



# Hashemite University

## Mechatronics Engineering Department

### Electrical Machines and Drive

### Laboratory Manual



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## Experiment 1

# Basic Measurements

### Objectives:

- To introduce basic lab equipments such as the multimeter and power supplies.
- To learn how to measure electrical quantities such as voltage, current, and power using lab instruments.
- To learn the basic concepts regarding three phase system connection and power calculations.

### Apparatus:

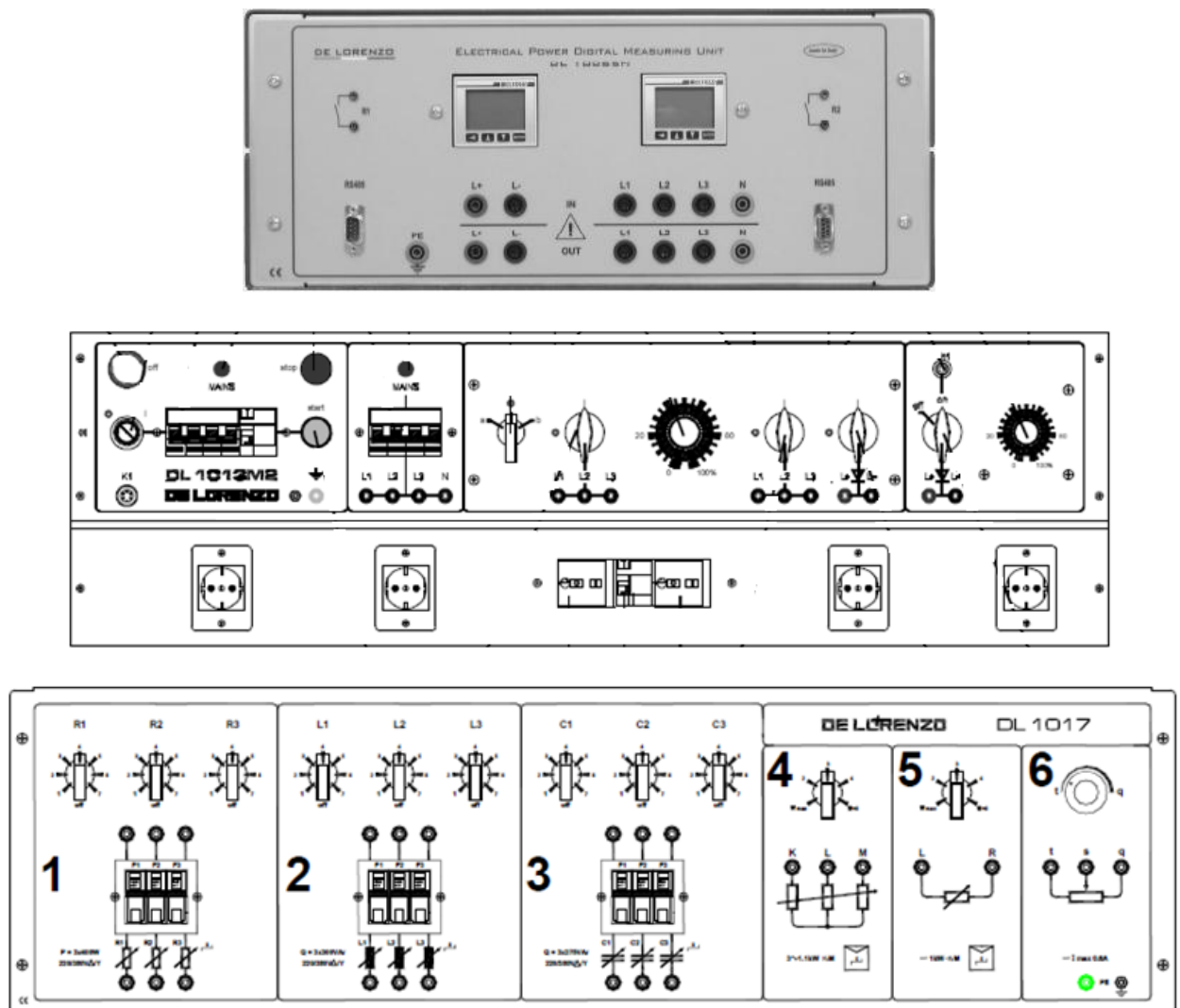


Figure 1.1: System Apparatus

## Theoretical Background:

### Digital Multimeter

Digital multimeter (DMM) is used to measure electrical quantities such as voltage, current, resistance, and power as well as to show these quantities digitally. The DMM is easy to use and necessary for all electrical and electronics laboratories.

### Voltage Measurement (The Voltmeter)

Voltage measurement is made by connecting the voltmeter in parallel with the electrical / electronic component(s) as shown in Figure 1.1. If the probes are reversed the reading will be the same as the original but negative when compared with the original one. The voltmeter has a very large internal resistance, which is considered as an open circuit during calculations.

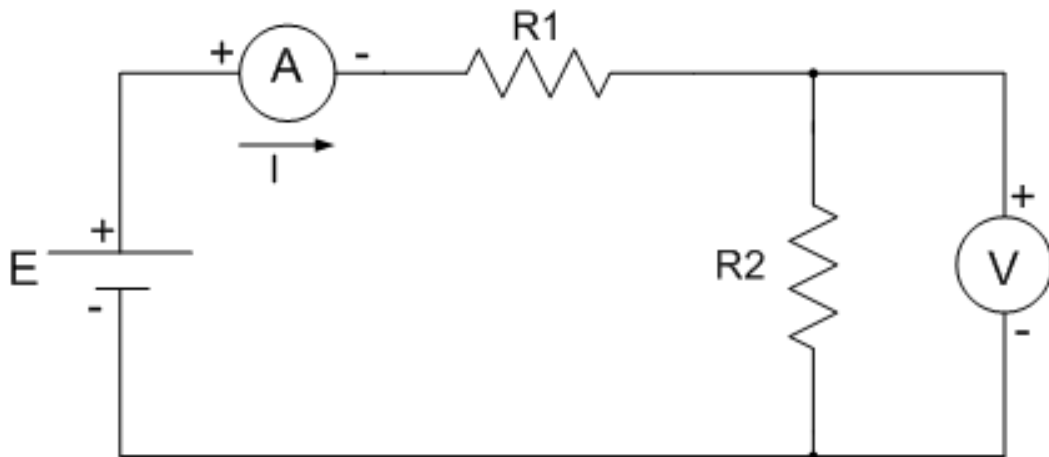


Figure 1.2: A circuit showing how to use two multimeters to measure the voltage and current

### Current measurement (The Ammeter)

Current measurement is made by connecting the ammeter in series with a circuit component as shown in Figure 1.2. The ammeter has very small internal resistance and considered as a short circuit element in calculations.

### Power Measurement (The Wattmeter)

Electric power may be measured by means of a wattmeter. This instrument is of the electrodynamic type. It consists of a pair of fixed coils, known as a current coil, and a movable coil known as the potential coil, (refer to Figure 1.3). The fixed coils are made up of few turns of a comparatively large conductance. The potential coil consists of many turns of fine wires. It is mounted on a shaft, carried in jeweled bearings, so that it may turn inside the stationary coils. The movable coil carries a needle which moves over a suitably marked scale. Spiral coil springs hold the needle to a zero position.

The current (stationary) coil of the wattmeter is connected in series with the circuit (load), and the potential (movable) coil is connected across the line. When line current flows through the current coil of a wattmeter, a field is set up around the coil. The strength of this field is proportional to the line current and in phase with it. The potential coil of the wattmeter generally has a high resistance. This is for the purpose of making the potential coil circuit of the meter as purely resistive as possible. As a result, current in the potential circuit is practically in phase with line voltage. Therefore, when voltage is applied to the potential circuit, current is proportional to and in phase with the line voltage. The actuating force of a wattmeter comes from the magnetic fields of its current and potential coils. The force acting on the movable coil at any instant (tending to turn it) is proportional to the instantaneous values of line current and voltage.

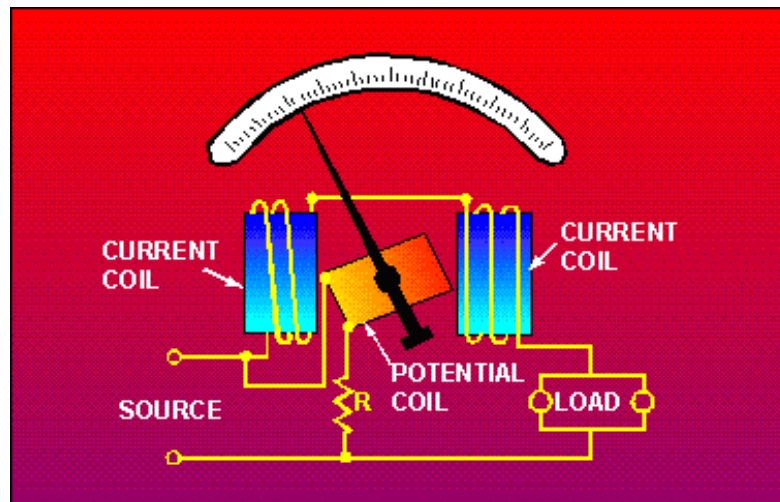


Figure 1.3: A simplified electrodynamic's wattmeter circuit

### Three-Phase Power System and Power Factor (PF)

An ac generator designed to develop a signal sinusoidal voltage for each rotation of the shaft (rotor) is referred to as a single-phase generator. If the number of coils on the rotor is increased in specified manner, the result is polyphase generator, which develops more than one ac phase voltage per rotation of the rotor.

The three-phase system is used by almost all commercial electric generators. This does not mean that single-phase and two-phase generating systems are out dated. Most small emergency generators, such as the gasoline type, are one phase generating systems. The two-phase system is commonly used in servomechanisms. In many cases, however, where single phase and two phase inputs are required, they are supplied by one and two phase of a three phase generating system rather than generated independently.

In general, three-phase system is preferred over single-phase systems for the transmission of power for many reasons, including the following:

1. Thinner conductors can be used to transmit the same kVA at the same voltage because the current is divided among the three phases instead of between just one. This reduces the

amount of copper required (typically about 25% less) and in turn reduces construction and maintenance costs.

2. The lighter lines are easier to install, and the supporting structures can be less massive and farther apart.
3. In general, most large motors are three-phase because they are essentially self-starting and do not require a special design or additional starting circuitry.
4. Easier motor wiring; Three-phase induction motors does not require brushes, start capacitors, or any of the complexities of single-phase motors, and are easy to reverse as needed.
5. Constant power delivery. Single-phase delivers zero power each time the voltage crosses zero (120 times per second in the US), while with three-phase each time a phase crosses zero there is still power being delivered. This leads to three-phase motors in machinery running more smoothly.

The frequency generated is determined by the number of poles in the motor (the rotating part of the generator) and the speed with which the shaft is turned. Throughout the United States, the line frequency is 60Hz, whereas in Europe and Jordan, the chosen standard is 50Hz. Both frequencies were chosen primarily because they can be generated by a relatively efficient and stable mechanical design that is sensitive to the size of the generating systems and the demand that must be met during peak periods. On aircraft and ships the demand levels permit the use of a 400Hz line frequency.

The three-phase generator of Figure 1.4 has three induction coils placed  $120^\circ$  apart on the rotor (armature), as shown symbolically by Figure 1.5. Since the three coils rotate with the same angular velocity, the voltage induced across each coil will have the same peak value, shape, and frequency. As the shaft of the generator is turned by some external means, the induced voltage  $e_{AN}$ ,  $e_{BN}$ , and  $e_{CN}$  will be generated simultaneously as shown in Figure 1.6. Note that there is 120 degrees phase shift between waveforms. In particular, at any instant of time, the algebraic sum of the three phase voltages of a three-phase generator is zero. This is shown at  $\omega t = 0$  in Figure 1.6, where it is also evident that when one induced voltage is zero, the other two are 86.6% of their positive or negative maximums. In additions, when any two are equal in magnitude and sign (at  $0.5E_m$  where  $E_m$  is the maximum peak), the remaining induced voltage has the opposite polarity and a peak value.

