Electric Machines Laboratory 1

Single Phase Transformers

OBJECTIVES

1. To determine the transformer turns ratio.
2. To perform the no-load and short circuit tests.
3. To determine the secondary voltage drop under load operation.
4. To calculate the transformer's equivalent circuit.

INFORMATION

A single-phase transformer will be investigated in this lab. It is a multiple voltage level step-down transformer 230/115/24 V with the rated power of 1000 VA and rated frequency of 50 Hz.

THEORETICAL BACKGOUND

1. Ideal Transformer

An *electric 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 Fig.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.

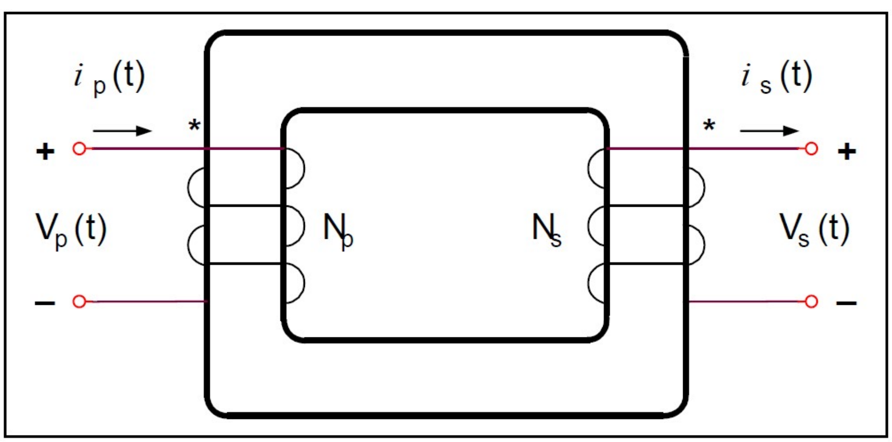

Fig.1: Single phase electric transformer

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

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 Fig.2 fully represents all these effects.

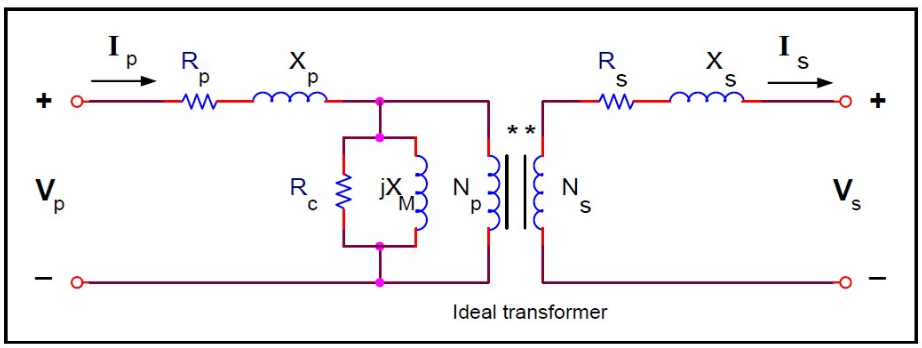

Fig.2: A real transforme model

The resistance R_P represents the ohmic resistance of the primary winding and R_S of the secondary winding. 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 Fig.3.

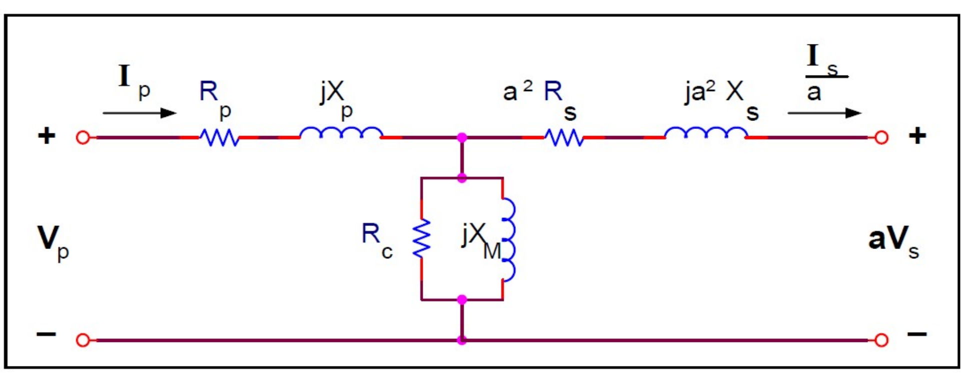

Fig.3: The transformer model referred to the primary voltage level

3. Determining Equivalent Circuit

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

• measurement of the primary resistance

• open-circuit test

• short circuit test

a. Measurement of the Primary Resistance

A DC ohmmeter should be connected across the primary terminals and R_p should be recorded.

b. Open-Circuit Test

The transformer's secondary should be open-circuited and primary winding supplied with a full rated voltage (Fig.4). The input voltage (V_{OC}), primary current (I_{OC}) and power (P_{OC}) are measured.

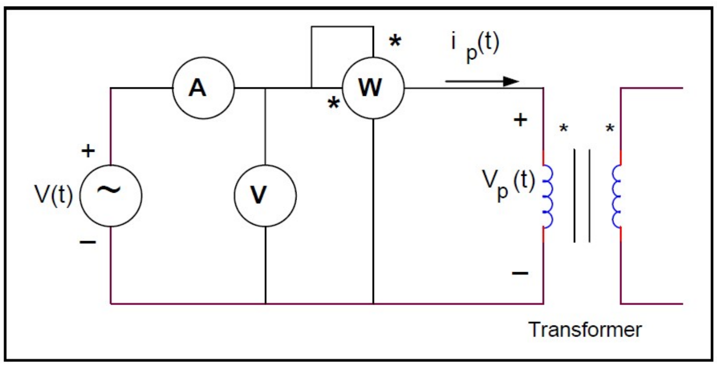

Fig.4: Connection for transformer open–circuit test.

This test is sufficient to calculate the core resistance and magnetizing reactance. The conductance of the core-loss resistor is given by:

$$G_C = \frac{1}{R_C}$$

$$B_M = \frac{1}{X_M}$$

Since these two elements are in parallel, their admittances add and the total excitation admittance is:

$$Y_E = G_C - jB_M = \frac{1}{R_C} - j\frac{1}{X_M}$$

The magnitude of the excitation admittance can be determined by:

$$|Y_E| = \frac{I_{OC}}{V_{OC}}$$

The angle of the admittance can be found from knowledge of a circuit power factor.

The open circuit power factor (PF) is given by:

$$PF = \cos\varphi = \frac{P_{OC}}{V_{OC}I_{OC}}$$

The power factor is always lagging for a real transformer, so the angle of the current always lags the angle of the voltage by φ degrees. Therefore, the admittance Y_E is:

$$Y_E = \frac{1}{R_C} + \frac{1}{jX_M}$$

c. Short-Circuit Test

The transformer's secondary terminals are short-circuited and the primary voltage is supplied with the voltage, much reduced comparing with the rated value (Fig.5). In practical situation, this voltage is adjusted so that the primary current is approximately rated, and the primary voltage (V_{SC}), primary current (I_{SC}) and power (P_{SC}) are measured.

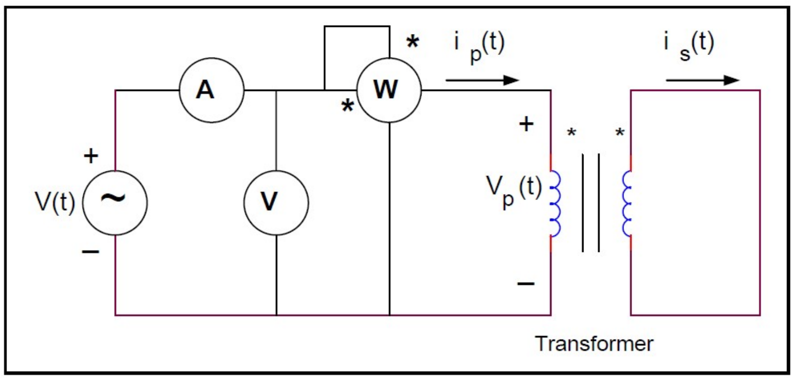

Fig.5: Connection for transformer short–circuit test.

The following equations can be used to calculate elements in the primary and secondary branches.

The magnitude of the series impedances referred to the primary side of the transformer is

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

The short circuit power factor (PF) is given by:

$$PF = \cos\varphi = \frac{P_{SC}}{V_{SC}I_{SC}}$$

The series impedance Z_{SC} is equal to

$$Z_{SC} = R_{eq} + jX_{eq}$$

PROCEDURE

1. Rated Quantities

From the transformer nameplate, note the rated values of S_1, V_1, and V_2. Calculate the rated maximum currents for the ammeters on the primary and secondary sides-do not exceed these values.

2. Resistance Measurements

Measure the resistance of the transformer primary (R_1) and secondary (R_2) windings using an ohmmeter.

3. Turns Ratio

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

$$a = \frac{N_P}{N_S} = \frac{V_{P0}}{V_{S0}}$$

where: V_{P0} – primary voltage

V_{S0} – secondary voltage

In order to determine the turns ratio, connect the circuit as shown in Fig.6. The transformer is supplied with a variable voltage and both primary and secondary voltages are measured and recorded. Do not turn the power on before your circuit has been checked by your supervisor.

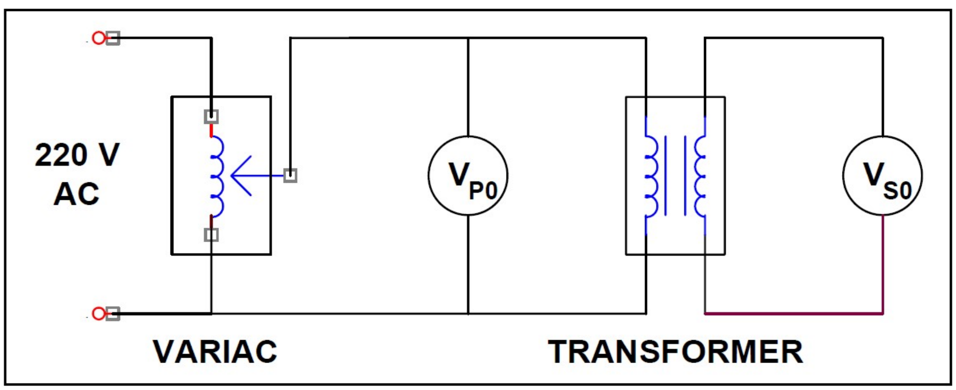

Fig.6: Transformer ratio measurements

Starting from V_{P0} = 55 V turn the variac knob and slowly increase the input voltage.

Measurements and calculations of the turns ratio should be done for V_{P0} = 55, 110, 165 and 220 V. Complete all the data in Table 1.

Table 1

V_{P0} [V]	V_{S0} [V]	Turns Ratio - *a*
55		
110		
165		
220		
Average Turns Ratio		

4. Open Circuit Test

Connect the apparatus as shown in Fig.7. Apply the rated input voltage to the primary winding and measure input voltage, current, power, and output voltage.

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

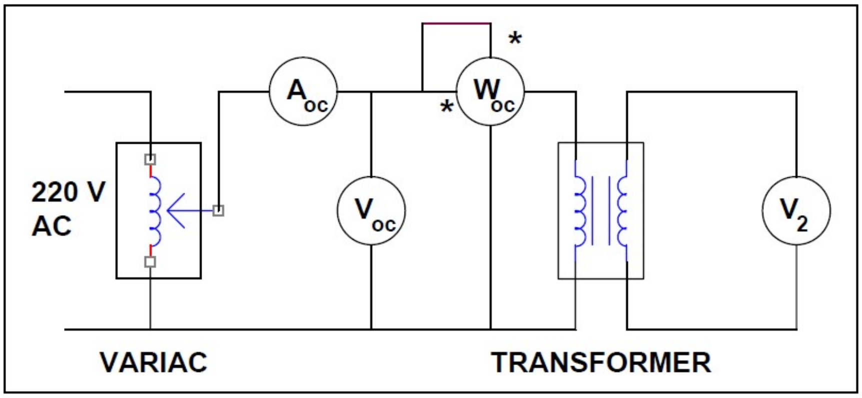

Fig.7: Transformer open circuit test measurements

Starting from V_{OC} =55 V, turn the variac knob and slowly increase the input voltage. Complete all the data in Table 2 and determine the parameters of the magnetizing branch.

