and to determine its equivalent circuit.

To accurately determine a motor's response to a change in its load, it is necessary to determine the motor's equivalent circuit. To determine a motor's equivalent circuit we must do a series of tests much like we did with the transformer. It takes three tests to determine a motor's equivalent circuit: no-load test, DC test, and the locked-rotor test. The details on how to accurately determine an induction motors equivalent circuit can be found in IEEE Standard 112. This complicated standard will not be followed precisely in this lab but the general process will be used.

Determination of the Induction Motor Equivalent Circuit

No Load Test

The no-load test is used to determine an induction motor's rotational losses, and to find out some information about its magnetization current. The single-phase equivalent circuit of a 3-phase induction motor is shown in figure 8-1:
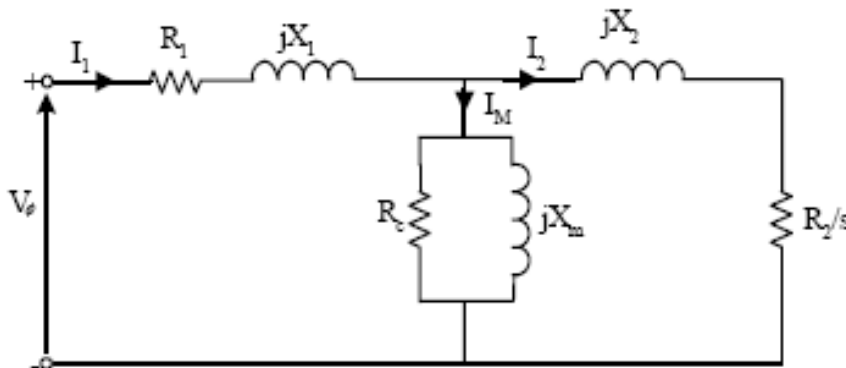

Figure 8-1: Equivalent Circuit of an Induction Motor

Since slip is extremely small, R_2 is very large, resulting in almost no current to flow through that branch; therefore, the rotor copper losses can be neglected. The only loads on the motor are its core losses, friction and windage losses, and stator copper losses; therefore, the three-phase induction motor no-load losses are:

$$P_{in} = 3I_1^2.R_1 + P_c + P_{F+W} \quad \ldots\ldots\ldots\ldots(8.1)$$

Where:

P_{in} : input power

P_c : core losses

P_{F+W}: friction and windage losses

The equivalent circuit that describes the motor under no-load conditions has the resistors R_c and R_2/s in parallel with the magnetizing reactance X_m. X_m will be much smaller than the resistances in parallel with it; therefore, most of the voltage drop will occur across the inductive components of the circuit. As a result the magnetizing reactance X_m can be estimated from the following equation when you are given X_1:

$$X_1 + X_m = |Z_{nl}| = \frac{\sqrt{3}\, V_{ln}}{I_{l,nl}} \quad \ldots\ldots\ldots\ldots\ldots\ldots(8.2)$$

where:

X_1: stator reactance

X_m: magnetizing reactance

Resistance Measurement

This test is used to determine the stator winding resistance, R_1. In the DC test a DC current is applied to the motor, since the current is DC, there is no induced voltage in the rotor and therefore no current in the rotor, so no R_2 losses.

Supplying a DC current to 2 of the terminals of a Y connected induction motor causes current to flow in two phases of the motor; therefore, when calculating the resistance we must remember that the resistance seen is twice the stator winding resistance for one phase.

Therefore, the stator winding resistance is: $\qquad R_1 = \dfrac{V_{dc}}{2 \cdot I_{dc}}$

Locked Rotor Test

The locked rotor test for induction motors is like the short circuit test for transformers. In this test we lock the rotor in place preventing it from moving. A voltage is applied to the stator of the motor and the corresponding current and power is measured. Since the slip is equal to 1, R_2/s is equal to R_2, a small number; therefore, most of the current will flow through R_2 and X_2 instead of the large magnetizing reactance, X_m. From this we can determine the total impedance and phase angle from the formulas:

$$|Z_{LR}| = \frac{\sqrt{3}V_{\phi}}{I_L}$$

$$\theta = \cos^{-1}\left[\frac{P_{in}}{\sqrt{3}V_T I_L}\right]$$

Now that we know the impedance and phase angle it's possible to determine R_{LR} and X'_{LR} from the equations:

$$R_{LR} = R_1 + R_2 = Z_{LR} \cdot \cos\theta .$$

$$X'_{LR} = X'_1 + X'_2 = Z_{LR} \cdot \sin\theta .$$

Where:

R_1: stator resistance

R_2: rotor resistance

X'1: stator reactance at test frequency

X'2': rotor reactance at test frequency

To determine XLR from $X'LR$ we can use the formula:

$$X_{LR} = \frac{f_{rated}}{f_{test}} \cdot X'_{LR} = X_1 + X_2$$

Where:

X_1: stator reactance

X_2: rotor reactance

A test frequency is used because when the rotor is locked, the rotor frequency is equal to the line frequency, but when the machine is at operating conditions the rotor's frequency is approximately 1 to 3 Hz. Since reactance is largely dependent on frequency, this will cause inaccurate results. A compromise typically used is to do the test at 25% or less the rated frequency. However, in this lab we do not have access to a variable frequency drive, so $f_{test} = f_{rated}$ and therefore:

$$X_{LR} = X'_{LR}$$

To determine how XLR breaks up into X_1 and X_2, we refer to the motor class being used. Experience has shown that each motor class follows a typical reactance break down according to the Table 7-1:

Rotor Design	X_1	X_2
Wound Rotor	0.5 X_{LR}	0.5 X_{LR}
Class A	0.5 X_{LR}	0.5 X_{LR}
Class B	0.4 X_{LR}	0.6 X_{LR}
Class C	0.3 X_{LR}	0.7 X_{LR}
Class D	0.5 X_{LR}	0.5 X_{LR}

Table 8-1: Reactance breakdown for Different Classes of Induction Motors

The induction motor used in this lab is a Class B motor and therefore from the table above:

$$X_1 = 0.4X_{LR}.$$

$$X_2 = 0.6X_{LR}$$

Procedure:
1- Resistance Measurement

By using ohmmeter measure the three winding resistances between:

$U_1,U_2 = $ ……………$V_1,V_2 = $……………$W_1,W_2 = $…………

$$R_1 = \frac{R_U + R_V + R_W}{3} = ...$$

2- No Load Test
1. Connect the eddy current brake and the induction motor in accordance with the circuit diagram figure (8.2). Make sure that the power pack is in the "off" position.
2. Note and record the motor ratings.
3. Eddy current brake set up:
3.1 Check that the tachogenerator terminals and the strain gauge lead are connected to the specified terminals at the back of the control unit.
3.2 Set the main switch to the (off) position.
3.3 Turn on the main switch, the light from the digital display indicates that the eddy current brake is ready for manipulation.
3.4 Turn the "brake force" knob anti-clockwise to minimum torque position.
3.5 Read and make a note of the speed value. Set the (torque/power) switch to "torque" position. Turn "zero adjust" knob until a zero reading is shown on the corresponding display.
   <u>Note: At least 5 minutes warming up time needed   before zeroing.</u>
3.6 Turn the switch to "power" position and check that the display reading is also zero.
3.7 Turn off the main switch. The eddy current brake is now set and ready for operation.
3.8 The supervisor should now check the connections.
1. Switch on the power pack.
2. Turn on the variable AC voltage switch and adjust the voltage to 220 V. Note all deflections of the instruments and record at table (8.2). Turn off the AC voltage switch.

Table (8.2)

MEASURED VALUES			CALCULATED VALUES				
$V_{(v)}$	$I_{1\,(A)}$	$P_{in\,(w)}$	$\cos\theta$	θ	Z_m	R_c	X_m

$$\cos\theta = \frac{P_{in}}{\sqrt{3}V_T I_{1n}} \ , \quad R_c = \left(\frac{Z_m}{\cos\theta}\right) - R_1 \ , \quad X_m = \frac{Z_m}{\sin\theta}$$

3- Locked Rotor Test

1. Set the star/delta switch to position "Δ" and the reversing starter switch (**Z**) to position "Forward". Hold on to the rotor so that the motor does not start. Check that the eddy current brake is turn on, at maximum.
2. Record in table (8.4) the rated current to motor.
3. Turn on the AC voltage switch and cautiously increase the voltage so that the stator current increases to rated current. Make a note of U, I₁ and Pin at table (8.4). Then turn the AC voltage down to zero.