The sinusoidal expression for each of the induced voltages of Figure 1.5 is:

$$\begin{aligned}e_{AN} &= E_{m(AN)} \sin \omega t \\e_{BN} &= E_{m(BN)} \sin(\omega t - 120^\circ) \\e_{CN} &= E_{m(CN)} \sin(\omega t - 240^\circ) = E_{m(CN)} \sin(\omega t + 120^\circ)\end{aligned}\tag{1.1}$$

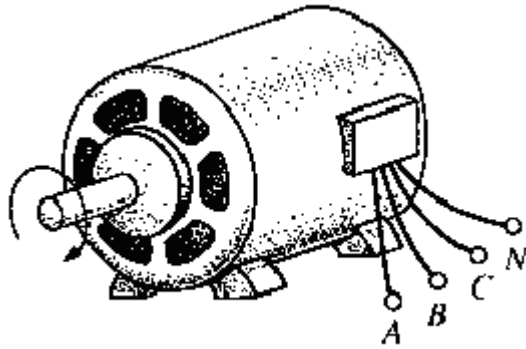


Figure 1.3: Three-phase generator

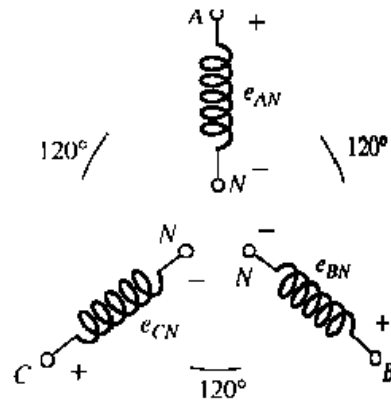


Figure 1.4: Induced voltages of a three-phase generator

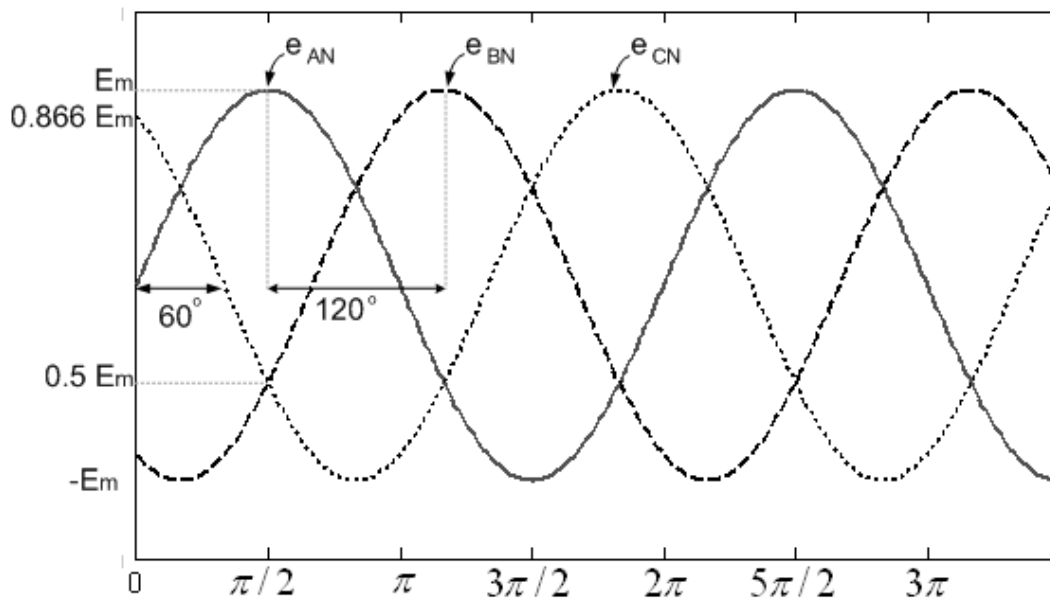


Figure 1.5: Phase voltage of a three phase generator

The phasor diagram of the induced voltages is shown in Figure 1.6 where the effective value of each one is determined by

$$\begin{aligned}
 e_{AN} &= 0.707E_{m(AN)} = E_{AN} \angle 0 \\
 e_{BN} &= 0.707E_{m(BN)} = E_{BN} \angle -120^\circ \\
 e_{CN} &= 0.707E_{m(CN)} = E_{CN} \angle -240^\circ
 \end{aligned}
 \tag{1.2}$$

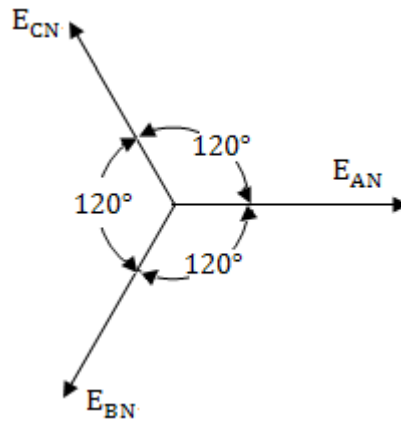


Figure 1.6: Phasor diagram for phase voltages of a three phase generator

The source can be either delta or star connected, as follows:

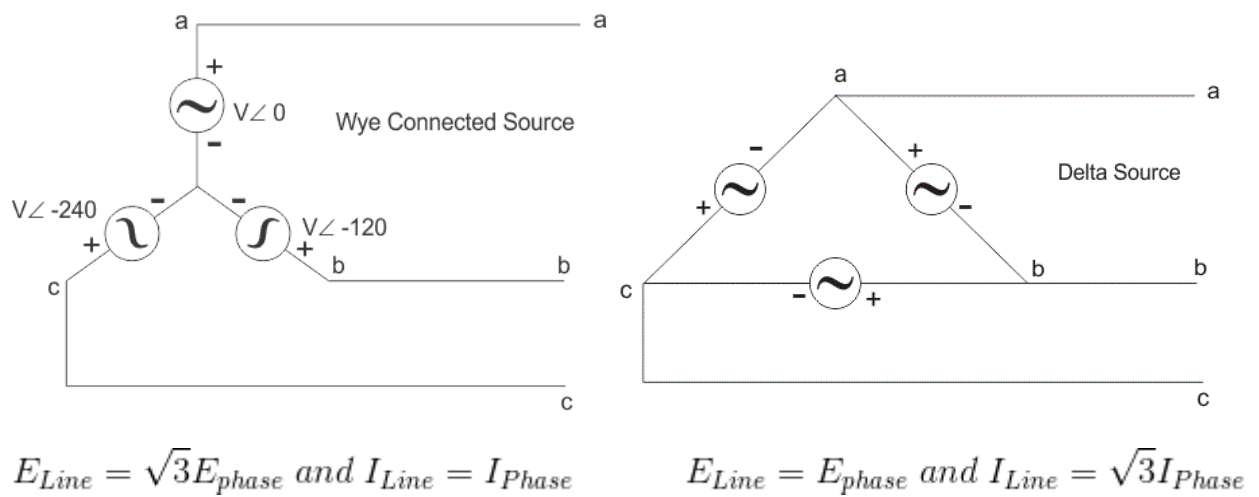


Figure 1.7: Star and Delta sources

The same applies for **loads** which means that there are four different combinations of sources and loads.

1. Star-Star connection
2. Star-Delta connection
3. Delta-Star connection
4. Delta-Delta connection

**Keep in mind that the power is independent of the circuit arrangement of the three phase system. The net power in the circuit will be same in both star and delta connection.**

### Three Phase Power Calculations

AC power flow has three components:

1. Real power or active power (P), expressed in watts (W) and it is consumed as heat losses.
2. Apparent power (S), usually expressed in volt-amperes (VA)
3. Reactive power (Q), usually expressed in reactive volt-amperes (var) and it is either absorbed by inductive loads or generated by capacitive loads.

The complex power is a vector that can be defined as:

$$\vec{S} = |S| \angle \theta = P + jQ = |S| \cos \theta + j|S| \sin \theta \quad (1.3)$$

$$|S| = \sqrt{P^2 + Q^2} \quad (1.4)$$

$$\theta = \tan^{-1} \frac{Q}{P} \quad (1.5)$$

The power supplied by a three phase source or drawn by a three phase load is calculated as follows:

- The power supplied to or drawn by a single phase is:

$$P_{\phi} = V_{\phi} I_{\phi} \cos \theta \quad (1.6)$$

- The power supplied to or drawn by the three phase ( total input power or complete load power):

$$P_{tot} = 3V_{\phi} I_{\phi} \cos \theta = \sqrt{3} V_{LL} I_L \cos \theta \quad (1.7)$$

### Impedance

Impedance is defined as the frequency domain ratio of the voltage to the current. The impedance consists of two components:

- The magnitude of the complex impedance is the ratio of the voltage amplitude to the current amplitude.
- The phase of the complex impedance is the phase shift by which the current lags the voltage.

$$\vec{Z} = |Z| \angle \theta = \frac{\vec{V}}{\vec{I}} = |Z| \cos \theta + j|Z| \sin \theta = R + jX \quad (1.8)$$



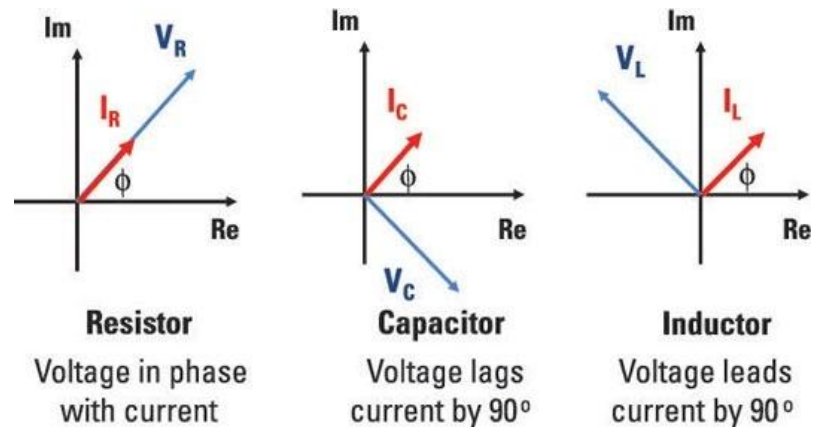


Figure 1.8: Voltage Current Phase Shift

### Power Factor

The power factor is defined as:

$$PF = \cos \theta = \frac{P}{|S|} = \frac{R}{|Z|} \quad (1.9)$$

Power factor can be either leading or lagging (depending on whether current is leading or lagging voltage in a load). A lagging power factor signifies that the load is inductive, as the load will “consume” reactive power, and therefore the reactive component Q is positive as reactive power travels through the circuit and is “consumed” by the inductive load. A leading power factor signifies that the load is capacitive, as the load “supplies” reactive power, and therefore the reactive component Q is negative as reactive power is being supplied to the circuit.