Table 2

V_{OC} [V]	I_{OC} [A]	P_{OC} [W]	V_{20} [V]	$\lvert Y_E \rvert$	$\cos \varphi$	R_{eq}	X_{eq}
55							
110							
165							
220							

5. Short-Circuit Test

Short-circuit the secondary winding through an ammeter as shown in Fig.8.

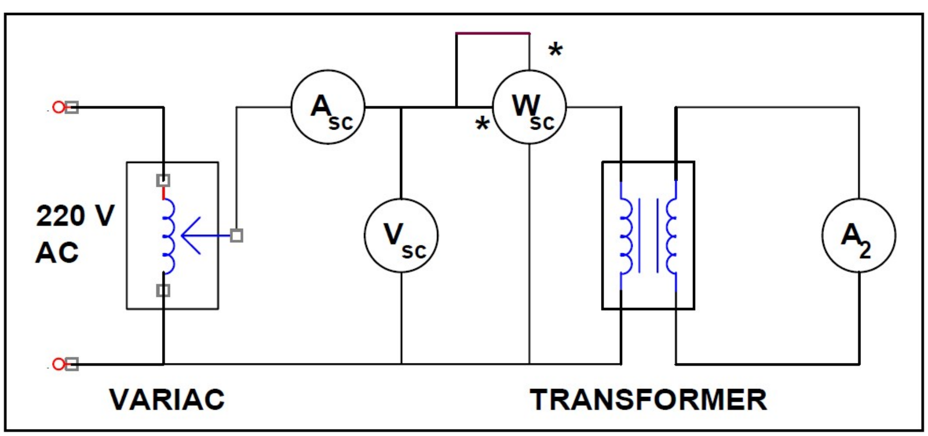

Fig.8: Transformer short-circuit test measurements

Do not turn the power on before your circuit has been checked by your supervisor! Slowly and gradually increase the applied voltage and carefully watch the primary and secondary currents. Measurements and calculations ratio should be done for short circuit current values specified in Table 3. Calculate the short circuit impedance as measured from the primary.

Table 3

I_{SC} [A]	V_{SC} [V]	P_{SC} [W]	I_{20} [A]	$\lvert Z_{SC}\rvert$	$\cos\varphi$	R_C	X_M
1							
2							
3							
4							
5							

6. Secondary voltage drop under load operation

The test setup is shown in Fig.9.

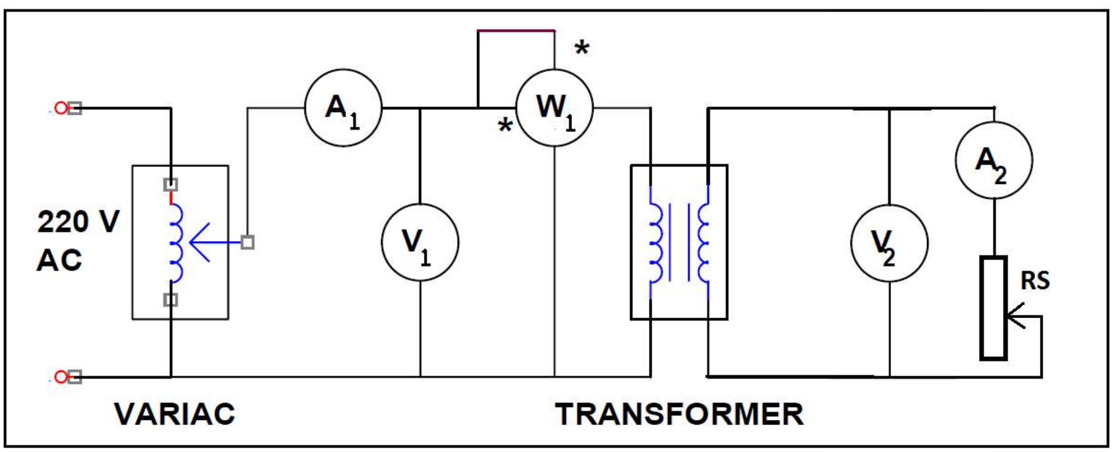

Fig.9: Secondary voltage drop test measurements

For V_1 = 220 V, slowly increase the *RS* value, complete the data for different load currents in Table 4 and determine the efficiency η voltage drop Δu, using the following relations:

$$\eta = \frac{P_2}{P_1}$$

where:

$$P_2 = V_2 I_2$$

$$\Delta u = \frac{V_{20}}{V_2}$$

Next, plot the $V_2=f(I_2)$, $\Delta u=f(I_2)$ and $\eta=f(P_2)$ characteristics.

Table 4

V_1 [V]	I_1 [A]	P_1 [W]	V_2 [V]	I_2 [A]	P_2 [W]	η	Δu
220				1			
220				2			
220				3			
220				4			

Electric Machines Laboratory 2

Transformers in parallel and 3-phase transformers

OBJECTIVES

1. to learn how to connect transformers in parallel;
2. to determine the efficiency of parallel connected transformers;
3. to connect transformers in delta and Y configurations;
4. to study the voltage and current relationships.

INFORMATION

Two parallel connected single-phase transformers will be investigated in this lab, as well as a 3-phase transformer with different connection types.

THEORETICAL BACKGOUND

In an ideal transformer, the power in the secondary windings is exactly equal to the power in the primary windings. This is true for transformers with a coefficient of coupling of 1.0 (complete coupling) and no internal losses. In real transformers, however, losses lead to secondary power being less than the primary power. The degree to which a real transformer approaches the ideal conditions is called the efficiency of the transformer:

$$\eta = \frac{P_{out}}{P_{in}} \cdot 100\ [\%]$$

where: P_{out} and P_{in} are the real output and the input powers. Apparent and reactive powers are not used in efficiency calculations.

Transformers may be connected in parallel to supply currents greater than rated for each transformer. Two requirements must be satisfied:

1) The windings to be connected in parallel must have identical output ratings;

2) The windings to be connected in parallel must have identical polarities.

Severe damage may be made to circuitry if these requirements are not satisfied.

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-d, Y-y, Y-d, and Δ-y connections.

An advantage of Δ-d 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 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 3.

The Y-d connection may be used for stepping down voltages.

The four connection types are shown in Fig.1.

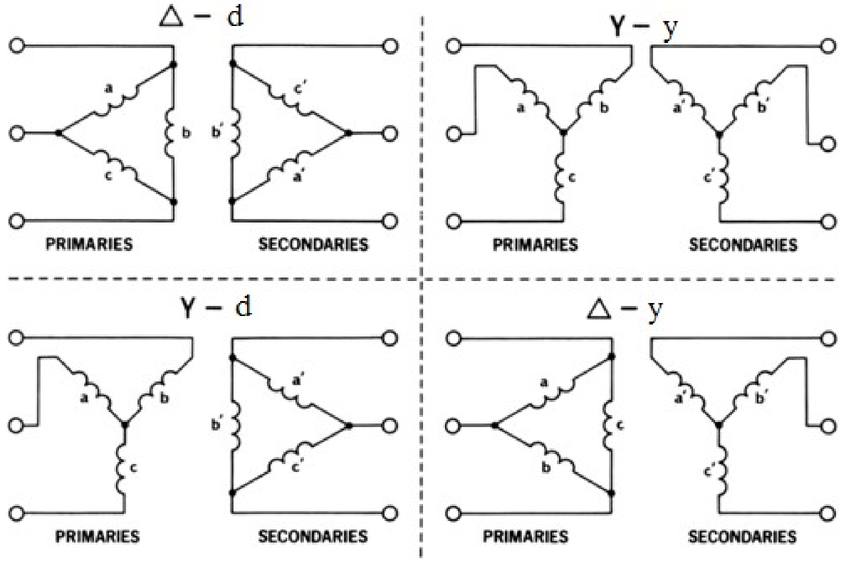

Fig.1: 3-phase transformers connections.

Regardless of the connection method, the windings must be connected in the proper phase relationships. To determine these in a y-connected secondary winding, the voltage is measured across two windings as shown in Fig.2. The voltage A to B should be equal to $\sqrt{3}$ times the voltage across either winding. If the voltage is equal to that across either winding, then one of the windings must be reversed. The third winding *c* is then connected and the voltage C to A or B should also equal $\sqrt{3}$ times the voltage across any one winding. If not, the winding *c* must be reversed.

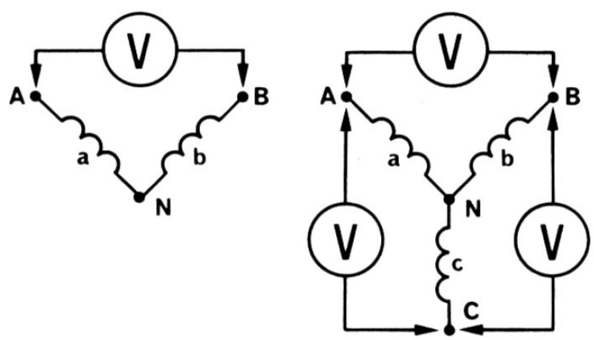

Fig.2: Polarity determination in y-connected secondary winding

To determine the proper phase relationships in a d-connected secondary winding, the voltage is again measured across two windings as shown in Fig3. The voltage A to C should equal the voltage across either winding. If not, one of the windings must be reversed. The winding *c* is then connected as shown, and the voltage C^1 to C should equal zero. If not, winding *c* must be reversed and open ends can be joined after that to form the d-connection.

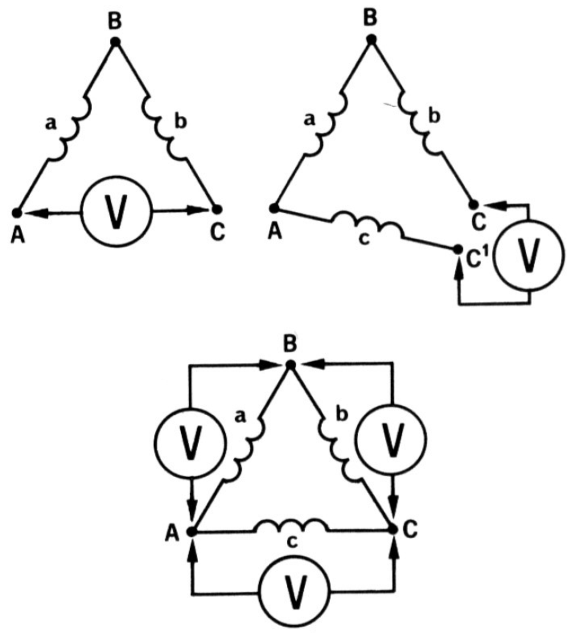

Fig.3: Polarity determination in d-connected secondary winding

Note: the d-connection should never be closed until the test is first made to verify that the voltage within the d is zero. Otherwise, severe damage may be made!

EXPERIMENT

1) Using two identical Transformer modules and a Variable resistance module, construct the circuit shown in Fig.4. All used meters (V_1, I_1, I_2, I_L. E_L) must be in the AC mode. While wiring your transformers, pay specific attention to the polarity of the windings. Place all the resistance switches to their OFF positions first for no-load current. Before turning ON the power, have your instructor to verify the correct wiring.