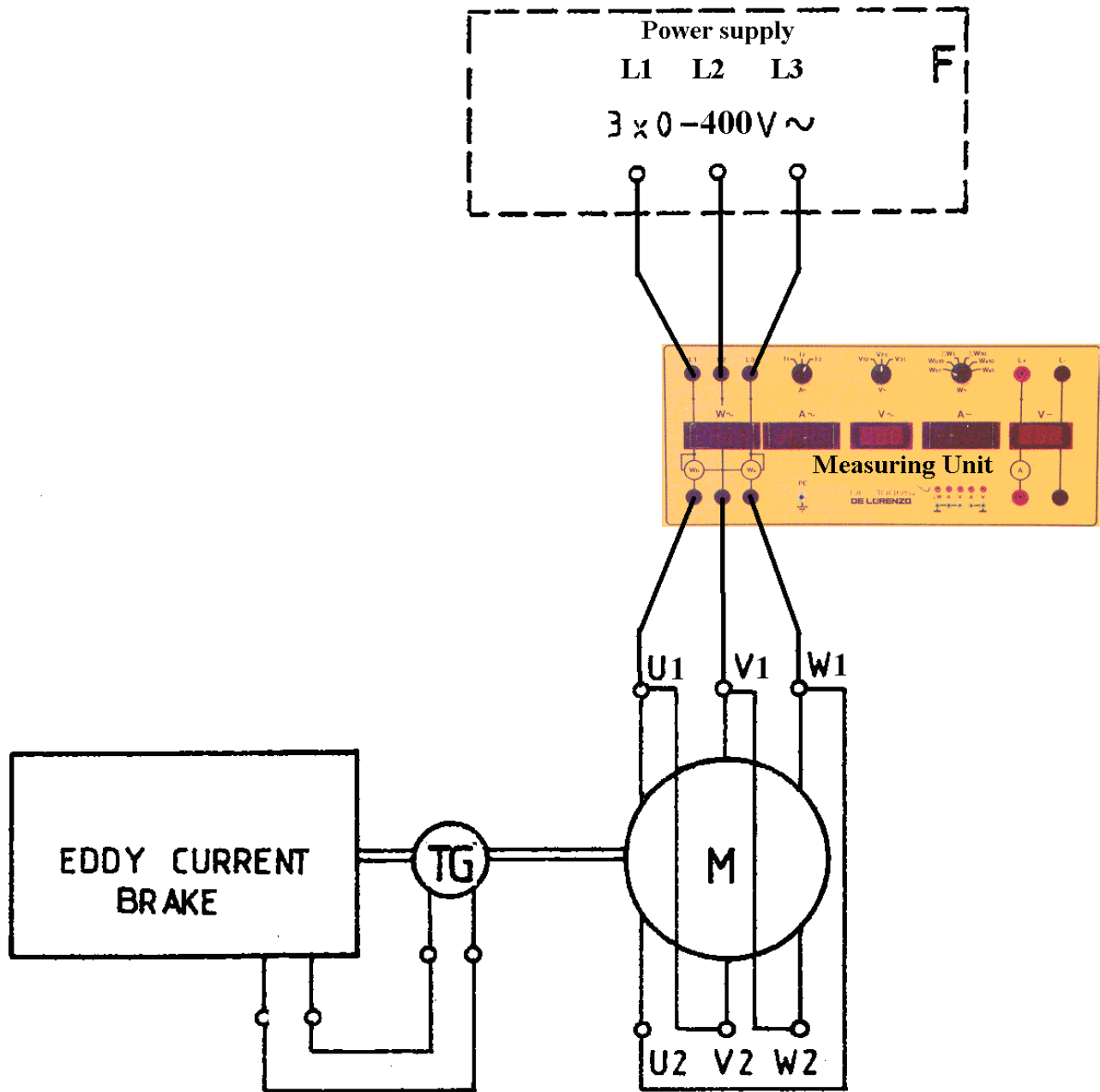| Table (8.3)							
"Δ" Rated current ( )A			CALCULATED VALUES				
I1 (A)	**V(v)**	**Pin(W)**	θ	Z_{LR}	R_2	X_1	X_2
4.8							

$$\cos\theta = \frac{P_{in}}{\sqrt{3}V_T I_{ln}} \ , \quad R_2 = \cos\theta \times Z_{LR} - R_1 \ , \quad X_{LR} = \sin\theta \times Z_{LR}$$

Questions:
1. Draw the equivalent circuit for the induction machine. Label the circuit parameters and the values obtained in the lab.

Diagram figure (8.2)

Experiment (9)
Induction Motor (2)

Objective

To investigate star-delta start and plugging, to measure the efficiency at different loads, and to measure the torque characteristic, T = f (s), i.e. the delivered torque as function of the slip.