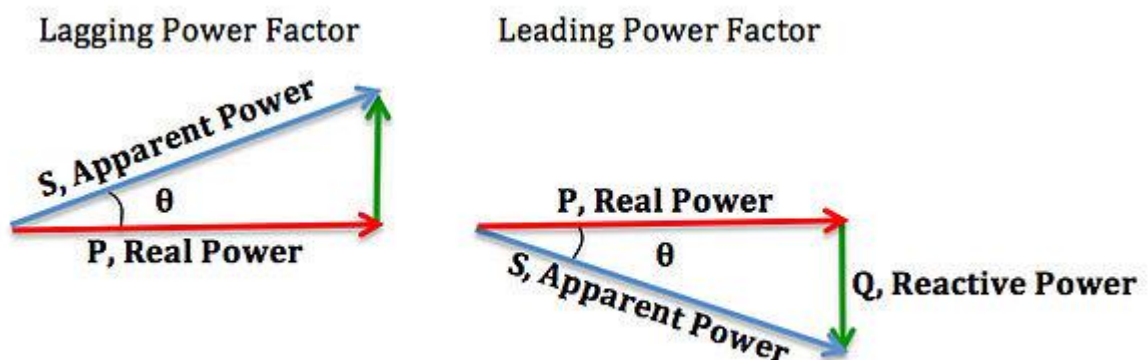


Figure 1.9: Power Factor

### Voltage Regulation

The voltage regulation is the percentage of voltage difference between no load and full load voltages of a power source with respect to its full load voltage. The source can be a power supply or a transformer.

$$VR_{\text{actual}} = \frac{|V_{2 \text{ (no-load)}}| - |V_{2 \text{ (with-load)}}|}{|V_{2 \text{ (with-load)}}|} \cdot 100\% \quad (1.10)$$

How can you see the phenomena?

Ideally if we measure the power source while the source is not connected to a load then we measure the voltage when a load is connected, the voltmeter reading should be the same but that is not what happens in real life. There will be a difference between the two readings!

The regulation can be measured in two cases:

1. Fixing the load and changing the source voltage while measuring the no load case and load case voltage.
2. Fixing the supply voltage, measuring it while the load is disconnected then connecting and changing the load while measuring voltage.

### Procedure:

Using the lab equipment in Figure 1.1, make the appropriate wiring and answer the following:

1. For the fixed three phase voltage terminals power supply, do the following measurements:

Table 1.1: Source Measurement

$V_{L1-2}$	$V_{L1-3}$	$V_{L2-3}$	$V_{L1-N}$	$V_{L2-N}$	$V_{L3-N}$

2. Connect a load of the instructor choice and measure the load regulation.
3. Connect one of the circuits shown in Figure 1.10 and do the measurements in Table 1.2.

Table 1.2: Three Phase Measurements

$V_{1-2}$	$I_1$	$V_p$	$I_p$	$P_p$	PF

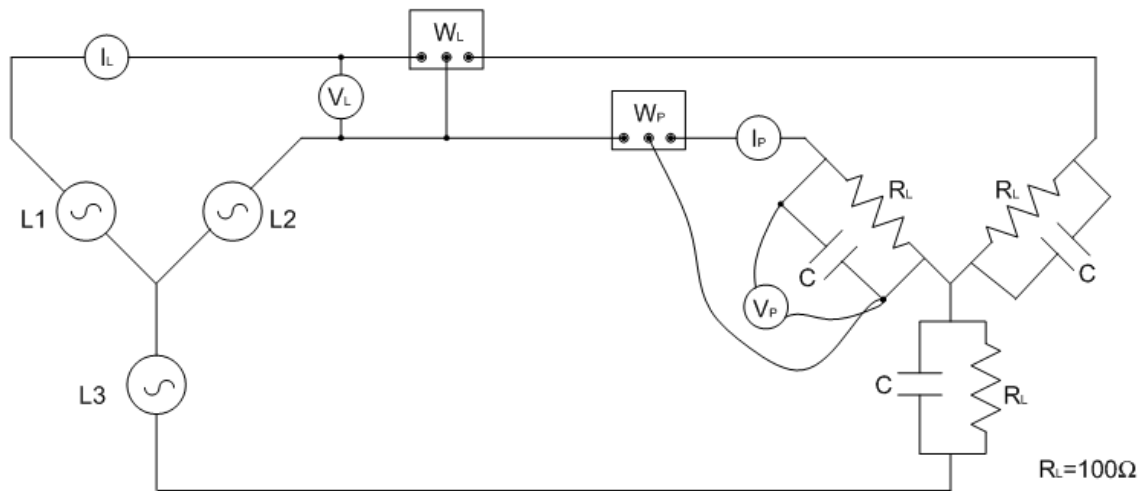


Figure 1.10.a: Three phase star-connected load

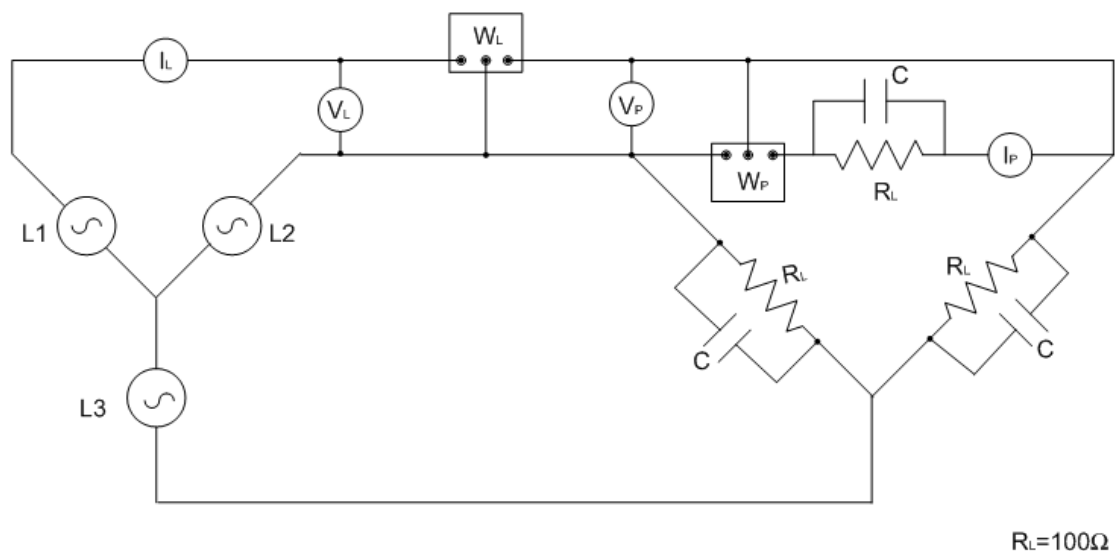


Figure 1.10.b: Three phase delta-connected load

### Discussion and Analysis:

1. Why is the measured voltage in part 2 decreases when a load is applied?
2. Plot the voltage regulation versus input voltage. Comment on the result.
3. What is the type of power measured by the wattmeter in (Real, Reactive, Apparent)?
4. (i) Discuss the effect of changing the capacitance on the power factor and derive a mathematical relationship that proves your result. (ii) Will this relationship change if the load configuration changes (i.g., if the resistor is in series with the capacitor)? Prove it.
5. Based on the measurements you obtained in part 1, does the laboratory equipment supply power with a star or delta connection?

### References:

1. <http://www.electrical4u.com/three-phase-circuit-star-and-delta-system/>
2. [https://en.wikipedia.org/wiki/Power\\_factor](https://en.wikipedia.org/wiki/Power_factor)

## Experiment 2

# Single Phase Transformer

### Objectives:

- To determine the turns ratio and the polarity of a single phase transformer.
- To determine the parameter values of the excitation branch that model the core and magnetization losses in a real transformer.
- To determine the parameter values of components that model the copper losses and leakage flux in a real transformer.

### Apparatus:

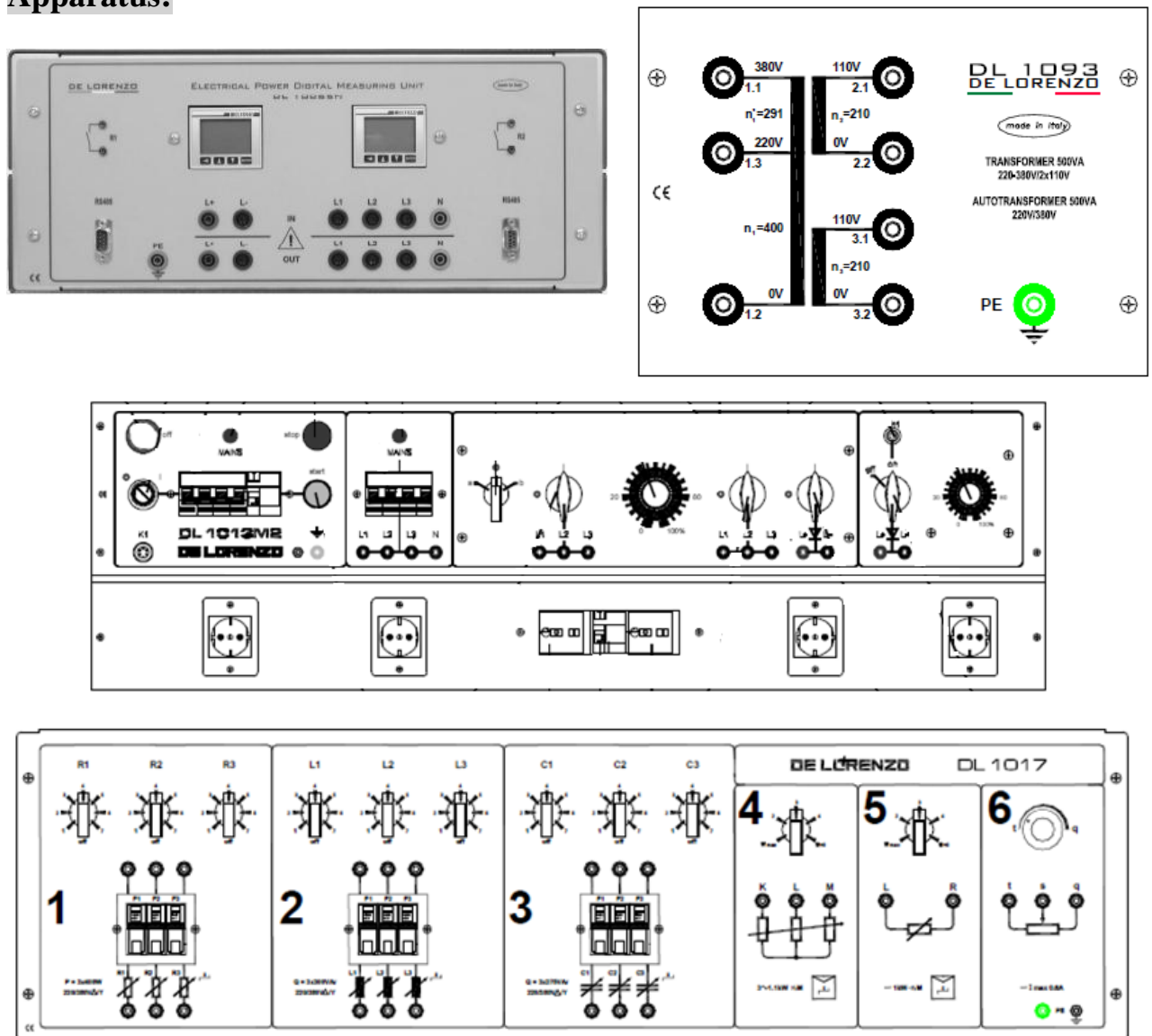


Figure 2.1: System Apparatus

**Theoretical Background:**

A transformer is an electrical device that transfers electrical energy between two or more circuits through electromagnetic induction. Electromagnetic induction produces an electromotive force within a conductor which is exposed to time varying magnetic fields. Transformers are used to increase or decrease the alternating voltages in electric power applications.

A varying current in the transformer's primary winding creates a varying magnetic flux in the transformer core and a varying field on the transformer's secondary winding. This varying magnetic field at the secondary winding induces a varying electromotive force (EMF) or voltage in the secondary winding due to electromagnetic induction.