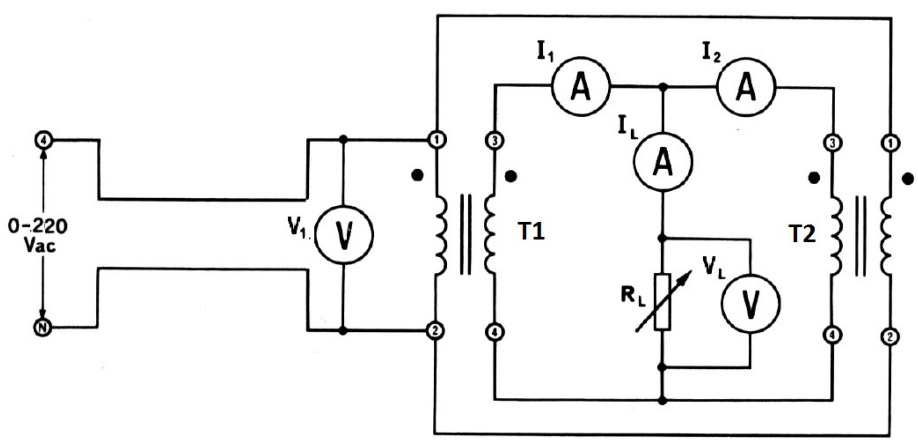

Fig.4: Single-phase transformers parallel connection.

2) Once the correct wiring has been verified, turn ON the PS and slowly adjust the input voltage to approximately 230 V. If the windings are properly wired, load and secondary

currents must be approximately zero. By closing the appropriate switch on the Variable resistance module, decrease the load resistance. Observe that the Ammeters I_1 and I_2 read approximately equal currents. If not, consult with your instructor.

3) Read all data for different load currents and write them down into the Table 1 in order to plot the $I_1=f(I_L)$, $I_2=f(I_L)$, $P_{out1}=f(I_L)$ and $P_{out1}=f(I_L)$ characteristics.

Table 1

V_1 [V]	I_L [A]	V_L [V]	I_1 [A]	I_2 [A]	$P_{out1}[W]$	$P_{out2}[W]$
230	0					
230	2					
230	4					
230	6					
230	8					
230	10					

4) Using three identical single phase transformers suitably connected for use in a three phase system or a single unit three phase transformer, different connection types will be made as shown below:

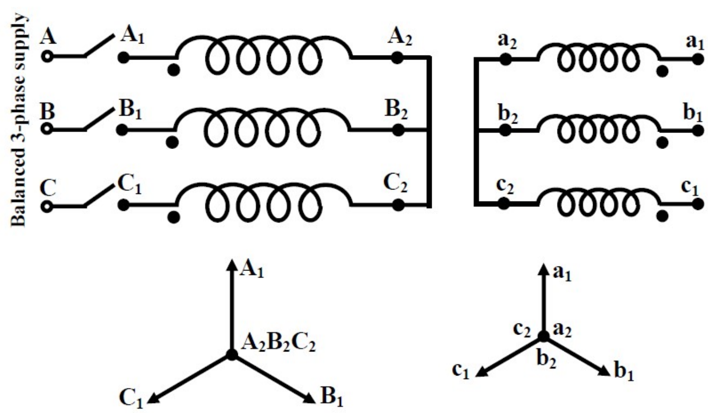

Fig.5: Y-Y connection.

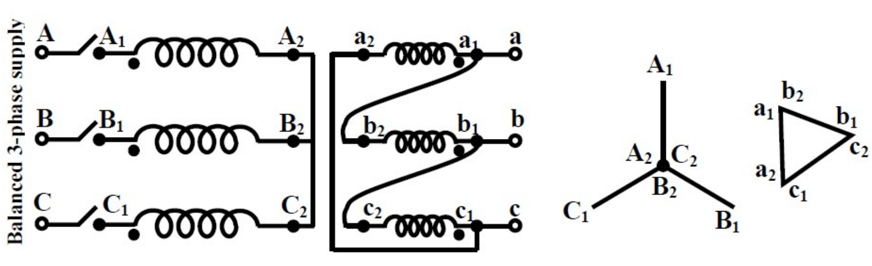

Fig.6: Y- d connection.

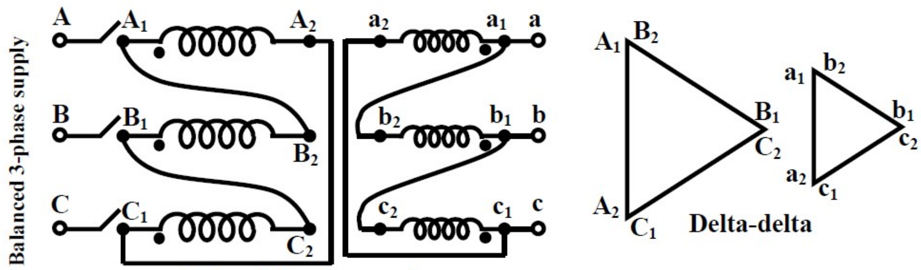

Fig.7: Δ - d connection.

5) Phase and line voltages will be measured and compared for each situation.

6) Turn OFF the PS and disassemble your circuit.

Electric Machines Laboratory 3

Autotransformers and Welding Transformers

OBJECTIVES

5. to learn about autotransformers and welding transformers construction;
6. to determine the working characteristics of autotransformers and welding transformers;
7. to study and analyze the performance characteristics of an autotransformer and a welding transformers

INFORMATION

An autotransformer and a welding transformer will be investigated in this lab for working characteristics determination.

THEORETICAL BACKGOUND

Most transformers use separate windings; one for the source and one for the load, and all energy is transferred by induction from the primary winding to the secondary winding through the magnetic field. When the primary and secondary windings are physically connected, the transformer is called an autotransformer. In an autotransformer on some occasions, it is desirable to change voltage levels by only a small amount. For example, it may be necessary to increase a voltage from 110 to 120 V or from 13.2 to 13 KV. These small rises could be necessary due to voltage drop that occurs in power systems a long way from the generator. In such circumstances, it is wasteful and excessively expensive to wind a transformer with two full windings, each rated at about the same voltages. A special purpose transformer, called an autotransformer, is used instead.

In the autotransformer, part of the energy is transferred by induction and the rest is by conduction. There are three types of autotransformers: step-up, step-down, and variable autotransformers which can be either step-up or step-down. Variable autotransformers are used in the laboratory and industry to provide a wide range of ac voltages from a single source. Fig. 1 shows step-up and step-down autotransformers.

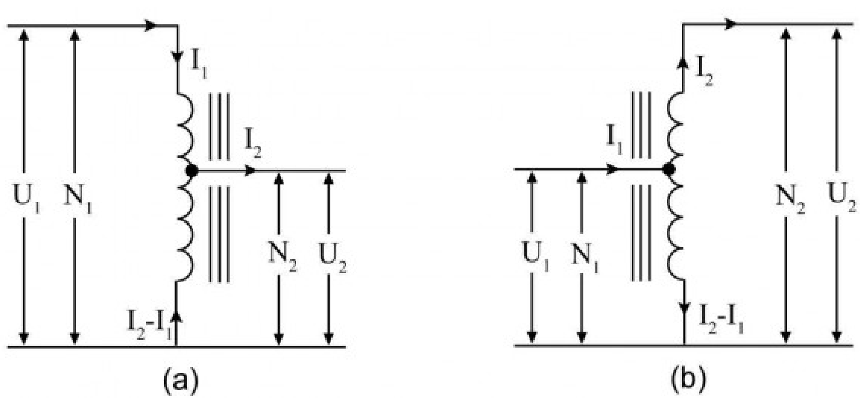

Fig.1: step-up and step-down autotransformers

In Fig.1, the first winding is shown connected in an additive manner to the secondary winding. Now, the relationship between the voltage on the first winding and the voltage on the second winding is given by the turns ratio of the transformer. However, the voltage at the output of the whole transformer is the sum of the voltage on the first winding and the voltage on the second winding. The first winding here is called the common winding, because its voltage appears on both sides of the transformer. The smaller winding is called the series winding, because it is connected in series with the common winding.

It is interesting to note that not all the power traveling from the primary to the secondary in the autotransformer goes through the windings. As a result, if a conventional transformer is reconnected as an autotransformer, it can handle mush more power than it is originally rated for.

Fig.2 shows a schematic diagram of a welding transformer having thin primary windings with a large number of turns. On the other hand, the secondary has more area of cross-section and less number of turns ensuring less voltage and very high current in the secondary. One end of the secondary is connected to the welding electrode, whereas the other end is connected to the pieces to be welded. If any high current flows, heat is produced due to the contact resistance between the electrode and the pieces to be welded. The generated heat melts a tip of the electrode and the gap between the two pieces is filled.

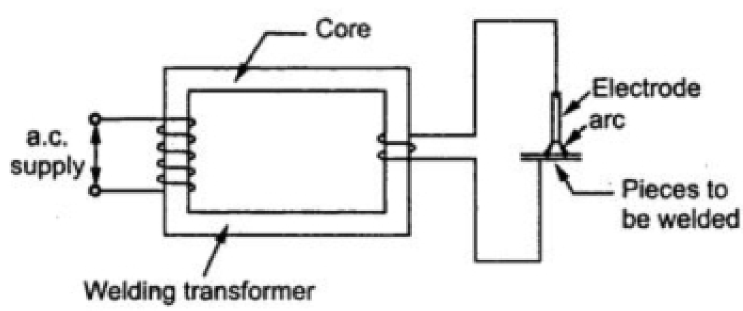

Fig.2 Diagram of a welding transformer

A winding used for the welding transformer is highly reactive or a separate reactor may be added in series with the secondary winding. Volt ampere characteristics for a welding transformer is shown in the Fig. 3.

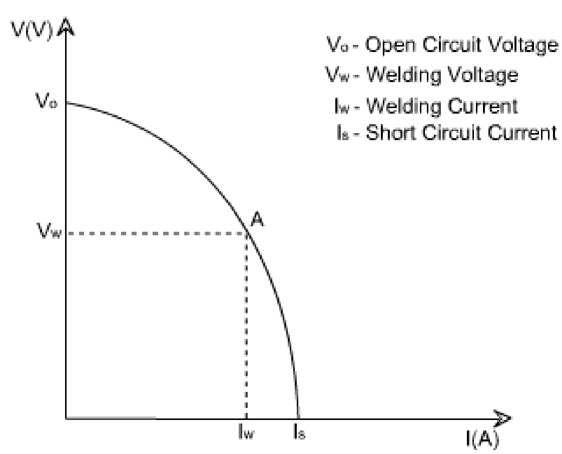

Fig.3: Volt ampere characteristics for a welding transformer

The welding transformer can be used with various reactors for control of arc. The various methods of such control are:

- *Tapped Reactor* (Fig.4): In this, output current is regulated by taps on the reactor. This has limited number of current settings.

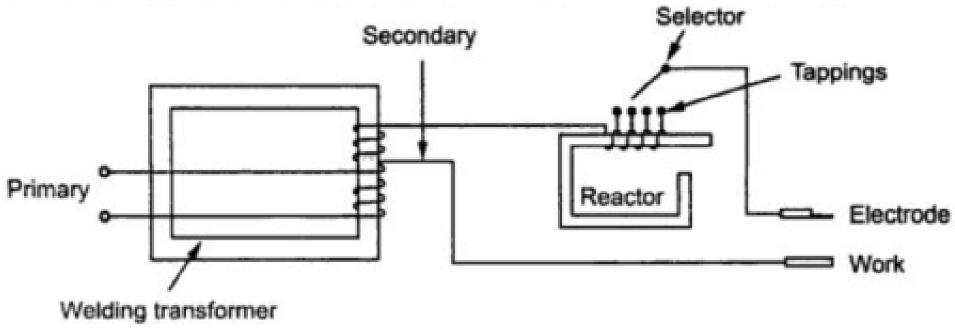

Fig.4: Tapped reactor

- *Moving Coil Reactor* (Fig.5): In this method, the relative distance between primary and the secondary is adjusted. When the distance between the coils is large the current obtained is less.

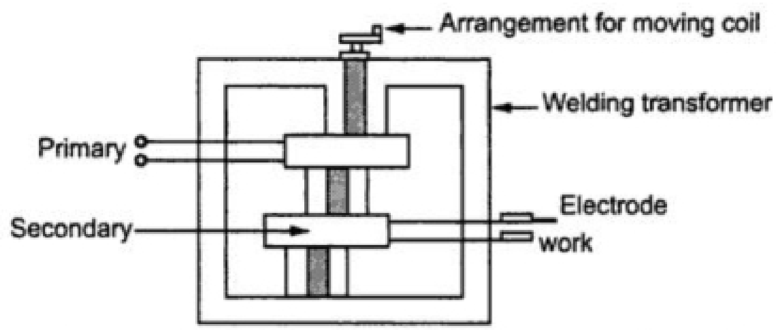

Fig.5: Moving Coil Reactor

- *Magnetic Shunt Reactor* (Fig.6): In this method, position of central magnetic shunt can be adjusted. This adjusts the shunted flux and hence output current gets changed.