Theory

Induction motors have a wide application in industry by virtue of the advantages they have over other types of motors:

A. simplicity in construction
B. reliability in service
C. less cost

The simplified speed-torque equation for the induction motor can be written in the following way:

$$T = \frac{90 \cdot V_p{}^2 \cdot R_r{}'}{\pi \cdot n_0 \cdot \left[\left(R_s + \frac{R_r{}'}{s}\right)^2 + (X_s + X_r{}')^2\right] \cdot s} \qquad \qquad \text{.......(9.1)}$$

Where Vp = stator phase voltage
Rs,Rr' = stator and referred rotor resistances
Xs,Xr' = stator and referred rotor inductances
n_o = synchronous speed of the motor, calculated from the equation :

$$n_0 = \frac{120 \cdot f_1}{P}$$

Where:
f_1 = frequency of the mains supply
P = number of poles
s = slip of the motor, calculated from the equation

$$s = \frac{n_1 - n_2}{n_1}$$

From the practical viewpoint, it is of prime importance to note how variations in the supply voltage will influence the torque characteristics of the induction motor. As can be seen from the equation (8.1), for any given value of slip, the torque developed by the motor, will be proportional to the square of the voltage applied to it. This means that the motor will be sensitive to fluctuations in the supply voltage. The following figure gives a typical induction motor torque- speed characteristic.
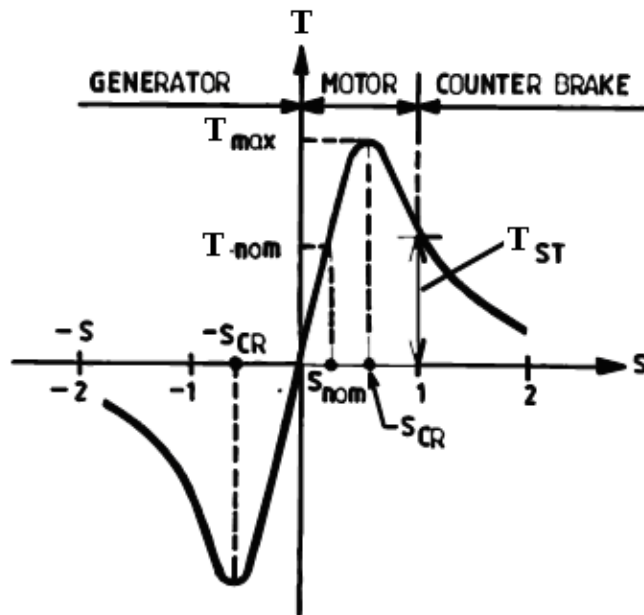
The points of particular interest along this curve are:.
1. $s = 0$, $T = 0$; the point at which the motor runs at synchronous speed.
2. $s = S_{nom}$, $T = T_{nom}$; the nominal point corresponding to rated speed and torque.
3. $s = S_{CR}$, $T = T_{max}$; the point of maximum torque on motor operation.
4. $s = 1.0$, $T = T_{ST}$; the starting torque point.

At slips $s > 1.0$, the motor operates in a counter-current braking condition, while at slips $s < 0$ the motor operates in regenerative braking condition.

By differentiating the torque equation (9.1) and taking $dT/ds = 0$, the so called critical slip S_{CR} at which the torque is a maximum is found to be

$$s_{CR} = \pm \frac{R_2'}{\sqrt{R_s^2 + (X_s + X_2')^2}}$$

It can be seen from an equation that the slip S_{CR} at maximum torque increases directly with rise in rotor resistance R_r. Consequently, each increase in the resistance inserted into the rotor circuit of a slip-ring motor will cause the motor characteristic to shift to a position of greater slip. This (max. torque point) is illustrated by the following family of rheostatic torque characteristics.
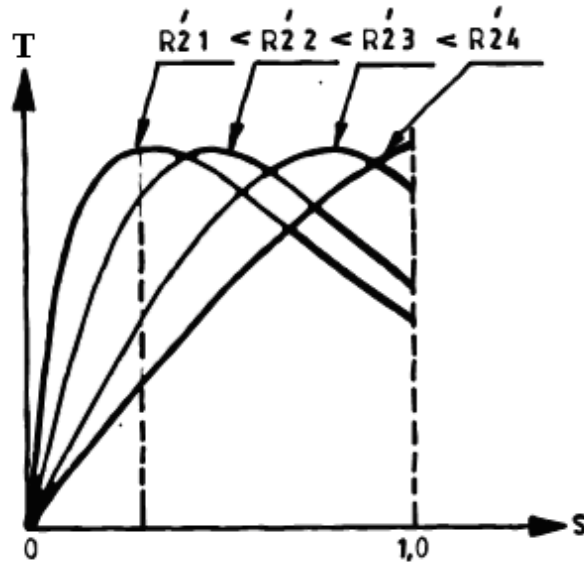
In the laboratory exercise the efficiency η of the motor is the ratio between output power Pout and input power Pin'

$$P_{in} = \sqrt{3}.I_{Ln}.V_{Ln}.cos\theta \qquad \eta = (P_{out}/P_{in}) * 100 \%$$

The output power (Pout) is determined by measuring the speed of the rotor **n**(rpm) and the torque **T**.

$$P_{out} = (2 \pi n / 60) * T$$

The input power is measured with a Measuring unit.