From Figure 2.2 the turn's ratio of a single phase transformer is defined as the ratio of the primary winding voltage  $V_1$  to the secondary winding voltage  $V_2$  when no load is applied as follow

$$a = \frac{V_1}{V_2} = \frac{V_P}{V_S} \tag{2.1}$$

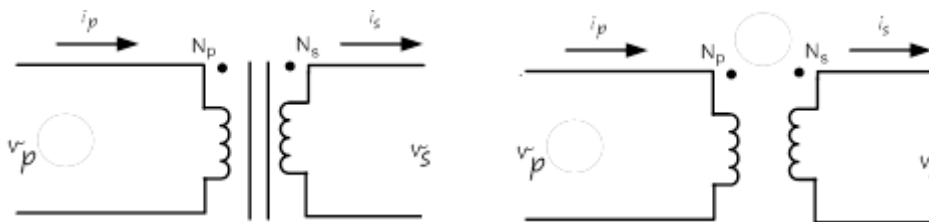


Figure 2.2: Schematic Symbol of a Transformer

In an ideal transformer, there is no leakage in the magnetic field ( $\Phi$ ) flowing through the iron core and since Faradays law states that "If a flux passes through a turn of a coil of wire, a voltage will be induced in the turns of wire that is directly proportional to the rate of change in the flux with respect to time" so that

$$e_{ind} = -N \frac{d\phi}{dt} \tag{2.2}$$

then, it is clear that

$$-\frac{d\phi}{dt} = \frac{V_1}{N_1} = \frac{V_2}{N_2} \tag{2.3}$$

thus

$$a = \frac{V_1}{V_2} = \frac{N_1}{N_2} \tag{2.4}$$

Moreover, the apparent power consumed in both sides of the transformer is the same such that

$$S_1 = V_1 I_1 = V_2 I_2 = S_2 \quad (2.5)$$

then, it is clear that

$$a = \frac{V_1}{V_2} = \frac{I_2}{I_1} \quad (2.6)$$

The exact equivalent circuit of a **real** transformer is shown in Figure 2.3 where  $V_1$  is the supply voltage (primary),  $V_2$  is the load voltage (secondary),  $R_1$  and  $R_2$  are the winding internal resistances,  $X_1$  and  $X_2$  are the winding leakage reactances,  $R_c$  is the core loss resistance,  $X_m$  is the magnetizing reactance, and  $a$  is transformer turns ratio. From Figure 2.3, the following relationship can be obtained

$$Z_L = \frac{V_L}{I_L} = \frac{V_s}{I_s} = \frac{V_2}{I_2} \quad (2.7)$$

then

$$Z'_L = a_2 \cdot Z_L \quad (2.8)$$

where  $Z'_L$  is the apparent impedance of the primary circuit of the transformer.

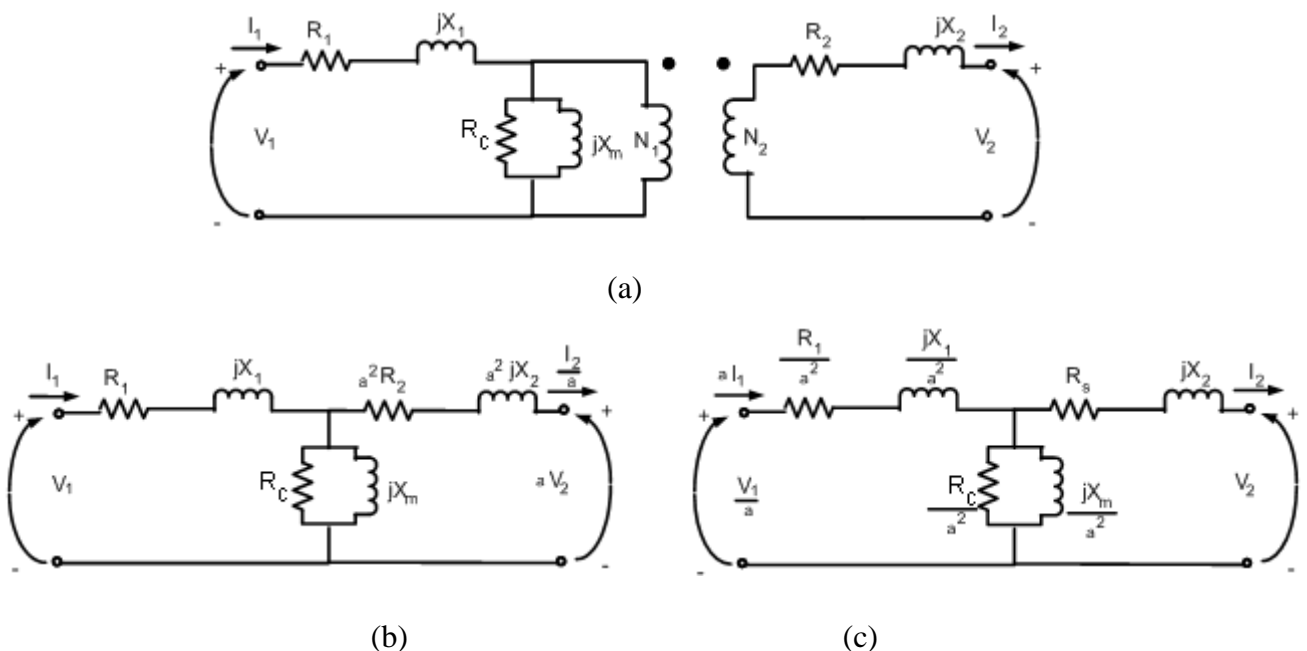


Figure 2.3: (a) Transformer equivalent circuit, (b) Transformer model referred to its primary voltage, and (c) Transformer model referred to its secondary voltage

### Core form and shell form transformers

Closed-core transformers are constructed in 'core form' or 'shell form'. When windings surround the core, the transformer is core form; when windings are surrounded by the core, the transformer is shell form. Shell form design may be more prevalent than core form design for distribution transformer applications due to the relative ease in stacking the core around winding coils. Core form design tends to, as a general rule, be more economical, and therefore more prevalent, than shell form design for high voltage power transformer applications at the lower end of their voltage and power rating ranges (less than or equal to, nominally, 230 kV or 75 MVA). At higher voltage and power ratings, shell form transformers tend to be more prevalent. Shell form design tends to be preferred for extra-high voltage and higher MVA applications because, though more labor-intensive to manufacture, shell form transformers are characterized as having inherently better kVA-to-weight ratio, better short-circuit strength characteristics and higher immunity to transit damage.

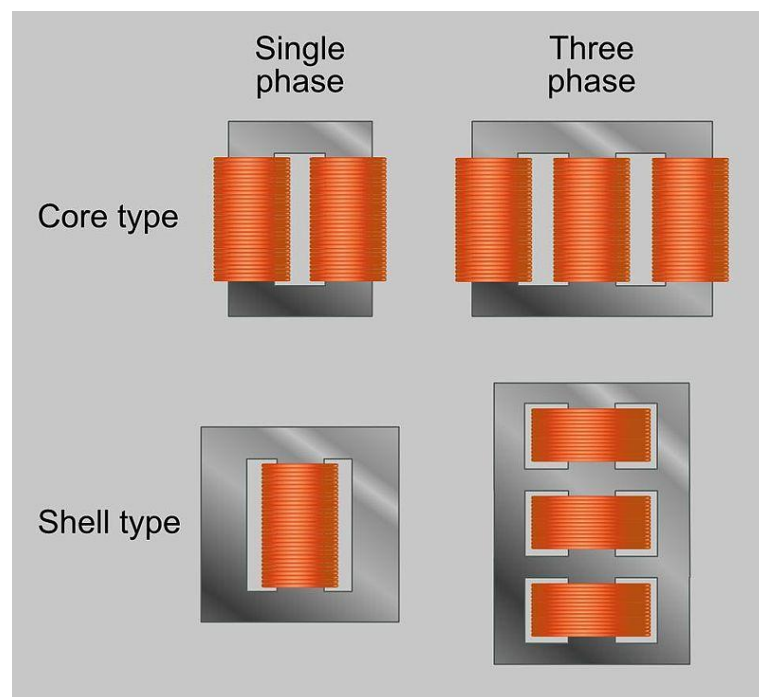


Figure 2.4: Core and Shell Type Transformers

### Transformer tests

Different tests are made on the transformer to model its circuit and obtain its turn ration and dot convention. An important point is to define the transformer's low voltage side and high voltage side. The sides for the transformer in the laboratory are illustrated by Figure 2.5.

#### 1. Turns Ratio Test

This test is done when **no load** is connected to the secondary by applying any voltage level at the primary side and measuring the voltage at the secondary side.

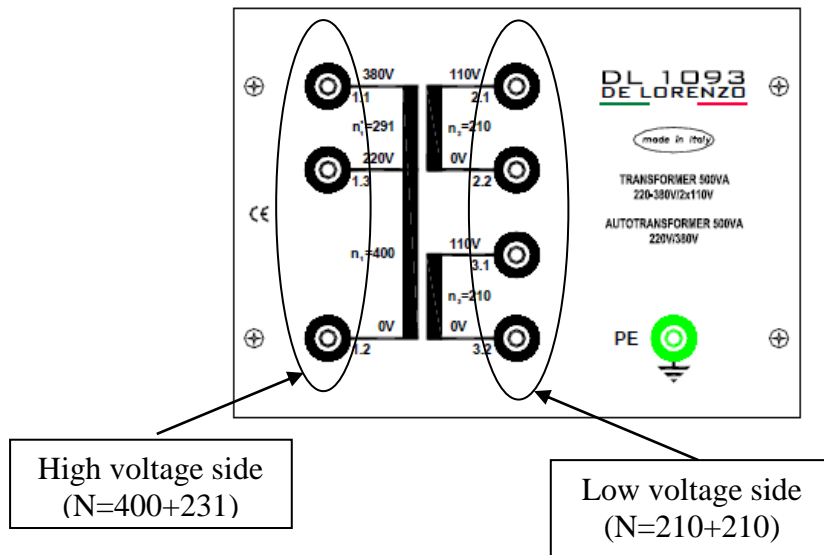


Figure 2.5: Laboratory Transformer Sides

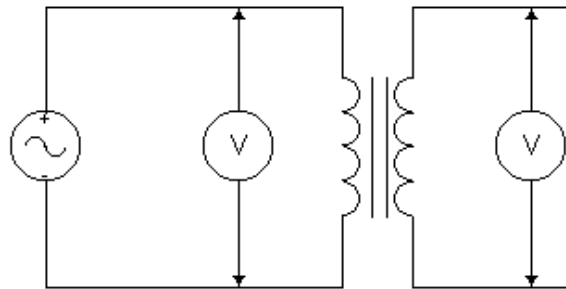


Figure 2.6: Turns Ratio Circuit Test Schematic

2. Windings Polarity Test (Dot Convention)

The dots appearing at the primary winding in Figure 2.7 indicate the polarity of the voltage and current on the secondary winding of the transformer. The relationship is as follows:

1. If the primary voltage is positive at the dotted end of the winding with respect to the undotted end, then the secondary voltage will be positive at the dotted end also. Voltage polarities are the same with respect to the dots on each side of the core
2. If the primary current of the transformer flows into the dotted end of the primary winding, the secondary current will flow out of the dotted end of the secondary winding.

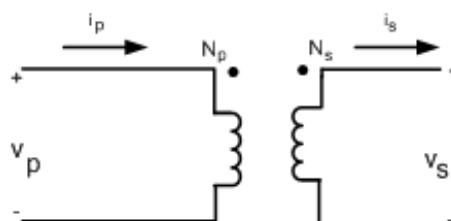


Figure 2.7: Schematic Diagram for a Single Phase Transformer.