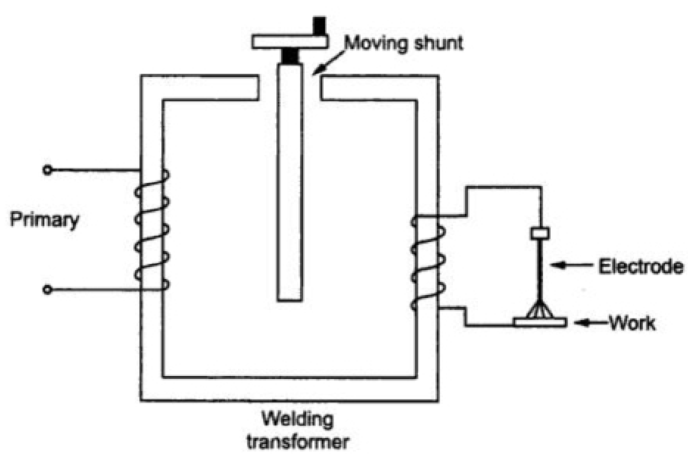

Fig.6: Magnetic Shunt Reactor

- *Continuously Variable Reactor* (Fig.7): The height of the reactor is continuously varied in this method. Greater the core insertion greater is the reactance and less is the output current.

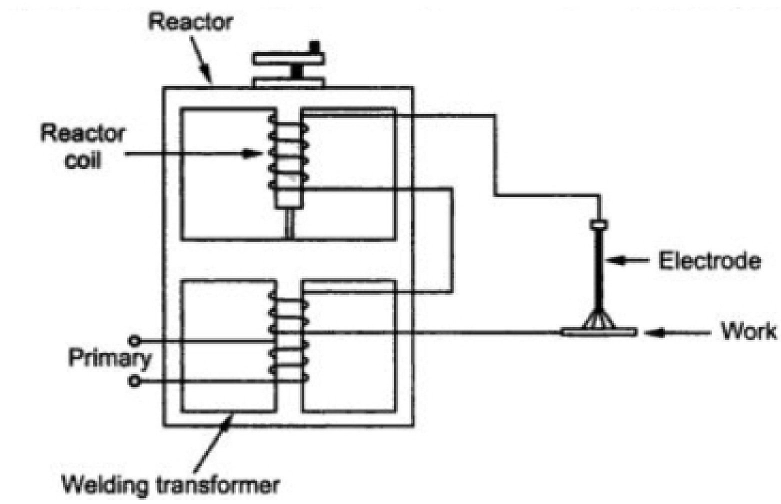

Fig.7: Continuously variable reactor

- *Saturable Reactor* (Fig.8): The reactance of the reactor is adjusted by changing the value of d.c. excitation obtained from d.c. controlled transducer. More the d.c. currents, reactor approaches to saturation. This changes the reactance of reactor and hence changing the current.

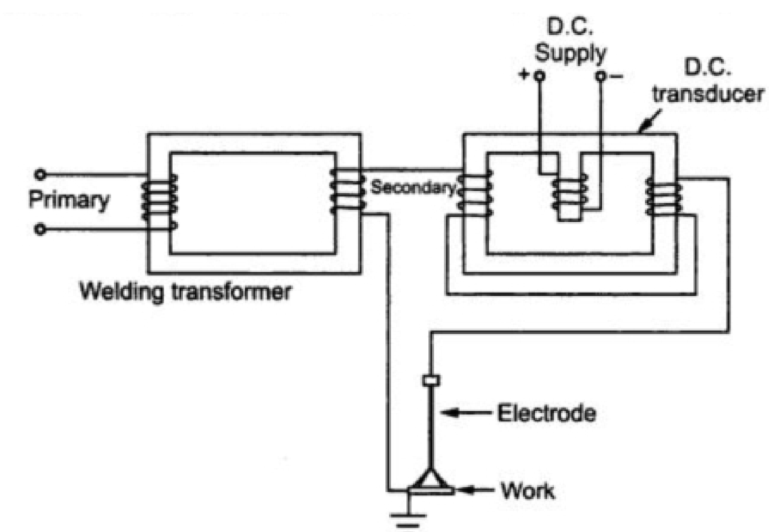

Fig.8: Saturable Reactor

EXPERIMENT

1) Using the same working techniques as in the single phase lab, an autotransformer for three different ratios and a welding transformer with magnetic shunt will be tested.

2) Read all data for different load currents and write them down into the Table 1 and Table 2, in order to plot the $U_L=f(I_L)$, $\eta=f(P_{out})$ characteristics.

Table 1

V_1 [V]	I_1 [A]	$P_{in}[W]$	V_L [V]	I_L [A]	$P_{out}[W]$	η
230			50	0		
				2		
				4		
				6		
				8		
				10		
V_1 [V]	I_1 [A]	$P_{in}[W]$	V_L [V]	I_L [A]	$P_{out}[W]$	η
			100	0		
				2		
				4		
				6		
				8		
				10		
V_1 [V]	I_1 [A]	$P_{in}[W]$	V_L [V]	I_L [A]	$P_{out}[W]$	η
			150	0		
				2		
				4		
				6		
				8		
				10		

Table 2

0% shunt						
V_1 [V]	I_1 [A]	$P_{in}[W]$	V_L [V]	I_L [A]	$P_{out}[W]$	η
230				0		
				10		
				20		
				30		
				40		
				50		
50% shunt						
V_1 [V]	I_1 [A]	$P_{in}[W]$	V_L [V]	I_L [A]	$P_{out}[W]$	η
				0		
				10		
				20		
				30		
				40		
				50		
				60		
100% shunt						
V_1 [V]	I_1 [A]	$P_{in}[W]$	V_L [V]	I_L [A]	$P_{out}[W]$	η
				0		
				10		
				20		
				30		
				40		
				50		
				60		

Electric Machines Laboratory 4

Direct Current Generators

OBJECTIVES

The main purpose of this laboratory session is to observe the saturation curve of dc generators, to observe their characteristics curves (terminal voltage vs. load current) in different types of connection and to learn how to connect the different dc generators configurations.

The specific objectives of this lab session are:

1) To study the properties of the separately excited, the shunt, the series, the differential compound, and additive compound dc generators under no-load and full-load condition.
2) To obtain the saturation curve of the generator.
3) To learn how to connect the different dc generators.
4) To obtain the armature voltage vs. armature current load curve of the dc generators.

THEORETICAL BACKGOUND

DC Separately Excited Generator

A DC machine can run either as a motor or as a generator. A motor converts electrical power into mechanical power while a generator converts mechanical power into electrical power. A generator must, therefore, be mechanically driven in order that it may produce electricity.

Since the field winding is an electromagnet, current must flow through it to produce a magnetic field. This current is called the excitation current, and can be supplied to the field winding in one of two ways; it can come from a separate, external dc source, in which case the generator is called a separately excited generator; or it can come from the generator's own output, in which case the generator is called a self-excited generator.

Assume that the shunt field is excited by a dc current, thereby setting up a magnetic flux in the generator. If the rotor (or more correctly, the armature) is rotated by applying mechanical effort to the shaft, the armature coils will cut the magnetic flux, and a voltage will be induced in them. This voltage is ac and in order to get dc out of the generator, a rectifier must be employed. The commutator and the brushes carry out this role.

The voltage induced in the coils (and, therefore, the dc voltage at the brushes) depends only upon two things-the speed of rotation and the strength of the magnetic field. If the speed is doubled, the voltage doubles. If the field strength is increased by 20%, the voltage also increases by 20%.

Although separate excitation (Fig.1) requires a separate dc power source, it is useful in cases where a generator must respond quickly and precisely to an external control source, or when the output voltage must be varied over a wide range.

With no electrical load connected to the generator, no current flows and only a voltage appear at the output. But if a resistance load is connected across the output, current will flow and the generator will begin to deliver electric power to the load.

The machine that drives the generator must then furnish additional mechanical power to the generator. This is often accompanied by increased noise and vibration of the motor and the generator, together with a drop in speed.

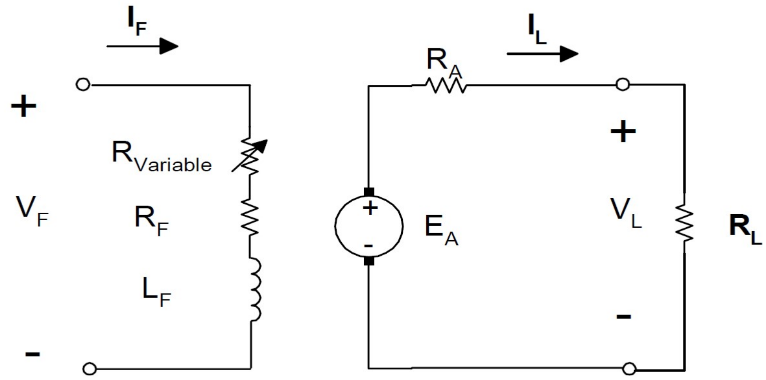

Fig.1: Separately Excited DC Generator

DC Shunt Generator

The separately excited generator has many applications. However, it does have the disadvantage that a separate direct current power source is needed to excite the shunt field. This is costly and sometimes inconvenient; and the self-excited dc generator is often more suitable.

In a self-excited generator, the field winding is connected to the generator output. It may be connected across the output, in series with the output, or a combination of the two. The way in which the field is connected (shunt, series or compound) determines many of the generator's characteristics.

All of the above generators can have identical construction. Self-excitation is possible because of the residual magnetism in the stator pole pieces. As the armature rotates a small voltage is induced across its windings. When the field winding is connected in parallel (shunt) with the armature (Fig.2) a small field current will flow. If this small field current is flowing in the proper direction, the residual magnetism will be reinforced which further increases the armature voltage and thus, a rapid voltage build- up occurs.

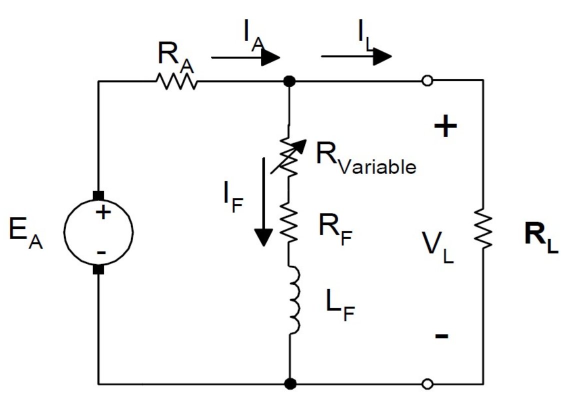

Fig.2: Shunt Generator

If the field current flows in the wrong direction, the residual magnetism will be reduced and voltage build-up cannot occur. In this case, interchanging the shunt field leads will correct the situation. It is the purpose of this Laboratory Experiment to show these major points.

DC Series Generator

When the field winding is connected in series (Fig.3) with the armature winding, the generator is called a series generator. The exciting current through the field winding of a series generator is the same current the generator delivers to the load.

If the load has high resistance only a minimum output voltage can be generated because of the minimum field current. On an open circuit, the generator will only have a minimum output voltage due to its residual magnetism. If the load draws current, the excitation current increases, the magnetic field becomes stronger and the generator delivers an output voltage.