The slip S is calculated from the speed, $\qquad s = \dfrac{n_1 - n_2}{n_1}$

Where n1 = 1500 rpm using an induction motor 4 poles.

When the load on the motor shaft is small, the speed will be close to n1, hence the accuracy in the calculation of the slip is poor. In such case the rotor frequency f_r is found by calculating the number of oscillations during e.g. 30 seconds on the ammeter in the rotor circuit. Hence, slip is equal:

$$s = f_2/f_1, \text{ where } f_1 = 50 \text{ Hz}.$$

Star-delta start is effected by changing over the windings. The start current for star-delta start is reduced.

Plugging is effected by reversing two of the motor terminations, so causing a tendency to rotate in the opposite direction.

Measurement of efficiency characteristic and torque characteristic
Procedure:
1. Connect the eddy current brake and the induction motor in accordance with the circuit diagram figure (9.3). Make sure that the power pack is in the "off" position.
2. Note and record the motor ratings.
3. Eddy current brake set up:
   3.1 Check that the tachogenerator terminals and the strain gauge lead are connected to the specified terminals at the back of the control unit.
   3.2 Set the main switch to the (off) position.
   3.3 Turn on the main switch, the light from the digital display indicates that the eddy current brake is ready for manipulation.
   3.4 Turn the "brake force" knob anti-clockwise to minimum torque position.
   3.5 Read and make a note of the speed value. Set the (torque/power) switch to "torque" position. Turn "zero adjust" knob until a zero reading is shown on the corresponding display.
   Note: At least 5 minutes warming up time needed   before zeroing.
   3.6 Turn the switch to "power" position and check that the display reading is also zero.
   3.7 Turn off the main switch. The eddy current brake is now set and ready for operation.
The supervisor should now check the connections.
4. Connect the induction motor (M) to the eddy current brake and check that the connection is in accordance with the circuit diagram Figure (9.3)
5. keep on all switches (X) and (Z) at zero position.
6. Turn on the variable AC voltage switch (F) and adjust to 220V.Turn the star/delta switch to "**Y**".
7. Turn on the switch (**Z**) to "Forward", whereupon the motor starts. When the speed of the motor has stopped increasing, set the star/delta switch to position "**Δ**".
8. Turn on the eddy current brake and set the load of the motor to minimum by turning the "brake force" knob.
9. Keep the voltage U constant at 220 V during the following measurements.
10. Vary the load with the "brake force" knob in steps of 1 Nm, up to 7 Nm.
11. Record **I1' Pin, T**, **N** and **Pout** at table (9.3).
12. Reduce the load of the motor to minimum. Turn off the AC voltage switch(F).

Table (9.3)

MEASURED VALUES						CALCULATED VALUES		
V (v)	I1 (A)	Pin (w)	T (NM)	N (r.p.m)	Poutput (w)	η (%)	cos θ	S
220V			0					
220V			1					
220V			2					
220V			3					
220V			4					
220V			5					
220V			6					
220V			7					

Starting Current

1. Set the star/delta switch to position "Δ" and the reversing starter switch (**Z**) to position "Forward". Hold on to the rotor so that the motor does not start. Check that the eddy current brake is turn on, at maximum.

2. Record in table(9.4) the rated current to motor at two connections

3. Turn on the AC voltage switch (F) and cautiously increase the voltage so that the stator current increases in steps of 1 A up to rated current. For each step make a note of U and I₁ at table (9.4). Then turn the AC voltage (F) down to zero.

4. Set the star/delta switch to position "**Y**". Repeat measurement 2.

	Table (9.4)							
	"Δ" Rated current ( )A					"Y" Rated current ( )A		
U(V)								
I₁(A)	**1**	**2**	**3**	**4**	**5**	**1**	**2**	**3**

Plugging

1. Set the star/delta switch to (**Y**) and the reversing starter(**Z**) to 0. Switch on the AC voltage(F) and turn it up to 220 V.,

2. Turn the reversing starter (**Z**) to "Forward", whereupon the motor starts. When the motor has reached full speed, turn the star/delta switch to "Δ".

3. Switch(**X**) to star connection(**Y**). Switch (**Z**) to "Reverse" and assess the time that elapses before the motor stops. Turn off the AC voltage (F) and switch off the power pack.

Problems

1. Fill in "Calculated values" columns in the tables.
2. Using the results from table (9.4), draw the graph $I_1 = f$ (V), the starting current as a function of the stator voltage. The V axis must run to 220 V. Extend the curve and read the starting current at rated voltage,
3. Calculate the ratio between starting current for delta and star connection. What is the theoretical value?