What determines the polarity is the direction the coils are wound around the core as shown by Figure 2.8. The primary current will induce a primary flux with direction determined using the right hand thumb rule. According to lenz law, the secondary coil will must induce a flux that will oppose the flux of the primary in direction. The direction of secondary current that will induce the opposing secondary flux is determined using the right hand thumb rule.

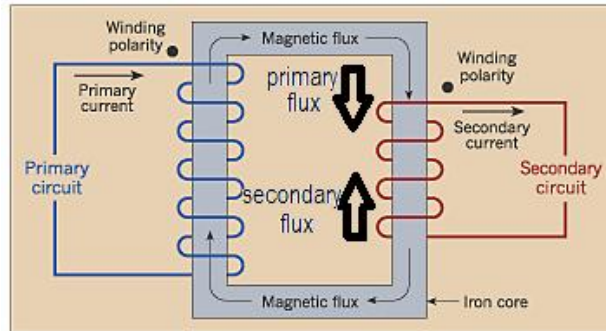


Figure 2.8: Dot convention determination

The test is done by applying voltage at the **high voltage side** and making a short between one terminal of the primary side and one terminal of the secondary sides and measuring the output voltage between the unshorted terminals. If  $V_1 < V_2$  then, the polarity is additive and the transformer voltages are out of phase, otherwise if  $V_1 > V_2$  then, the polarity is subtractive and the transformer voltages are in phase.

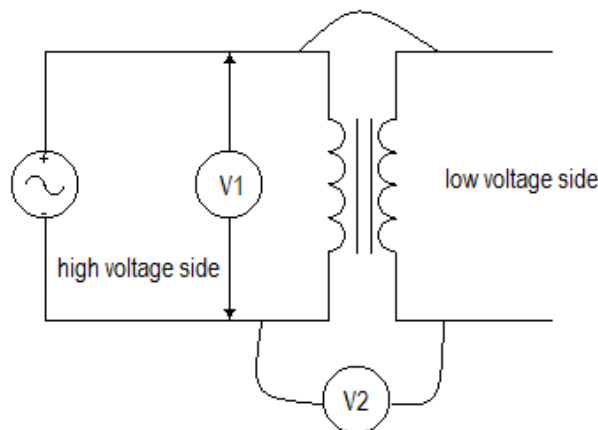


Figure 2.9: Polarity Test Schematic Circuit

### Importance of polarity test

It is essential to know the relative polarities at any instant of the primary and the secondary terminals for making the correct connections if the transformers are to be connected in parallel or they are used in a three phase circuit.

3. DC Test

The internal resistance of each winding in a transformer is measured using a small dc current to avoid thermal and inductive effects. If a voltage  $V_{dc}$  causes a current  $I_{dc}$  to flow through the transformer windings, then

$$\text{Internal Resistor} = R_X = \frac{V_{dc}}{I_{dc}} \quad (2.9)$$

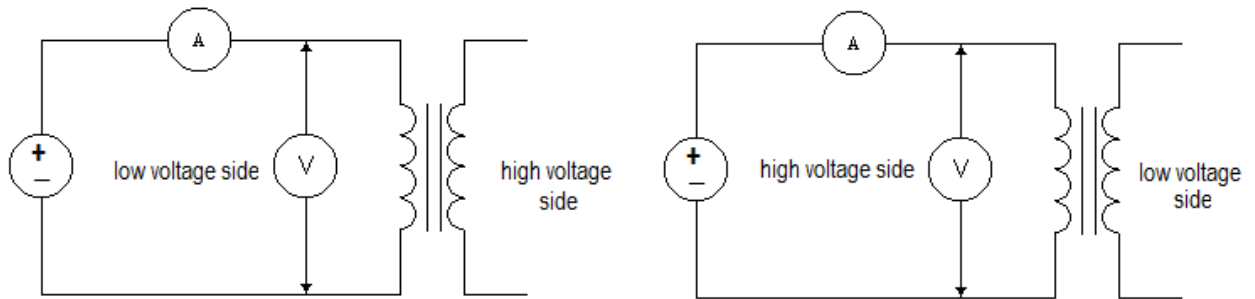


Figure 2.10: DC Test Schematic Circuit

4. Open-Circuit Test

In the open-circuit test, the transformer's high voltage side is open circuited, while its low voltage side is connected to a full-rated line voltage. Under the conditions described, all the input current must be flowing through the excitation branch of the transformer. The series elements  $R_P$  and  $X_P$  are too small in comparison to  $R_C$  and  $X_M$  to cause a significant voltage drop, so essentially all the input voltage is dropped across the excitation branch.

During the open-circuit test **Full line voltage is applied to the low voltage side** of the transformer, and the **input voltage, input current, and input power to the transformer are measured**. From this information, it's possible to determine the power factor of the input current and therefore both the magnitude and the angle of the **excitation impedance**.

The easiest way to calculate the values of  $R_C$  and  $X_M$  is to look first at the admittance of the excitation branch. The conductance of the core-loss resistor is given by:

$$G_C = \frac{1}{R_C} \quad (2.10)$$

And the susceptance of the magnetizing inductor is given by:

$$B_M = \frac{1}{X_M} \quad (2.11)$$

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

$$Y_E = G_C - jB_M = \frac{1}{R_C} - j \frac{1}{X_M} \quad (2.12)$$

The magnitude of the excitation admittance (referred to the primary circuit) can be found from the open-circuit test voltage and current as follows

$$|Y_E| = \frac{I_{OC}}{V_{OC}} \quad (2.13)$$

The angle of admittance can be found from the knowledge of the circuit power factor. The open circuit power factor (PF) is given by

$$PF = \cos \theta = \left( \frac{P_{OC}}{I_{OC} \cdot V_{OC}} \right) \quad (2.14)$$

and the power factor angle  $\theta$  is given by

$$\theta = \cos^{-1} \left( \frac{P_{OC}}{I_{OC} \cdot V_{OC}} \right) \quad (2.15)$$

The power factor is always lagging for a real transformer, so the angle of the current always lags the angle of the voltage by  $\theta$ . Therefore the admittance  $Y_E$  is

$$Y_E = \frac{I_{OC}}{V_{OC}} \angle \cos^{-1} PF \quad (2.16)$$

Using the above equations, it is possible to determine the values of  $R_C$  and  $X_M$  directly from the open-circuit test data.

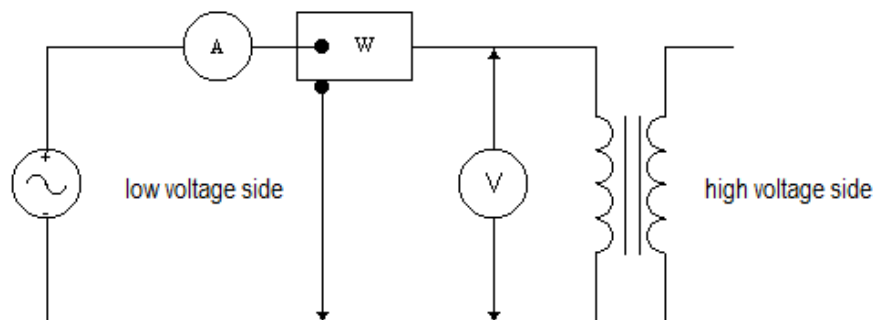


Figure 2.11: Open Circuit Test Schematic Circuit

### 5. Short-Circuit Test

In the short circuit test, the low voltage side terminals of the transformer are short-circuited, and the high voltage terminals are connected to fairly low-voltages source.

The input voltage is adjusted until the current in the short-circuited windings is equal to its rated value (be sure to keep the primary voltage at a safe level). Since the input voltage is too low during the short circuit test, negligible current flows through the excitation branch. If the excitation current is ignored, then the entire voltage drop in the transformer can be attributed to the series elements in the circuit. The magnitude of the series impedances referred to the primary side of the transformer is

$$|Z_{SE}| = \frac{V_{SC}}{I_{SC}} \quad (2.17)$$

The power factor of the current is given by

$$PF = \cos\theta = \left( \frac{P_{SC}}{I_{SC} \cdot V_{SC}} \right) \quad (2.18)$$

and is lagging. The current angle is thus negative, and the overall impedance angle  $\theta$  is positive as

$$\theta = \cos^{-1} \left( \frac{P_{SC}}{I_{SC} \cdot V_{SC}} \right) \quad (2.19)$$

therefore,

$$Z_{SE} = \frac{V_{SC} \angle 0^\circ}{I_{SC} \angle -\theta^\circ} = \frac{V_{SC}}{I_{SC}} \angle \theta^\circ \quad (2.20)$$

The series impedance  $Z_{SE}$  is equal to

$$Z_{SE} = R_{eq} + jX_{eq} = (R_p + a^2 R_s) + j(X_p + a^2 X_s) \quad (2.21)$$

It is possible to determine the total series impedance referred to the primary side by using this technique, but there is no easy way to split the series impedance into primary and secondary components. Fortunately, such separation is not necessary to solve normal problems.

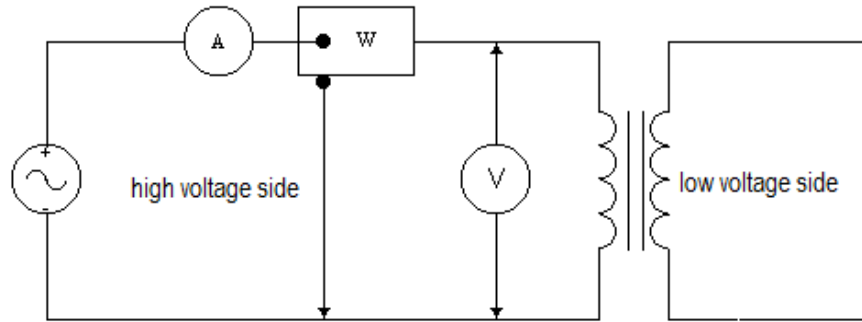


Figure 2.12: Short Circuit Test Schematic Circuit

## 6. Load Test

In the transformer load test the primary winding is connected to the supply voltage and various load levels are applied on the secondary winding. The with-load actual transformer efficiency ( $\eta_{\text{actual}}$ ) can be determined mathematically from experimental readings as

$$\eta_{\text{actual}} = \frac{P_{\text{out}}}{P_{\text{in}}} \cdot 100\% \quad (2.22)$$

where  $P_{\text{out}} = \{V \cdot I^*\}$ . If the load is purely resistive, then

$$P_{\text{out}} = V_2 \cdot I_2 \quad (2.23)$$

Note that 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

$$\eta_{\text{actual}} = \frac{P_{\text{out}}}{P_{\text{out}} + P_{\text{Cu}} + P_{\text{iron}}} \cdot 100\% \quad (2.24)$$

Transformer iron core losses  $P_{\text{iron}}$  and copper losses  $P_{\text{Cu}}$  are defined as

$$P_{\text{iron}} = \frac{|V_1|^2}{R_m} \quad (2.25)$$

$$P_{\text{Cu}} = |I_2'|^2 \cdot R_1 \quad (2.26)$$

where  $I_2' = I_2 / a$ . The maximum transformer efficiency occurs when the variable losses (dependent upon the current drawn) equal the fixed losses (independent of the current drawn)

$$P_{\text{iron}} = P_{\text{Cu}} \quad (2.27)$$

For detail about the proof, refer to Appendix 2.1. Because a real transformer has series impedance within it, the output voltage of a transformer varies with load even if the input voltage remains constant. With-load voltage regulation (VR) is a quantity that compares the output voltage at no load with the output voltage at certain load. It is defined by the equation

$$VR_{\text{actual}} = \frac{|V_{2(\text{no-load})}| - |V_{2(\text{with-load})}|}{|V_{2(\text{with-load})}|} \cdot 100\% \quad (2.28)$$

### Protection resistor calculations

Since the resistive load to be connected is variable, its value may get dangerously small at any moment causing high currents in the transformer windings and if this lasts for a long time, the transformer will get damaged.