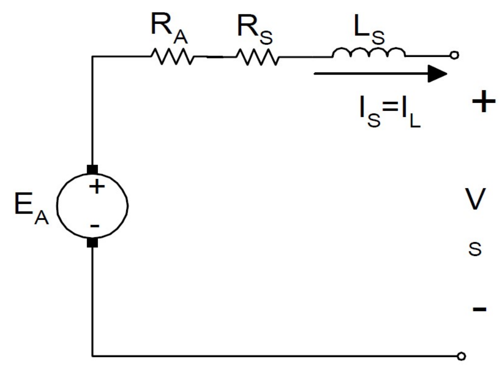

Fig.3: Series Generator

You can see then that in a series generator, changes in load current greatly affect the generator output voltage. A series generator has very poor voltage regulation and is not recommended for use as a power source.

DC Compound Generator

Self-excited shunt generators have the disadvantage in that changes in their load current from no-load to full-load cause their output voltage to change also. Their poor voltage regulation is due to three factors:

a) The magnetic field strength drops as the armature voltage drops, which further reduce the magnetic field strength, which in turn reduces the armature voltage etc.

b) The armature voltage drop from no-load to full-load.

c) The running speed of the driving motor may change with load. (This is particularly true of internal combustion engines and induction motors).

The two field windings (shunt and series) on the compound generator are connected so that their magnetic fields aid each other (Fig.4). Thus, when the load current increases, the current through the shunt field winding decreases, reducing the strength of the magnetic field. But, if the same increase in load current is made to flow through the series field winding, it will increase the strength of the magnetic field. With the proper number of turns in the series winding, the increase in magnetic strength will compensate for the decrease caused by the shunt winding. The combined magnetic field strength remains almost unchanged and little change in output voltage will take place as the load goes from no-load to full-load. If the series field is connected so that the armature current flows in such a direction as to oppose the shunt field, we obtain a differential compound generator. This type of generator has poor regulation, but is useful in applications such as welding and arc lights where maintaining a constant output current is more important than a constant output voltage. It is the purpose of this Laboratory Experiment to show these major points.

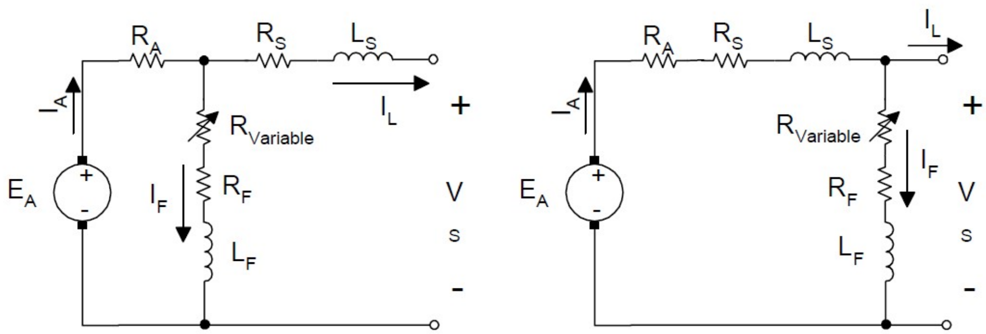

Fig.4: Compound Generator

EXPERIMENT

DC Separately Excited Generator

1. Connect the machine according to the circuit drawn in Fig.5.
2. Set the control unit for:
   - speed: n = 3000 rpm
   - operating mode: n = constant
3. Ranges on the multimeters:
   - Voltage: U_G = 300 V
   - Armature current: I_A = 10 A
   - Exciter current: I_E = 1 A
4. Operate the generator: Using the field regulator, set the excitation current to the values given into Table 1. Apply a load to the drive machine to obtain the speeds given in the table, starting from 2800 rpm. Measure the voltage generated at various exciter currents. Enter the measured values into the table.
5. Explain why the generator produces a voltage when the exciter current is zero.
6. State the variables which influence the magnitude of the generator voltage.

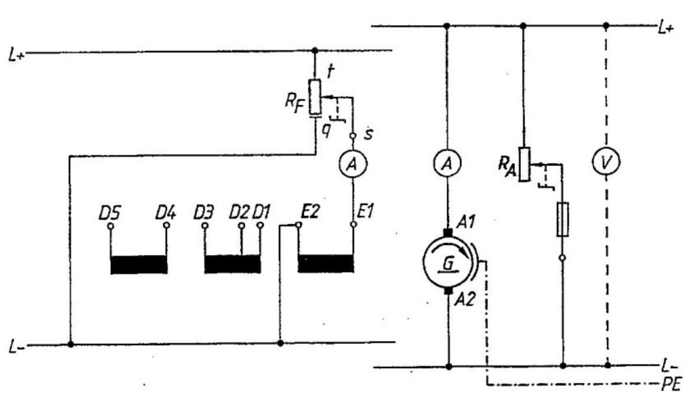

Fig.5: Circuit diagram

Table 1

	U_G [V]		
n[rpm]/I_E[A]	2800	2700	2600
0			
0.1			
0.2			
0.3			
0.4			
0.5			

7. Set the load resistor to 100%.
8. Adjust the torque on the control unit for a speed of 2800 rpm.
9. Using the field regulator, adjust for an exciter current of 0.5 A and keep this value constant.
10. Change the armature current to the values given in Table 2, by adjusting the load resistance. Measure the generator voltage and enter the values into the table.
11. Calculate the delivered electrical power: $P_2 = U_G I_A$. Enter the values into the table.
12. Draw the load characteristics: $U_G = f(I_A)$ and $P_2 = f(I_A)$.

Table 2

I_A[A]	1.0	1.5	2.0	2.5	3	3.5	4.0
U_G[V]							
P_2[W]							

DC Shunt Generator

1. Connect the machine according to the circuit drawn in Fig.6.
2. Set the control unit for:
   - speed: n = 3000 rpm
   - operating mode: n = constant
3. Ranges on the multimeters:
   - Voltage: U_G = 300 V
   - Armature current: I_A = 10 A
   - Exciter current: I_E = 1 A
4. Operate the generator: Apply a load to the drive machine to obtain the speeds as given in Table 3, commencing at 2800 r.p.m. Measure the generated voltage, the exciter current and the armature current. Enter the measured values into the table. The measurements must be completed as quickly as possible.
5. What is the effect of a reduction in speed?
6. What is the purpose of the field regulator?
7. What function has the load resistor?

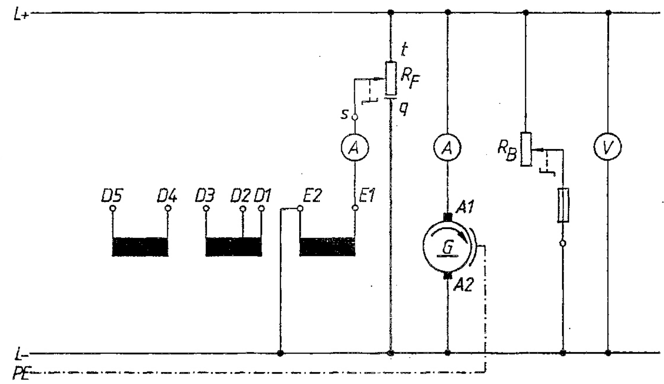

Fig.6: Circuit diagram

Table 3

n[rpm]	U_G[V]	I_E[A]	I_A[A]
2800			
2700			
1600			
2500			

8. Set the load resistor to 100%.
9. Adjust the torque on the control unit for a speed of 2800 rpm.
10. Adjust the load resistor to produce the generator voltage given in Table 4, starting from 275V. Measure the armature current and enter the values into the table ($I_A\uparrow$). Reduce the load to obtain the voltage level as given in the table. Measure the armature current and enter the values into the table ($I_A\downarrow$).
11. Calculate the delivered electrical power: $P_2 = U_G\ I_A\uparrow$. Enter the values into the table.
12. Draw the load characteristics: $U_G = f(I_A\uparrow)$, $U_G = f(I_A\downarrow)$ and $P_2 = f(I_A\uparrow)$.
13. Describe how the delivered power depends on the armature current.
14. Explain the shape of the characteristic.

Table 4

U_G[V]	275	265	250	240	230	130	120	100	80	60	40	20	0
$I_A\uparrow$[A]													
$I_A\downarrow$[A]													
P_2[W]													

DC Series Generator

1. Connect the machine according to the circuit drawn in Fig.7.
2. Set the control unit for:
   - speed: n = 3000 rpm
   - operating mode: n = constant

3. Ranges on the multimeters:
   - Voltage: $U_G = 300$ V
   - Armature current: $I_A = 10$ A
4. Load resistor to 100%
5. Operate the generator: Adjust the load resistor to obtain the armature current values as given into Table 5, starting from 0 A. Measure the generated voltage and enter the measured values into the table.
6. Explain why the generator produces a small voltage when off-load.
7. What is the effect of a large load on the generator?
8. Calculate the delivered electrical power: $P_2 = U_G I_A$. Enter the values into the table.
9. Draw the load characteristics: $U_G = f(I_A)$ and $P_2 = f(I_A)$.
10. Up to what value does the generator voltage increase?
11. Why does the voltage fall when the load is further increased?

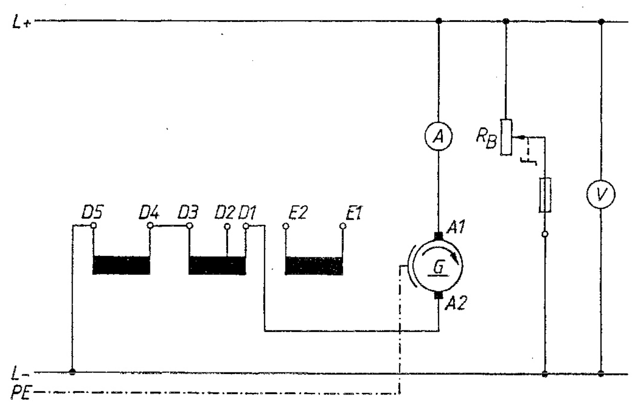

Fig.7: Circuit diagram

Table 5

n[rpm]	I_A[A]	U_G[V]	P_2[W]
2800	0		
	0.5		
	1.0		
	1.5		
	2.0		
	2.5		
	3.0		
	3.5		
	4.0		
	4.5		
	5.0		

DC Compound Generator

1. Connect the machine according to the circuit drawn in Fig. 8.
2. Set the control unit for:
   - speed: n = 3000 rpm
   - operating mode: n = constant
3. Ranges on the multimeters:
   - Voltage: U_G = 300 V
   - Armature current: I_A = 10 A
   - Exciter current: I_E = 1 A
4. Operate the generator: Adjust the torque on the control unit for a speed of 2800 r.p.m. Adjust the field regulator for an exciter current of 0.5 A. This value must be kept constant during the measurements. Adjust the load resistor on the generator, for an armature current of 1.0 A. At this value, measure the generated voltage and enter the value into Table 6.
5. Now, adjust the load resistance for armature currents of 2; 2.5; 3 and 3.5 A, measure the generator voltage in each case and enter the values into the table.
6. Set the field regulator to 100% and the load resistor to 0% loading. Adjust the starter resistor for an armature current of 2 A. This value must be kept constant during the measurements, with the load resistor. Adjust the field regulator for an exciter current of 0.2; 0.4 and 0.6 A. Measure the generator voltage and enter the measured value into Table 7.
7. What is the function of the field regulator?
8. What is the function of the starter resistor?

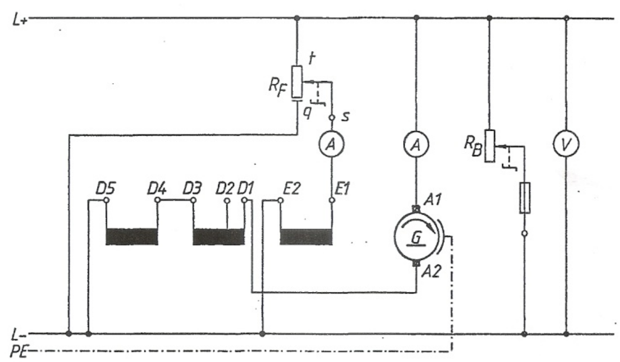

Fig.8: Circuit diagram

Table 6

I_A[A]	1.5	2.0	2.5	3.0	3.5
U_G[V]					

Table 7

I_E[A]	2.0	4.0	6.0
U_G[V]			

9. Set the field regulator to ∞ and the load resistor to 100%
10. Apply a load to drive the machine to obtain a speed of 2700 rpm and keep this speed constant during the measurements.
11. Adjust the field regulator for an exciter current of 0.5 A and keep this value constant.
12. Reduce the load resistance to obtain the values of armature current given into Table 8, starting from 1.5 A. Measure voltage generated at each value of armature current. Enter the value into the table.
13. Plot the load characteristics.