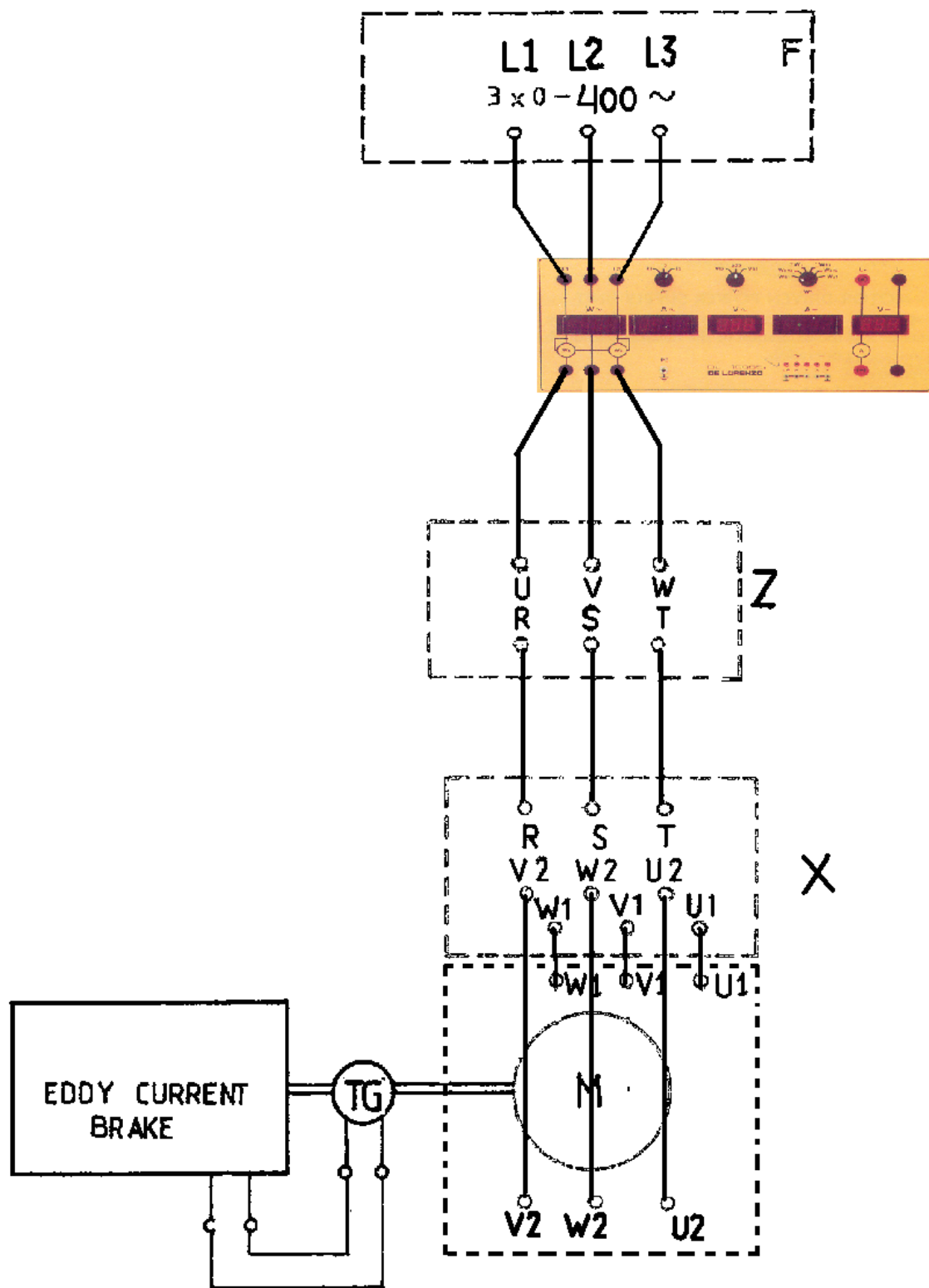$$\beta_{start} = \frac{I_{start}}{I_{Rated}}$$

4. Draw the graphs ($\eta = f(P_{out})$) for measurements at Table (9.3).Draw the graphs $T = f(s)$ for measurements at Table (9.3).

Extrapolate the graphs to $T = 0$. What should be the slip for $T = 0$? Explain the difference

5. Calculate the percentage of no-load currant in relation to the rated current.

$$\beta_o = \frac{I_o}{I_{Rated}}$$

Diagram Figure (9.3)

Experiment (9)
Synchronous Generator

Objectives
To determent the no-load characteristic, the short-circuit characteristic and the load characteristics.