In order to protect the transformer, a protection resistor is added in series with the load with a minimum value that will prevent the current in the secondary side to exceed its rated value.

That rated current value may be calculated using the transformer rated power and voltage of the load side.

$$I_{\text{rated}} = \frac{P_{\text{rated}}}{V_{\text{rated}}} \quad (2.29)$$

The rated values are obtained from the transformer name plate.

$$R_{\text{min}} = \frac{V_{\text{rated}}}{I_{\text{rated}}} \quad (2.30)$$

Or simply,

$$R_{\text{min}} = \frac{V_{\text{rated}}^2}{P_{\text{rated}}} \quad (2.31)$$

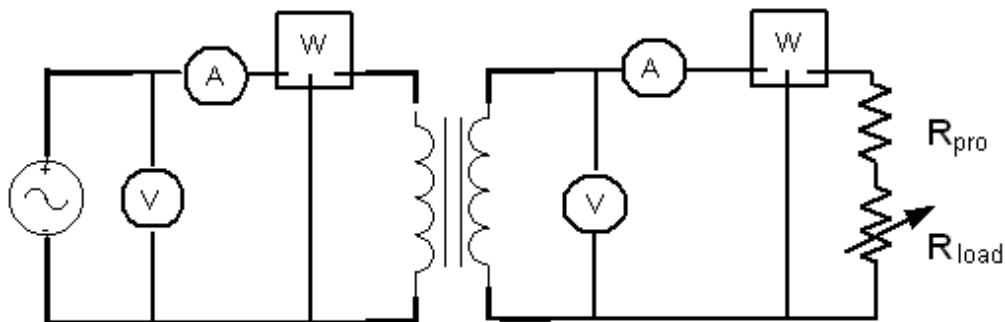


Figure 2.13: Load test schematic circuit

**Procedure:**

Using the lab equipment in Figure 2.1, make the appropriate wiring and follow the procedure.

Part 1: Turns ratio test

1. Connect the circuit show in Figure 2.14.
2. Calculate the transformer turns ratio "a" from the measurement of primary and secondary voltages

Table 2.1: Turns Ratio Test Data

$V_1$ [V]	$V_2$ [V]	$a = \frac{V_1}{V_2}$

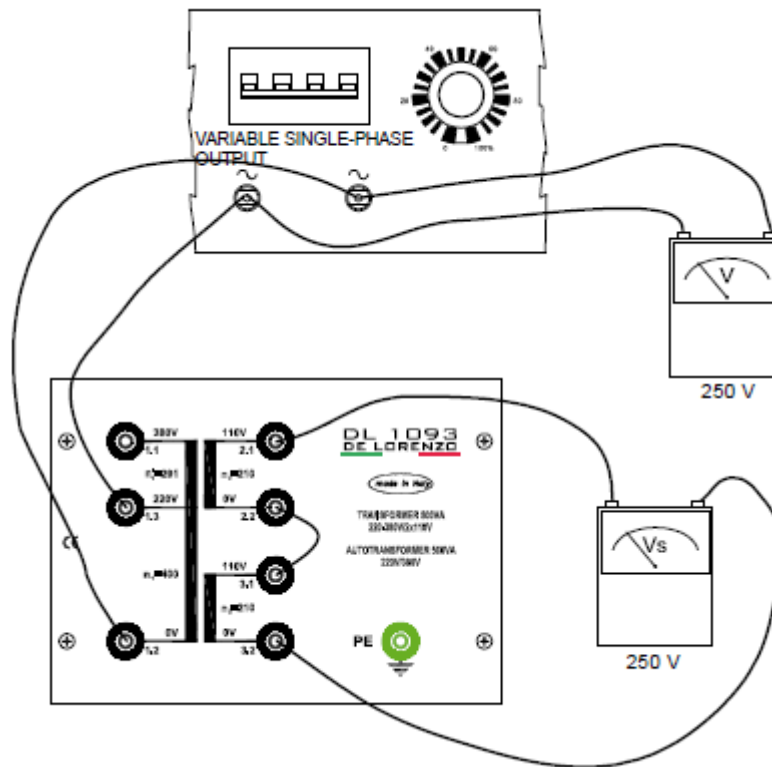


Figure 2.14: Turns Ratio Test Wiring Diagram

Part 2: Polarity test

1. Connect the circuit shown in Figure 2.15.
2. Read the voltages of Voltmeter (1) and (2).

Table 2.2: Polarity Test Data

$V_1$ [V]	$V_2$ [V]	The polarity of tested transformer

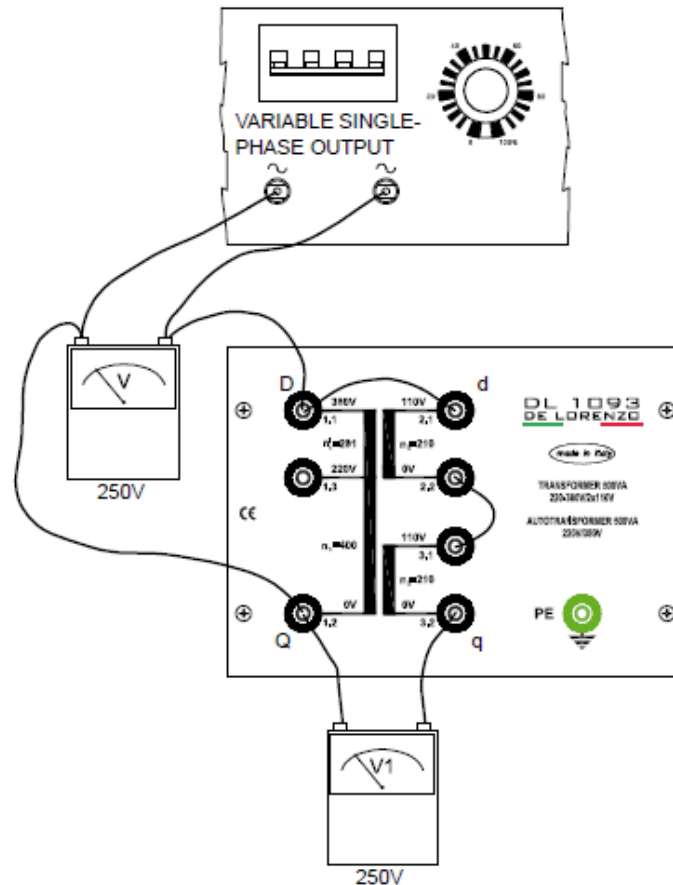


Figure 2.15: Polarity Test Wiring Diagram

Part 3: DC test

1. Connect the high voltage side of the transformer to a dc power source as shown in Figure 2.16.
2. Adjust the voltage source to a suitable voltage but avoid high currents.
3. Repeat the previous steps to measure the resistance of the low voltage winding.

Table 2.3: DC test readings

Winding	Ammeter Reading [A]	Voltmeter Reading [V]	$R_x$ [ $\Omega$ ]
High voltage side 380V			
Low voltage side 2 x 110V			



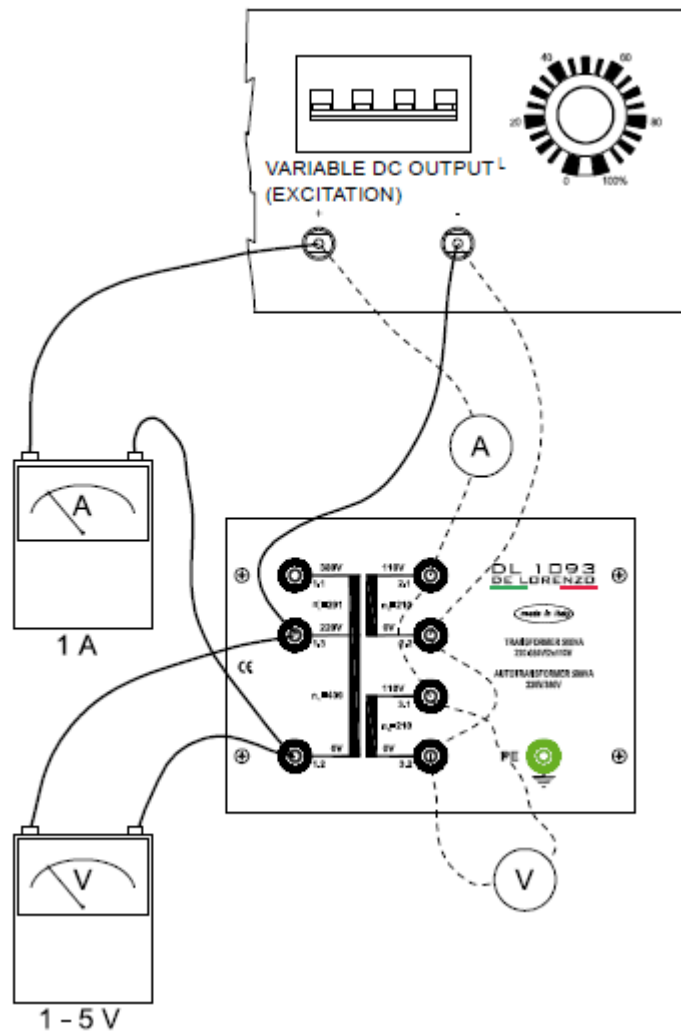


Figure 2.16: DC Test Circuit Wiring Diagram

Part 4: Open circuit test

1. Connect the circuit shown in Figure 2.17.
2. Apply the **rated voltage** to the **low voltage side** of the transformer.
3. Record the readings required in Table 2.4

Table 2.4: Open circuit test measurements and calculations.

Measured			Calculated		
$V_{in}$	$I_{in}$	$P_{in}$	PF	$R_c$	$X_M$
Rated voltage of the low voltage side					

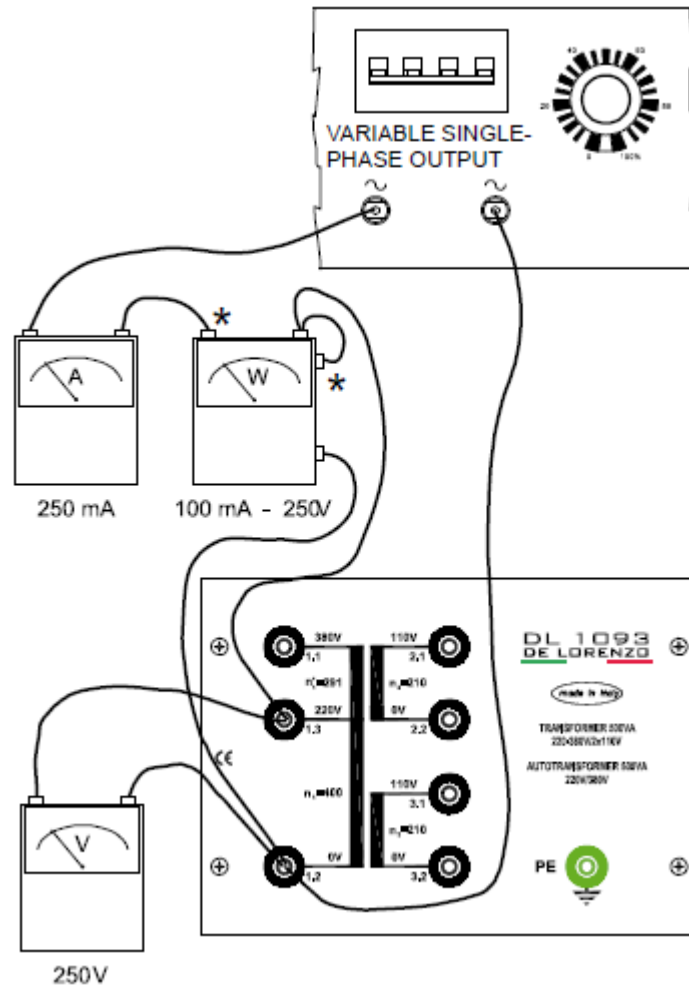


Figure 2.17: Open Circuit Test Schematic and Wiring Diagram

Part 5: Short circuit test

1. Connect the circuit shown in Figure 2.18.
2. Increase the supply voltage gradually from zero until rated current is measured in the high voltage side.
3. Record the readings in Table 2.5.