Table 8

I_A[A]	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0
U_G[V]								
P_2[W]								

Electric Machines Laboratory 5

Direct Current Motors

OBJECTIVES

The main purpose of this laboratory session is to observe the variable speed range of the different dc motors and to produce the load-speed characteristic curves of each one. Furthermore, we are interested in calculate the efficiencies of the different dc motors, to connect, operate, and understand the necessity for a direct current motor starter switch, and to observe the circuit changes necessary to reverse a dc motor.

The specific objectives of this lab session are:

1) To study the torque vs. speed characteristics of shunt wound, series, and compound dc motors.
2) To calculate the efficiency of shunt wound, series, and compound dc motors.

THEORETICAL BACKGOUND

Direct current motors are unsurpassed for adjustable-speed applications, and for applications with severe torque requirements. Uncounted millions of fractional horsepower DC motors are used by the transportation industries in automobiles, trains and aircraft where they drive fans and blowers for air conditioners, heaters and defrosters; they operate windshield wipers and raise and lower seats and windows. One of their most useful functions is starting of gasoline and diesel and boats.

The DC motor contains a stator and a rotor, the latter being more commonly called an armature. The stator contains one or more windings per pole, all of which are designed to carry direct current, thereby setting up a magnetic field.

The armature and its winding are located in the path of this magnetic field, and when the winding also carries a current, a torque is developed, causing the motor to turn.

A commutator associated with the armature winding is actually a mechanical device, to assure that the armature current under any given stator pole will always circulate in the same direction irrespective of position. If a commutator were not used, the motor could not make more than a fraction of turn, before coming to halt.

In order for a DC motor to run, current must flow in the armature winding. The stator must develop a magnetic field (flux), either by means of a shunt winding or a series winding (or both).

The torque developed by a DC motor is directly proportional to the armature current and the stator flux. On the other hand, the armature voltage and the stator flux mainly determine motor speed. Motor speed increases when the voltage applied to the armature increases. Motor speed will also increase when the stator flux is reduced. As a matter of fact, the speed can attain dangerous proportions if, accidentally, there is a complete loss of the stator field. However, your DC motor has been carefully designed to withstand possible over speed conditions.

Dc Shunt Motor

The speed of any dc motor depends mainly upon its armature voltage and the strength of the magnetic field. In a shunt motor, the field winding, as well as the armature winding, is connected in parallel (shunt) directly to the dc supply lines. If the dc line voltage is constant, then the armature voltage and the field will be constant. It is, therefore, apparent that the shunt motor should run at a reasonably constant speed.

The speed does tend to drop with an increasing load on the motor. This drop in speed is mainly due to the resistance of the armature winding. Shunt motors with low armature windings resistance run at nearly constant speeds.

Just like most energy conversion devices, the dc shunt motor is not 100% efficient. In order words, all of the electric power, which is supplied to the motor, is not converted into mechanical power. The power difference between the input and output is dissipated in the form of heat, and constitutes what are known as the "losses" of the machine.

These losses increase with load; with the result that the motor gets hot as it delivers mechanical power.

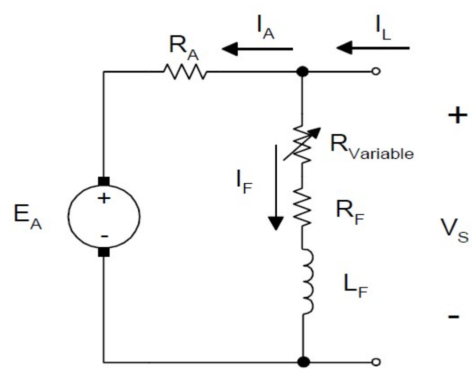

Fig.1: DC shunt motor

DC Series Motor

The shunt wound dc motor was seen to have almost constant speed because its armature voltage and magnetic field remained substantially unchanged from no-load to full-load. The series motor behaves quite differently.

In the series dc motor, the magnetic field is produced by the current, which flows through the armature winding; with the result that the magnetic field is weak when the motor load is light (the armature winding draws minimum current). The magnetic field is strong when the load is heavy (the armature winding draws maximum current). The armature voltage is nearly equal to the supply line voltage (just as in the shunt wound motor if we neglect the small drop in the series field). Consequently, the speed of the series wound motor is entirely determined by the load current. The speed is low at heavy loads, and very high at no load. In fact, many series motors will, if operated at no load, run so fast that they destroy themselves. The high forces, associated with high speeds, cause the rotor to fly apart, often with disastrous results to people and property nearby.

The torque of any dc motor depends upon the product of the armature current and the magnetic field. For the series wound motor this relationship implies that the torque will be very large for high armature currents, such as occur during start-up. The series wound motor is, therefore, well adapted to start large heavy-inertia loads, and is particularly useful as a drive motor in electric buses, trains and heavy-duty traction applications.

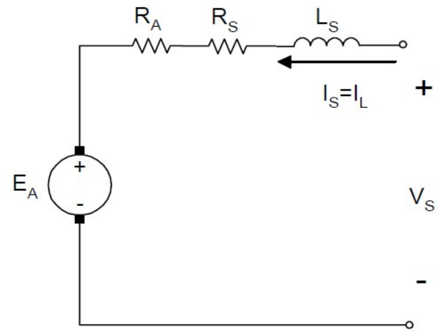

Fig.2: DC series motor

The DC Compound Motor

The high torque capability of the series wound dc motor is somewhat compromised by its tendency to over speed at light loads. This disadvantage can be overcome by adding a shunt field; the motor then becomes a cumulative compound machine. Again, in special applications where dc motors are used in conjunction with flywheels, the constant speed characteristic of the shunt wound motor is not entirely satisfactory, because it does not permit the flywheel to give up its kinetic energy by an appropriate drop in motor speed. This kind of application (which is found in punch-press work), requires a motor with a “drooping” speed characteristic, that is, the motor speed should drop significantly with an increase in load. The cumulative compound wound dc motor is well adapted for this type of work.

The series field can also be connected so that it produces a magnetic field opposing that of the shunt field. This produces a differential compound motor, which has very limited application, principally because it tends to be unstable.

Thus, as the load increases, the armature current increases, which increases the strength of the series field. Since it acts in opposition to the shunt winding, the total flux is reduced, with the result that the speed increases. An increase in speed will generally further increase the load which raises the speed still more and could cause the motor to run away.

Differential compound motors are sometimes made with weak series fields that compensate somewhat for the normal slowing of a shunt motor under load and, hence, have more constant speed. Differential compound motors are not used very often.

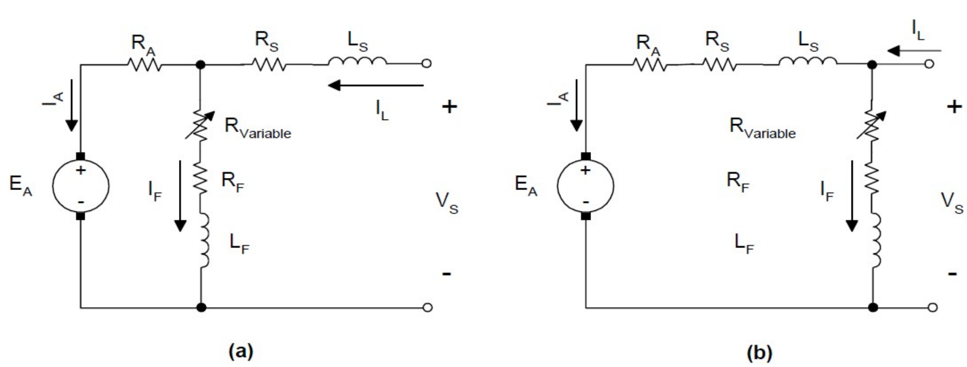

Fig.3: DC compound motor

EXPERIMENT

DC Shunt Motor

15. Connect the machine according to the circuit drawn in Fig.4.
16. Set the control unit for:
    - speed: n = 3000 rpm
    - operating mode: M = constant
17. Ranges on the multimeters:
    - Voltage: U_A = 300 V
    - Armature current: I_A = 10 A
18. Operate the motor: Set the d.c. power supply to 220V. Apply a load to the drive machine according to the values in table 1. Measure the speed, armature voltage and exciter current. Enter the measured values into the table.
19. Calculate the consumed electric power:

$$P_1 = U_A(I_A + I_E)$$

20. Calculate the delivered mechanical power:

$$P_2 = \frac{2\pi n}{60} M$$

21. Calculate the efficiency of the motor:

$$\eta = \frac{P_2}{P_1}$$

22. From the results, measured and calculated, plot the load characteristics: n=f(M), η=f(P_2).
23. Describe the response of the speed of the motor under load conditions.

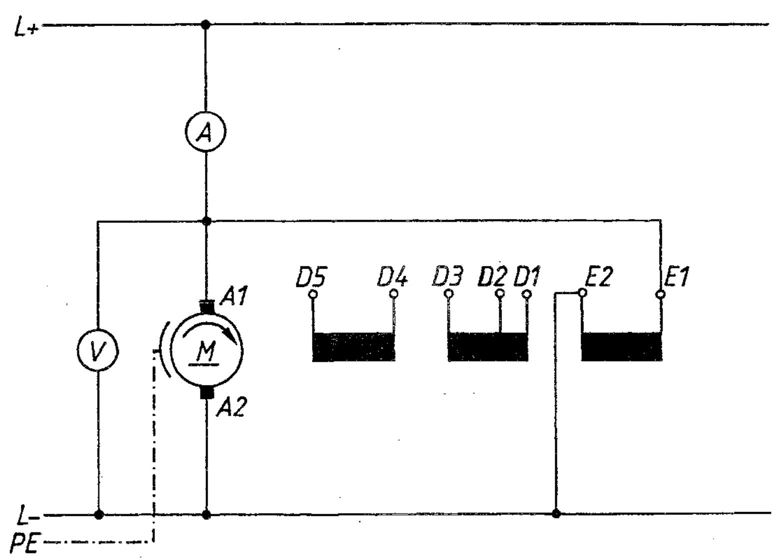

Fig.4: Circuit diagram

Table 1

U_A[V]	220	220	220	220	220	220	220	220	220	220
M[Nm]	0	0.5	1	1.5	2	2.5	3	3.5	4	4.5
n[rpm]										
I_{tot}[A]										
P_1										
P_2										
η										

DC Series Motor

12. Connect the machine according to the circuit drawn in Fig.5.
13. Set the control unit for:
    - speed: n = 3000 rpm
    - operating mode: M = constant
14. Ranges on the multimeters:
    - Voltage: U_A = 300 V
    - Armature current: I_A = 10 A
15. Operate the motor: Set the d.c. power supply to 220V. Apply a load to the drive machine according to the values in table 2. Measure the speed, armature voltage and current. Enter the measured values into the table.
16. Calculate the consumed electric power:
$$P_1 = U_A I_A$$
17. Calculate the delivered mechanical power:
$$P_2 = \frac{2\pi n}{60} M$$
18. Calculate the efficiency of the motor:
$$\eta = \frac{P_2}{P_1}$$
19. From the results, measured and calculated, plot the load characteristics: n=f(M), η=f(P2).
20. Describe the response of the speed of the motor under load conditions.