Theory
The synchronous generator or alternator is the most common machine used to convert mechanical power to electricity. The main object of this experiment is to gain experience in operating a synchronous machine as a generator.

The steady-state behavior of the synchronous machine may be explained with varying degrees of accuracy using per-phase equivalent circuit models. The simplest circuit model uses a voltage source E_f, the magnitude of which is proportional to the field current for a constant speed. E_f is in series with the synchronous reactance and the stator resistance.

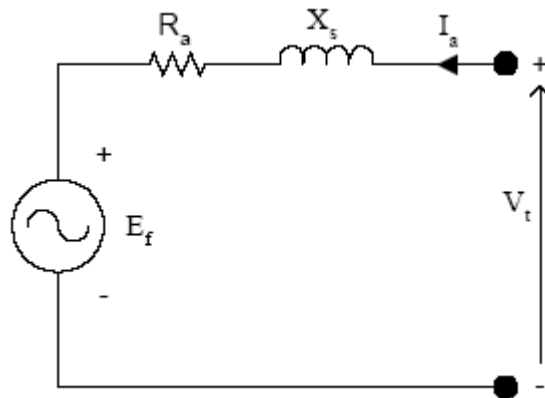$$V_t = E_f + (I_a \times R_a + jI_a \times X_s)$$

Figure 9-1: Equivalent Circuit of a Synchronous Machine

The variables shown in Figure 9-1 are defined as follows:

Ef: internal voltage (Back EMF)
Vt: terminal voltage
R: stator resistance
Xs: synchronous reactance
Ia: armature current

Since Xs >> R, stator resistance is often ignored. Eqn. 3.1 now becomes:

$$V_t = E_f + (jI_a \times X_s)$$
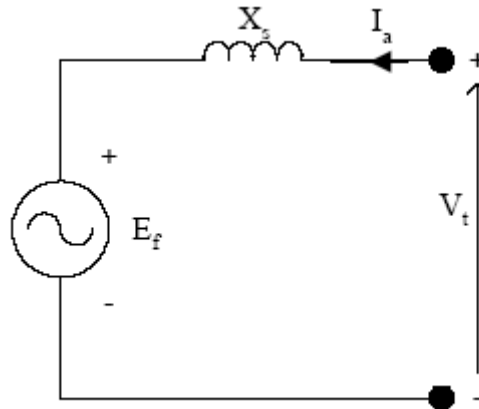
Figure 9.1 now becomes:

Figure 9-2: Equivalent Circuit of a Synchronous Machine (neglecting stator resistance)

For power system analysis this representation is usually sufficiently accurate, but better results and a greater insight into the machine is obtained when Xs is divided into two parts, X and XA. (X: armature leakage reactance X_A: reactance of armature reaction)

Referring back to the equivalent circuit, it can be seen, that in a synchronous machine when Vt lags Ef the machine is generating and when Vt leads Ef the machine is motoring. Putting this in other words, when the machine is generating the rotor magnetic field is pulling around the stator magnetic field. The opposite is true for motoring; the stator magnetic field is pulling around the rotor magnetic field.

Generating

In a synchronous generator, there is a magnetic field produced on the rotor by either an electro-magnet or a permanent magnet. The rotor of the generator is than turned by a prime mover, producing a rotating magnet field within the machine. This rotating magnetic field induces a three-phase set of voltages within the stator windings of the generator. The prime mover can be a combustion engine, wind turbine, moving water (steam) or even a hamster, as long as it can produce the required power.

Typically a synchronous machines rotor is a large electromagnet. The poles of the rotor can be either salient or non-salient. Since the rotor is moving, it is difficult to supply the rotor with the DC current required for generating. Currently, there are two ways to achieve this:
(1) Use slip rings and carbon brushes to supply the DC current from an external source. (2) By mounting the DC power source directly onto the shaft of the synchronous generator.
Method 1 is often used because of a lower initial cost. The down side of this method is that it requires more maintenance because the slip rings and brushes wear down due to friction. Also, when using larger field currents, the voltage drop across the brushes can be a source of significant losses.

Method 2 is used in larger machines. In these machines a small ac generator called a brushless exciter has its armature circuit mounted on the shaft of the rotor, and its field circuit mounted on the stator. The generated AC current is then rectified directly on the rotor using a 3-phase rectifier. For the generator to be completely independent of external power sources, a pilot exciter (a small ac generator that has

permanent magnets mounted on the shaft of the rotor and a three-phase winding on the stator) is used to supply the field circuit with power.

When generating power using a synchronous machine you must be able to keeps the generator rotating at the same speed regardless of the load; otherwise the resulting output frequency would not remain constant.