Table 2.5: Short Circuit Test Measurements and Calculations

Measured			Calculated		
$V_{in}$	$I_{in}$	$P_{in}$	PF	$R_{eq}$	$X_{eq}$
	Rated voltage of the high voltage side				

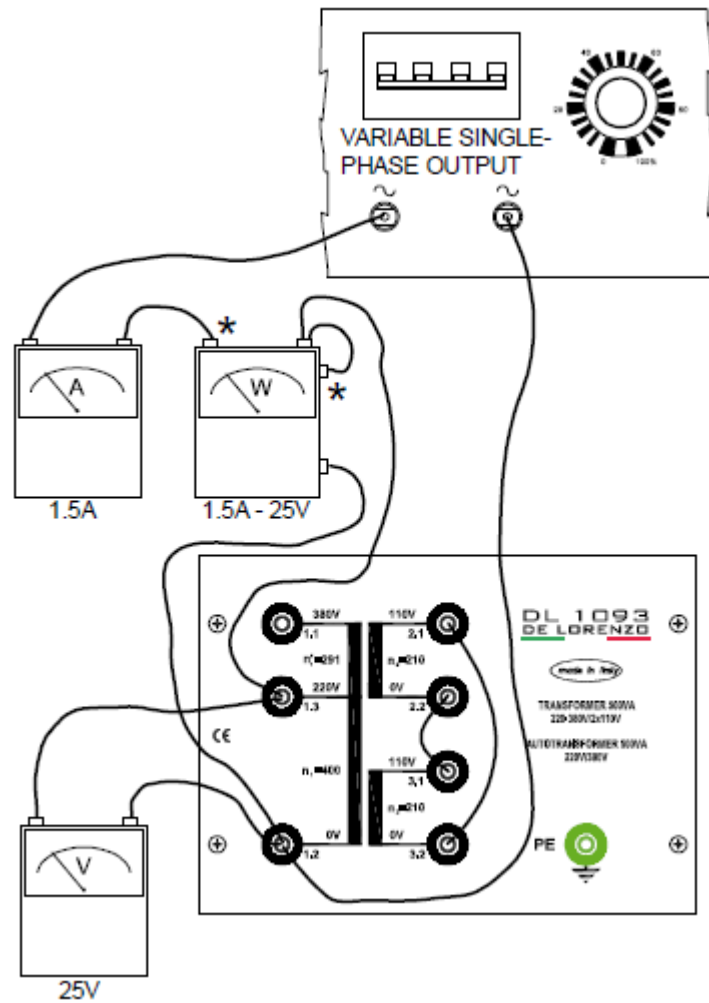


Figure 2.18: Short circuit test schematic circuit and wiring diagram

Part 6: Load test

1. Calculate the value of the protection resistance that must be inserted in the circuit shown in Figure 2.19.
2. Connect a resistive load to the transformer as shown in Figure 2.19.
3. Adjust the primary voltage to **its rated value**, and keep it constant during the test.
4. Slowly increase the load current by decreasing the ohmic value of the resistive load, and then complete Table 2.6.

Table 2.6: Load Test Results

$I_1$ - primary current[A]	$P_1$ -input power[W]	$V_2$ – load voltage[V]	$I_2$ – load current[A]	$P_2$ – output power[W]	$\eta$	Voltage Regulation

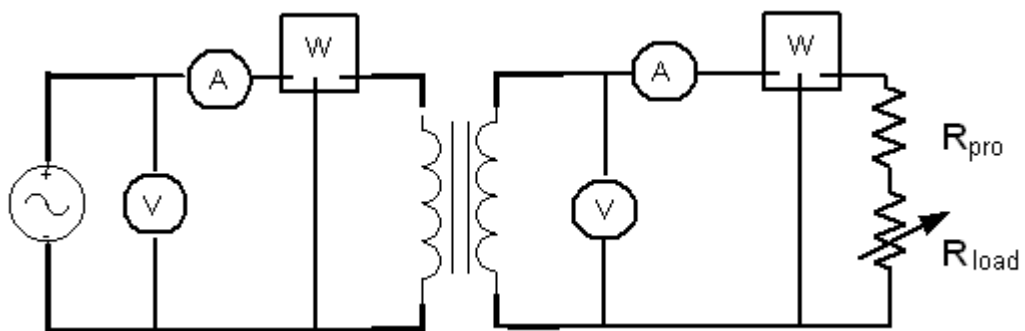


Figure 2.19: Load Test Schematic Circuit

**Discussion and Analysis:**

1. How does the transformer change the voltage from one level to another?
2. Does the transformer voltage ratio stay the same when a load is applied? Why?
3. Why does the wattmeter in the no-load test read the iron core losses only?
4. Plot the applied voltage versus IM and versus the no-load power. Comment on the curves.
5. Show sample of calculations for each of the following:

$$PF, I_{R_C}, I_{X_M}, R_C, X_M$$

6. Calculate the average value for  $R_C, X_M$  from the four cases in Table 2.1.
7. What losses are negligible in short-circuit test?
8. Why the open-circuit test is done in the low voltage side while the short-circuit test is done on the high voltage side?

9. What would happen to the transformer if rated voltage is applied to the winding during the short-circuit test?
10. Show sample of calculations for each of the following:  
$$PF, Z_{eq}, R_{eq}, X_{eq}$$
11. Calculate the average value for  $R_{eq}, X_{eq}$ .
12. Draw the equivalent circuit of the transformer (referred to the primary side) indicating the average values of the parameter  $R_{eq}, X_{eq}, R_C, X_M$  on the circuit.
13. Based on your calculations, does the PF changes as in the case of the open circuit test? Why?
14. What does the additive polarity mean in a transformer?
15. Explain the importance of polarity test in transformers.
16. Why is the protector resistor used in the experimental setup? How it was calculated?
17. Why does the transformer consume more current when it is loaded?
18. Calculate the voltage regulation ratio (VR) for the transformer. Show one sample of calculation

Given that

$$V_{\text{no-load}} = V_1 / a$$

19. Calculate the iron losses and the core losses for each of the above cases and show one sample of calculation.
20. Plot the load voltage versus the load current. Comment on the plot.
21. Plot the efficiency versus the load current. Comment on the plot.

### References:

- 1- <https://en.wikipedia.org/wiki/Transformer>
- 2- [http://homepages.uel.ac.uk/W.N.Bailey/BEng3\\_Projects/Images/open\\_cct\\_test.gif](http://homepages.uel.ac.uk/W.N.Bailey/BEng3_Projects/Images/open_cct_test.gif)

### Appendix 2.1

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The transformer efficiency can be written as

$$\eta = \frac{V_2 I_2 \cos \theta}{V_2 I_2 \cos \theta + P_{iron} + P_{cu}} \quad (2.32)$$

to find out the maximum efficiency when the load power factor and secondary voltage are constants, the first time derivative of efficiency is taken to the secondary current as

$$\frac{\partial \eta}{\partial I_2} = 0 \quad (2.33)$$

thus,

$$\frac{\partial \eta}{\partial I_2} = \frac{\partial}{\partial I_2} \left[ \frac{V_2 I_2 \cos \theta}{V_2 I_2 \cos \theta + I_2^2 R_{02} + P_{iron}} \right] \quad (2.34)$$

where  $R_{02} = R_{eq}$  referred to the secondary. Equation (2.34) can be re-written as

$$\frac{\partial \eta}{\partial I_2} = \frac{V_2 \cos \theta (V_2 I_2 \cos \theta + P_{iron} + I_2^2 R_{02}) - V_2 I_2 (V_2 I_2 \cos \theta + 2 I_2 R_{02})}{(V_2 I_2 \cos \theta + P_{iron} + I_2^2 R_{02})^2} \quad (2.35)$$

thus, when equation (2.32) is applied, the following expression is obtained

$$V_2 \cos \theta (V_2 I_2 \cos \theta + P_{iron} + I_2^2 R_{02}) - V_2 I_2 (V_2 I_2 \cos \theta + 2 I_2 R_{02}) = 0 \quad (2.36)$$

and then

$$P_{iron} = I_2^2 R_{02} = P_{cu} \quad (2.37)$$

## Experiment 3

# Shunt DC Motor

### Objectives:

- To determine the torque-speed and efficiency characteristic curves.
- To find out how to reverse the direction of rotation of a shunt dc motor.
- To study the behavior of a shunt dc motor speed when an armature voltage is altered.
- To study the behavior of a shunt dc motor speed when a resistor is inserted in the field resistance.
- To study the behavior of a shunt dc motor speed when a series resistor is inserted in the armature circuit.

### Apparatus:

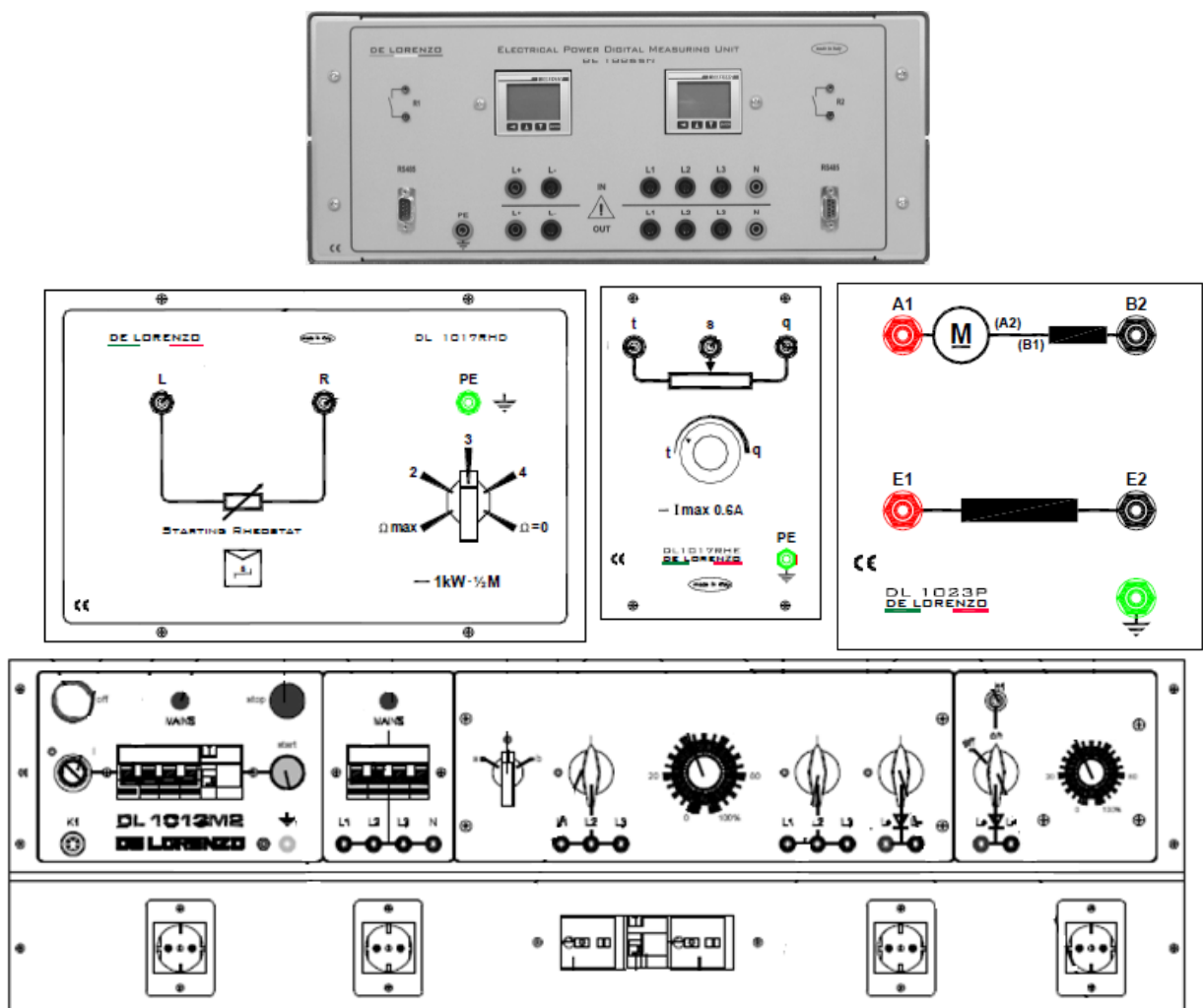


Figure 3.1: System Apparatus

**Theoretical Background:**

A shunt dc motor is essentially the same as a separately excited dc motor. The only difference is that a separately excited dc motor has its field circuit connected to an independent voltage supply (see Figure 3.1) while the shunt dc motor has its field circuit connected to the armature terminals of the motor (see Figure 3.2). If we assume that the supply voltage to the motor is constant, the principles of operation for the separately excited and shunt dc motors are the same.