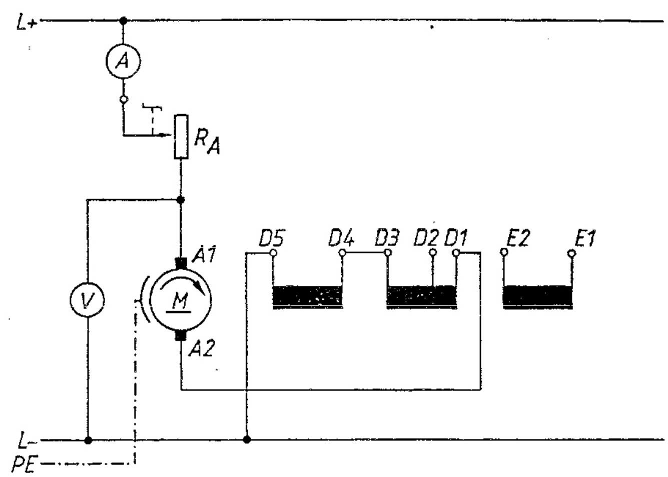

Fig.5: Circuit diagram

Table 2

U_A[V]	220	220	220	220	220	220	220	220
M[Nm]	1	1.5	2	2.5	3	3.5	4	4.5
n[rpm]								
I_{tot}[A]								
P_1								
P_2								
η								

DC Compound Motor

1. Connect the machine according to the circuit drawn in Fig.6.
2. Set the control unit for:
   - speed: n = 3000 rpm
   - operating mode: M = constant
3. Ranges on the multimeters:
   - Voltage: UA = 300 V
   - Armature current: IA = 10 A
4. Operate the motor: Set the d.c. power supply to 220V. Apply a load to the drive machine according to the values in table 3. Measure the speed, armature voltage and exciter current. Enter the measured values into the table.
5. Calculate the consumed electric power:

$$P_1 = U_A(I_A + I_E)$$

6. Calculate the delivered mechanical power:

$$P_2 = \frac{2\pi n}{60} M$$

7. Calculate the efficiency of the motor:

$$\eta = \frac{P_2}{P_1}$$

8. From the results, measured and calculated, plot the load characteristics: n=f(M), η=f(P2).
9. Change the shunt exciter field direction and repeat the previously presented steps.
10. Describe the response of the speed of the motor under load conditions.

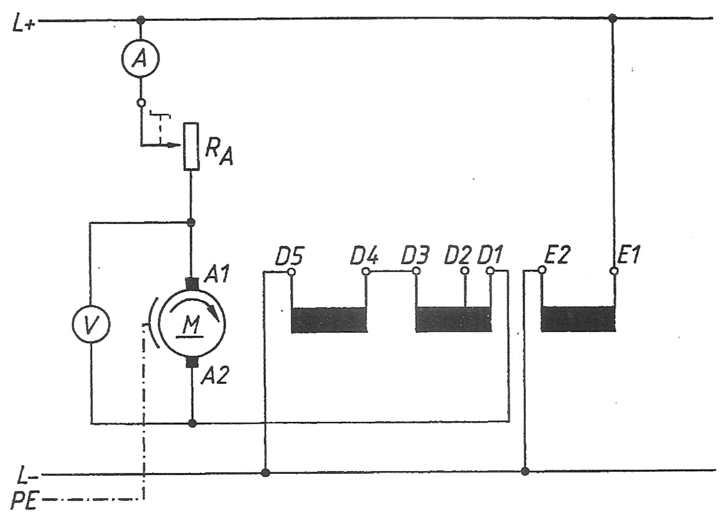

Fig.6: Circuit diagram

Table 3

U_A[V]	220	220	220	220	220	220	220	220	220	220
M[Nm]	0	0.5	1	1.5	2	2.5	3	3.5	4	4.5
n[rpm]										
I_{tot}[A]										
P_1										
P_2										
η										

Table 4

U_A[V]	220	220	220	220	220	220	220	220	220	220
M[Nm]	0	0.5	1	1.5	2	2.5	3	3.5	4	4.5
n[rpm]										
I_{tot}[A]										
P_1										
P_2										
η										

Electric Machines Laboratory 6

Three-Phase Induction Motor

OBJECTIVES

The main purpose of this laboratory session is to comprehend the working principle of the three-phase induction motor, to observe the constructive elements of the two induction motor types: squirrel-cage and wound rotor induction machine, and to demonstrates the performance of induction motors and the method for starting and speed adjustment.

The specific objectives refer to:

- to fully characterize a small industrial Induction Motor;
- to observe the start up transient when the motor is directly connected to the source and started from stall;
- to observe the load characteristics when the motor is supplied from a fixed frequency AC source;
- attempt to control the motor speed by adjusting the source voltage;
- demonstrate the motor control using Variable Frequency Drive (VFD).

THEORETICAL BACKGOUND

The AC induction motor is well suited to applications requiring constant speed operation. In general, the induction motor is cheaper and easier to maintain compared to other alternatives.

The induction motor is made up of the stator, or stationary windings, and the rotor. The stator consists of a series of wire windings of very low resistance permanently attached to the motor frame. As a voltage and a current is applied to the stator winding terminals, a magnetic field is developed in the windings. By the way the stator windings are arranged, the magnetic field appears to synchronously rotate electrically around the inside of the motor housing.

The rotor is comprised of a number of thin bars, usually aluminum, mounted in a laminated cylinder or has a similar construction with the stator. The bars or windings are arranged horizontally and almost parallel to the rotor shaft. At the ends of the rotor, the bars are connected together with a “shorting ring.”

The rotor and stator are separated by an air gap which allows free rotation of the rotor.

The magnetic field generated in the stator induces an EMF in the rotor bars. In turn, a current is produced in the rotor bars and shorting ring and another magnetic field is induced in the rotor with an opposite polarity of that in the stator. The magnetic field, revolving in the stator, will then produce the torque which will “pull” on the field in the rotor and establish rotor rotation.

In the design of the induction motor, operational characteristics can be determined through a series of calculations. Performing these calculations can help the engineer provide a motor that is best suited to a particular application. This paper will demonstrate their application.

Synchronous speed

The speed with which the stator magnetic field rotates, which will determine the speed of the rotor, is called the Synchronous Speed (SS). The SS is a function of the frequency of the power source and the number of poles (pole pairs) in the motor. The relationship to calculate the SS of an induction motor is:

$$SS = \frac{60f}{p}$$

where:

f – frequency

p – pole pairs

Motor slip

The rotor in an induction motor cannot turn at the synchronous speed. In order to induce an EMF in the rotor, the rotor must move slower than the SS. If the rotor were to somehow turn at SS, the EMF could not be induced in the rotor and therefore the rotor would stop. However, if the rotor stopped or even if it slowed significantly, an EMF would once again be induced in the rotor bars and it would begin rotating at a speed less than the SS.

The relationship between the rotor speed and the SS is called the Slip. Typically, the Slip is expressed as a percentage of the SS. The equation for the motor Slip is:

$$s = \frac{SS - RS}{SS}$$

where: RS – rotor speed

EXPERIMENT

24. Connect the machine according to the circuit drawn in Fig.1.
25. Set the control unit for:
    - speed: n = 3000 rpm
    - operating mode: M = constant
26. Ranges on the multimeters:
    - Voltage: U_A = 600 V
    - Armature current: I_A = 10 A
27. Operate the motor: Connect the motor stator terminals in wey or delta connection according to the voltage level of the power supply unit of 400V. Apply a load to the drive machine according to the values in table 1. Measure the speed and torque, and the input voltage, current and power. Enter the measured values into the table.
28. Calculate the delivered mechanical power:

$$P_2 = \frac{2\pi n}{60} M$$

29. Calculate the efficiency of the motor:

$$\eta = \frac{P_2}{P_1}$$

30. From the results, measured and calculated, plot the load characteristics: n=f(M), $\eta=f(P_2)$.
31. Describe the response of the speed of the motor under load conditions.

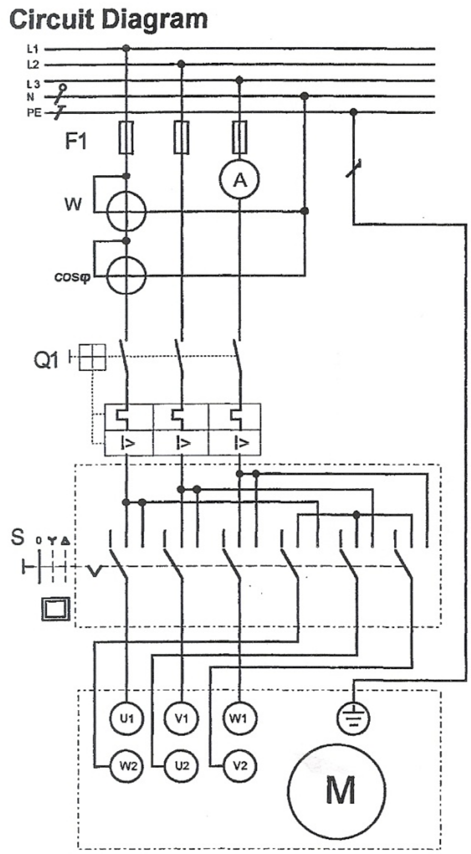

Fig.1: Circuit diagram

Table 1

M_2[Nm]	0	1	2	3	4	5	6
P_2[W]							
n[rpm]							
U_1[V]							
I_1[A]							
P_1							
η							

Electric Machines Laboratory 6

Single-Phase Induction Motors

OBJECTIVES

When you have completed this exercise, you will be able to demonstrate the main operating characteristics of single-phase induction motors. You will start by studying what happens when a three-phase squirrel-cage induction motor is powered by the three phases, two phases, and one phase of the three-phase ac power source. You will know how to connect a capacitor and an auxiliary winding to a single-phase induction motor to allow this motor to start and rotate normally. Finally, you will know how to use a centrifugal switch to disconnect the auxiliary winding and capacitor of a single-phase induction motor once the motor starts rotating.

THEORETICAL BACKGOUND

Simple single-phase squirrel-cage induction motor

It is possible to obtain a single-phase squirrel-cage induction motor, using a simple electromagnet connected to a single-phase ac power source as shown in Fig.1.

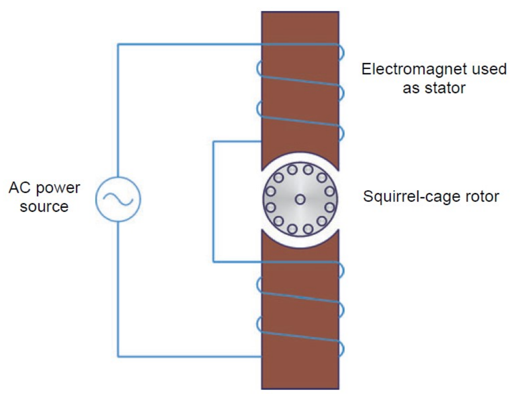

Fig.1: Simple single-phase squirrel-cage induction motor.

The operating principle of the single-phase induction motor is more complex than that of the three-phase squirrel-cage induction motor. The simple single-phase induction motor of Fig.1 can even be considered as an eddy-current brake that brakes in an intermittent manner since the sinusoidal current in the stator electromagnet continually passes from peaks to zeros. One could even wonder how this motor can turn since it seems to operate in a way similar to the eddy-current brake.

However, when the rotor of the simple single-phase induction motor of Fig.1 is turned manually, a torque which acts in the direction of rotation is produced, and the motor continues to turn as long as ac power is supplied to the stator electromagnet. This torque is due to a rotating magnetic field that results from the interaction of the magnetic field produced by the stator electromagnet and the magnetic field produced by the currents induced in the rotor.

Fig.2 shows a graph of the torque versus rotation speed for this type of motor. The curve shows that the torque is very small at low speeds. It increases to a maximum value as the speed increases, and finally decreases toward zero again when the speed approaches the synchronous speed n_s.

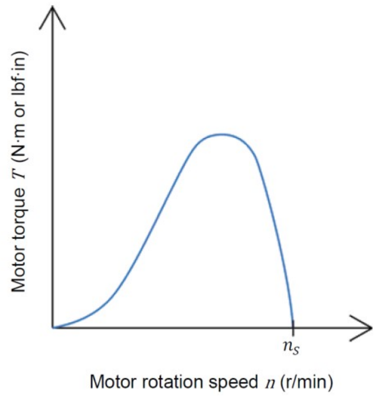

Fig.2: Torque-versus-rotation speed curve of a single-phase induction motor

The low torque values at low speeds are due to the fact that the currents induced in the rotor produce magnetic fields that create forces which act on the rotor in various directions. Most of these forces cancel each other and the resulting force acting on the rotor is weak. This explains why the single-phase induction motor shown in Fig.1 must be started manually.