Procedures:

1. Connect the DC machine as motor and the synchronous machine as generator in accordance with the circuit diagram (9.1)

2. Make a note of the ratings of the synchronous machine shown on the rating plate on the rear of the machine. These ratings must not be exceeded at any time during the laboratory exercises.

3. The supervisor should now check the connections. The switch S must be off.

4. Switch on the torque measuring unit and adjust the potentiometer to obtain max excitation current to the DC machine.

5. Set the variable DC voltage control on the power pack to zero and turn on the variable DC voltage switch. Then slowly turn up the variable DC voltage to 220 V and continuously check the rotor current (Ia) of the DC machine.

6. Adjust the DC machine to bring the speed to exactly 1500 rpm. This speed must be kept constant throughout the exercise.

Measurement of No-Load Characteristic $E = f (I_m)$

The induced no-load voltage as function of the exciting current.

1. Turn on the fixed DC voltage switch. Adjust the shunt rheostat so as to obtain minimum excitation current to the synchronous generator.

2. The switch S must be off. Vary the excitation current I_m in steps of 0.2 A from zero to maximum (see ratings). For every step make a note of I_m and the induced voltage read on the voltmeter U.

No-load characteristic

I_m(A)	E(V)
0	
0.2	
0.4	
0.6	
0.8	
1.0	
1.2	
1.4	

Measurement of Short-Circuit Characteristic I. = f (I$_m$)

The armature current, as function of the excitation current when the stator is short-circuited.

1. Adjust the shunt rheostat R of the synchronous machine to bring the excitation current to zero. Short-circuit all three phases on the switch S on the side to which the load resistor is connected.

2. Turn on switch S. Vary the armature current in steps of 0.5 A from zero to maximum (see ratings) with the shunt rheostat. R$_{my}$ and for each step make a note of I$_a$ and I$_m$.

3. Check the speed!

4. Adjust the shunt rheostat of the synchronous machine to bring the exciting current to zero. Turn off switch S and remove the short-circuit.

Short-Circuit Characteristic

I$_m$(A)	I$_a$(A)
	0
	0.5
	1.0
	1.5
	2.0

Measurement of Load Characteristics U = f (I$_A$)
The generator voltage as a function of the armature current.

1. Adjust the shunt rheostat R$_m$ of the synchronous machine to bring the voltage (U) to 230 V. Make a note of the setting of the generator exciting current I . This value of I , like the speed, must be kept constant throughout the experiment and should therefore be checked from time to time.

2. Turn on the switch S and with the load resistor R$_B$ vary the armature current in steps of 0.5 A up to maximum (see ratings)For each step make a note of the current I$_A$ and voltage U.Check the excitation current and speed !

3. Turn off switch S and replace the load resistor by the delta-connected load inductor.

4. Turn on switch S and with the load inductor vary the armature current in steps up to maximum (see ratings). For each step make a note of the current I$_A$ and voltage U.Check the excitation current and speed !

5. Turn off switch S and replace the load inductor by the star-connected load capacitor.

6. Turn on switch S and with the load capacitor vary the armature current in steps up to maximum (see ratings). For each step make a note of the current I$_A$ and voltage U. Terminate the measurement when the voltage has risen to 300 V. Check the excitation current and speed !

Load Characteristics U = f (I$_A$)

Im constant					
$\theta = 0$ Deg		$\theta = + 90$ Deg		$\theta = - 90$ Deg	
I$_a$(A)	U(V)	I$_a$(A)	U(V)	I$_a$(A)	U(V)
0	380	0	380	0	380
0.5					
1.0					
1.5					
2.0					

Problems

1. Draw graphs of the no-load characteristic and short-circuit characteristic in the same diagram and with common I axis.

2. Draw graphs of the three load characteristics in the same diagram and with common I$_A$ axis.

3. Read on the no-load characteristic the excitation current. I$_m$ corresponding to the rated voltage.

4. Read on the short-circuit, characteristic the short-circuit current I$_{ko}$ obtained at the exciting current Imo .

5. Calculate the synchronous reactance of the generator per phase as $X_s = \dfrac{U_n}{I_{ko}} = \dfrac{130}{I_{ko}} \Omega / phase$

6. Calculate he short-circuit ratio of the generator $k_c = \dfrac{I_{ko}}{I_n}$

7. Draw three vector diagrams to scale with E = 130 V, I$_A$ = 2 A and φ= 0 degrees, +90 degrees and - 90 degrees respectively. The numerical value of X$_s$ will be obtained from exercise .

8. Read U in the vector diagrams and compare with the corresponding values on the load characteristi

Circuit Diagram 9.1

Synchronous Generator