To obtain torque at low speeds (starting torque), a rotating magnetic field must be produced in the stator when the motor is starting. A rotating magnetic field can be produced by using two alternating currents, I_1 and I_2, that are phase shifted 90° from one another, and two electromagnets placed at right angles to each other.

Fig.3 shows the simple single-phase induction motor of Fig.1 with the addition of a second electromagnet placed at right angle to the first electromagnet. The second electromagnet is identical to the first one and is connected to the same ac power source. The currents I_1 and I_2, in the electromagnets (winding currents) are in phase because the coils have the same impedance. However, because of the inductance of the coils of the electromagnets, there is a phase shift between the currents I_1 and I_2, and the ac source voltage E_s, as shown in the phasor diagram of Fig.3.

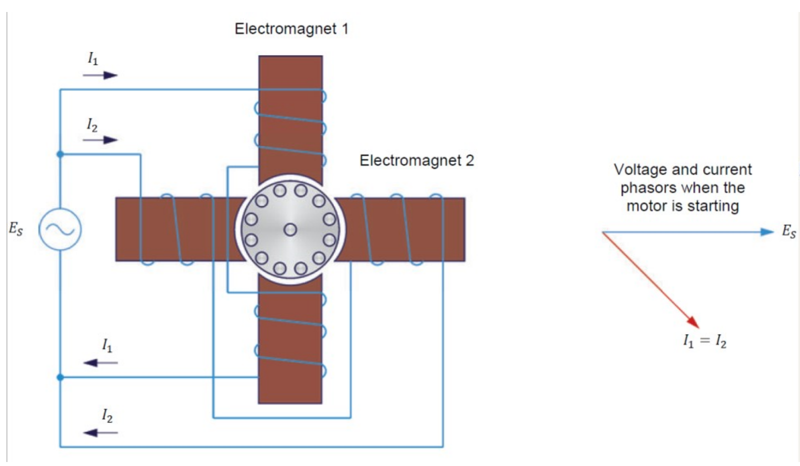

Fig.3: Adding a second electromagnet to the single-phase induction motor

Adding a capacitor and an auxiliary winding to the single-phase induction motor

Since currents I_1 and I_2 in the electromagnets (winding currents) of Fig3 are in phase, there is no rotating magnetic field produced in the motor stator. However, it is possible to phase shift current I_1 by connecting a capacitor (C_1) in series with the winding of electromagnet 2 as shown in Fig.4. The capacitance of capacitor C_1 can be selected so that current I_2 leads current I_1 by 90° when the motor is starting. As a result, a rotating magnetic field is created when the motor is starting. The capacitor creates the equivalent of a two-phase ac power source and allows the motor to develop starting torque.

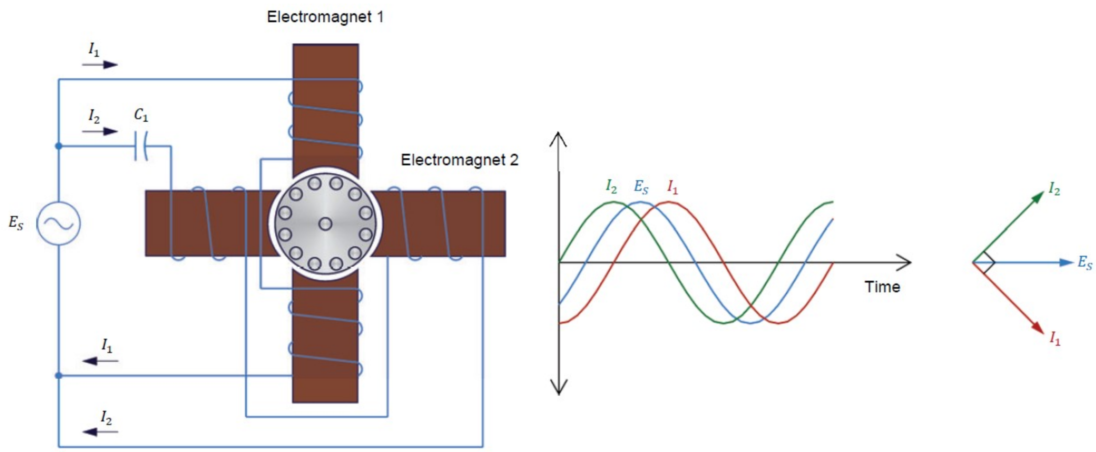

Fig.4: Adding a capacitor to the single-phase induction motor allows the motor to develop starting torque

Another way to create a phase shift between currents I_1 and I_2 is to use a winding with fewer turns of smaller-sized wire. The resulting winding, which is called auxiliary winding, has more resistance and less inductance, and the winding current is almost in phase with the source voltage. Although the phase shift between the two currents is less than 90° when the motor is starting, as shown in Fig.5, a rotating magnetic field is created. The torque produced is sufficient for the motor to start rotating in applications not requiring high values of starting torque.

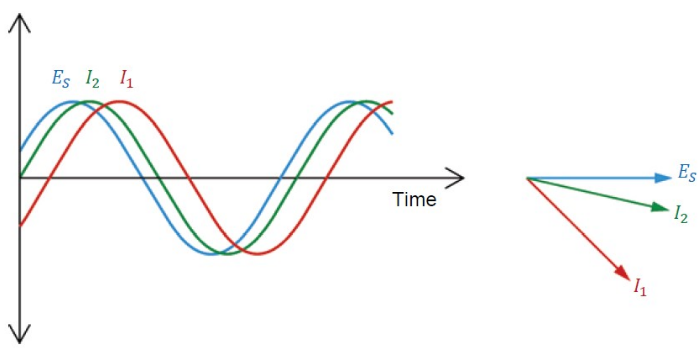

Fig.5: Phase shift between the winding currents when an auxiliary winding is used

Centrifugal switch

The auxiliary winding cannot support high currents for more than a few seconds without being damaged because it is made of fine wire. It is therefore connected through a centrifugal switch that opens and disconnects the winding from the motor circuit when the motor reaches about 75% of the normal speed. When the centrifugal switch opens, the rotating magnetic field is maintained by the interaction of the magnetic fields produced by the stator and the rotor.

EXPERIMENT

Operation of a single-phase induction motor (capacitor-start type)

In this section, you will observe the operation of a single-phase induction motor using the Capacitor-Start Motor.

32. Connect the capacitor-start motor circuit shown in Fig.6, use one phase only.
33. Using a variable-voltage single-phase power source, apply gradually voltage to the motor terminal,
34. Read E_1 and I_1 values.
35. Does the Capacitor-Start Motor start rotating?

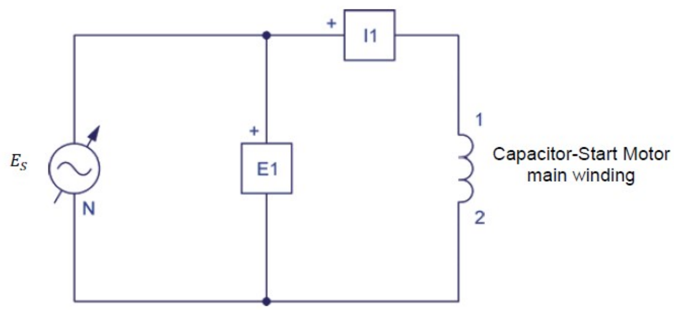

Fig.6: Capacitor-start motor circuit.

36. Turn the Power Supply off,
37. Connect the auxiliary winding of the Capacitor-Start Motor as shown in Fig.7

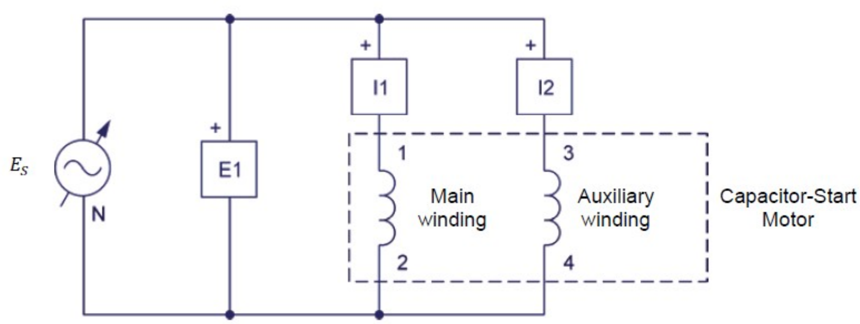

Fig.7: Connecting the auxiliary winding to the capacitor-start motor circuit

38. Turn the Power Supply on
39. Read E_1 and I_1 values.
40. Does the Capacitor-Start Motor start rotating?
41. Turn the Power Supply off
42. Modify the capacitor-start motor circuit so that the capacitor on the Capacitor-Start Motor is connected in series with the auxiliary winding as shown in Fig.8
43. Turn the Power Supply on,
44. Read E_1 and I_1 values.

45. Turn the Power Supply off

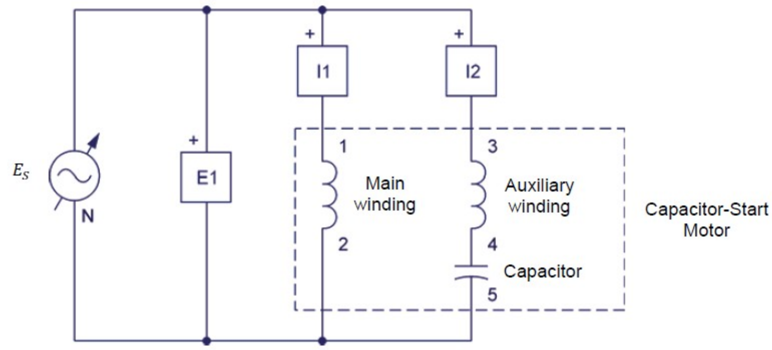

Fig.8: Connecting a capacitor in series with the auxiliary winding

46. Modify the capacitor-start motor circuit by connecting the centrifugal switch on the Capacitor-Start Motor in series with the auxiliary winding and the capacitor as shown in Fig.9

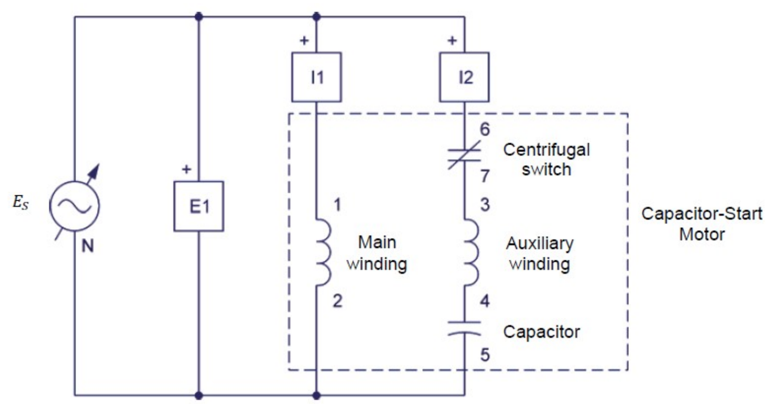

Fig.9: Connecting a centrifugal switch in series with the auxiliary winding and capacitor.

47. Turn the Power Supply
48. Read E_1 and I_1 values.
49. Does the Capacitor-Start Motor start rotating?
50. Operate the motor: Apply a load to the drive machine according to the values in table 1. Measure the speed and torque, and the input voltage, current and power. Enter the measured values into the table.
51. Calculate the delivered mechanical power:

$$P_2 = \frac{2\pi n}{60} M$$

52. Calculate the efficiency of the motor:

$$\eta = \frac{P_2}{P_1}$$

53. From the results, measured and calculated, plot the load characteristics: n=f(M), η=f(P_2).
54. Describe the response of the speed of the motor under load conditions.

Table 1

M_2[Nm]	0	1	2	3	4	5	6
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U_1[V]							
I_1[A]							
P_1							
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