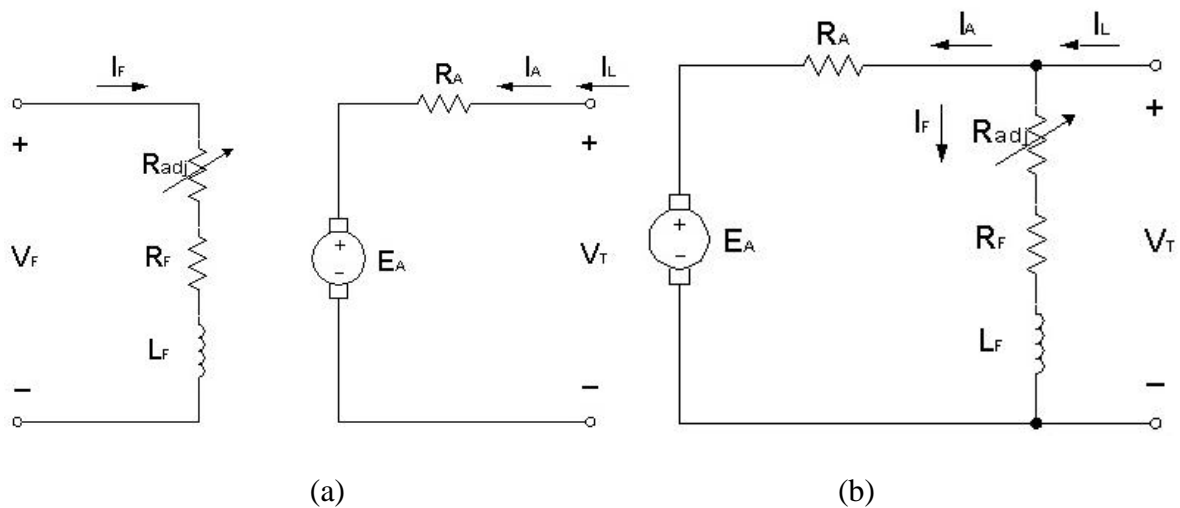


Figure 3.2: (a) Equivalent circuit of a separately excited dc motor (b) Equivalent circuit of a shunt dc motor

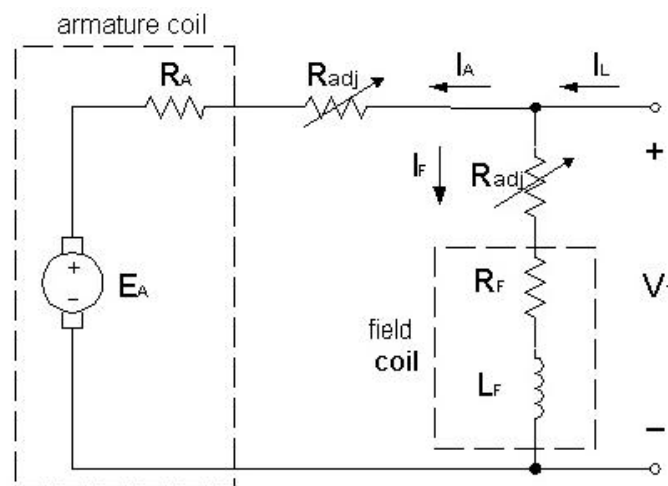


Figure 3.3: Equivalent Circuit of a Shunt Dc Motor With Inserted Armature and Field Resistors.

**The Terminal Characteristics of a Shunt DC Motor**

A terminal characteristic of a machine is a plot of the machine's output quantities versus each other. For a motor, the output quantities are shaft torque and speed, so the terminal characteristic of a motor is a plot of its output torque versus speed.



How does a shunt dc motor respond to a load? Suppose that the load on the shaft of a shunt dc motor is increased. Then the load torque  $\tau_{load}$  will exceed the induced torque  $\tau_{ind}$  in the machine, and the motor will start to slow down. When the motor slows down, its internal generated voltage drops  $E_A = K_E \phi \omega \downarrow$ , so the armature current in the motor  $I_A = (V_T - E_A \downarrow) / R_A$  increases. As the armature current rises, the induced torque in the motor increases  $\tau_{ind} = K_M \phi I_A \uparrow$ , and finally the induced torque will equal the load torque at a lower mechanical speed of rotation. The output characteristic of a shunt dc motor can be derived from the induced voltage and torque equations of the motor plus Kirchhoff's voltage law. The KVL equation for a shunt dc motor is

$$V_T = E_A + I_A R_A \quad (3.1)$$

The induced voltage  $E_A = K_E \phi \omega$ , so

$$V_T = K_E \phi \omega + I_A R_A \quad (3.2)$$

Since  $\tau_{ind} = K_M \phi I_A$ , current  $I_A$  can be expressed as

$$I_A = \frac{\tau_{ind}}{K_M \phi} \quad (3.3)$$

Combining Equations 3.2 and 3.3 produces

$$V_T = K_E \phi \omega + \frac{\tau_{ind}}{K_M \phi} R_A \quad (3.4)$$

Finally, solving for the motor's speed and assuming  $K_E = K_M$  yields

$$\omega = \frac{V_T}{K\phi} - \frac{R_A}{(K\phi)^2} \tau_{ind} \quad (3.5)$$

The equation is just a straight line with a negative slope. The resulting torque-speed characteristic for a shunt dc motor is shown in Figure 3.4.c.

It is important to realize that, in order for the speed of the motor to vary linearly with torque, the other terms in this expression must be constant as the load changes. The terminal voltage supplied by the dc power source is assumed to be constant. If it is not constant, then the voltage variation will affect the shape of the torque-speed curve.

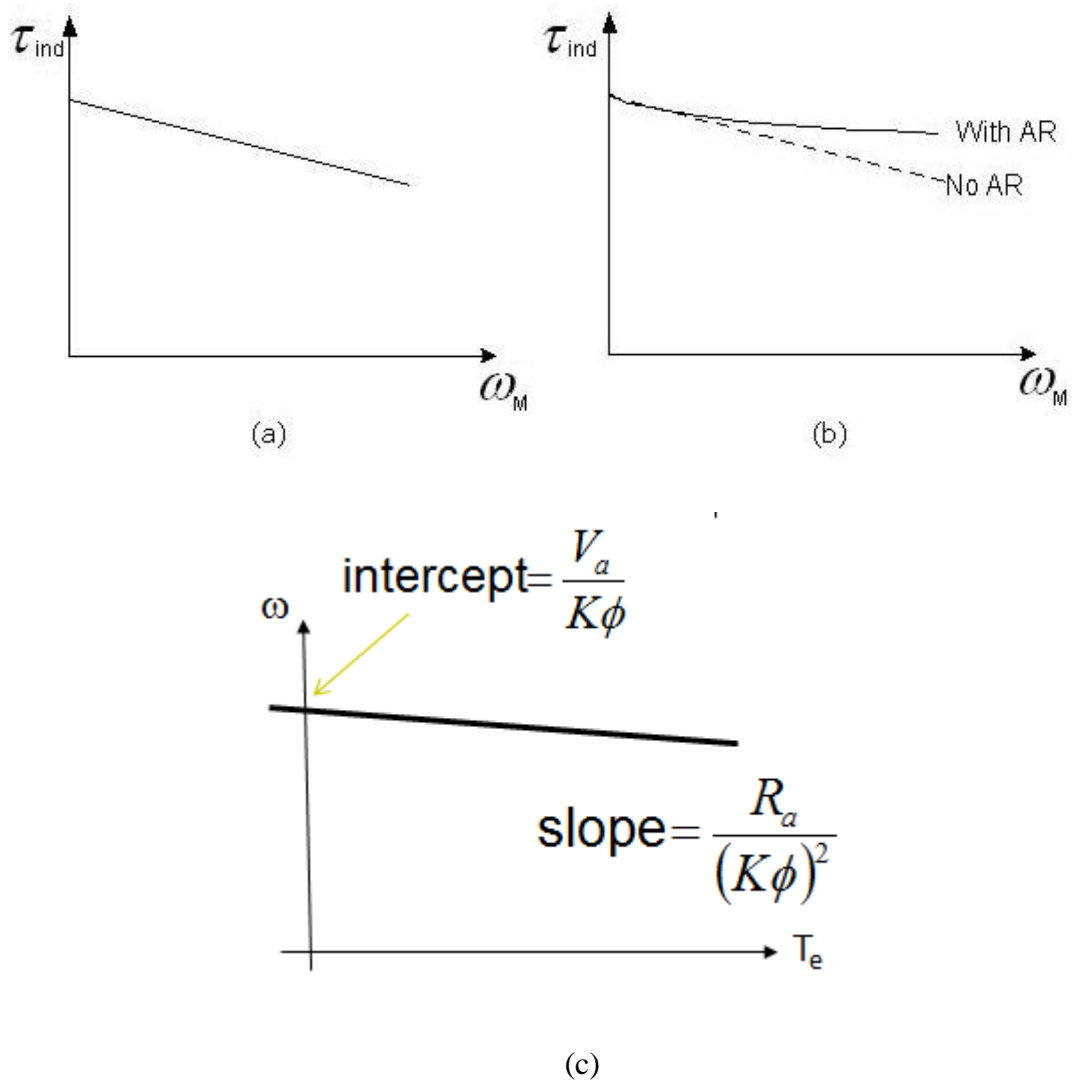


Figure 3.4: Torque-Speed Characteristics (a) Without Armature Reaction (b) With Armature Reaction.

Another effect internal to the motor that can also affect the shape of the torque-speed curve is armature reaction. If a motor has armature reaction, then as its load increases, the flux weakening effects reduce its flux. As Equation 3.5 shows, the effect of reduction in flux is to increase the motor's speed at any given load over the speed it would run at no-armature reaction. The torque-speed characteristic of a shunt dc motor with armature reaction is shown in Figure 3.4.b. if a motor has compensating windings, of course there will be no flux-weakening problems in the machine, and the flux in the machine will be constant.

If a shunt dc motor has compensating windings so that its flux is constant regardless of load, and the motor's speed and armature current are known at any one value of load, then it is possible to calculate its speed at any other value of load, as long as the armature current at that load is known or can be determined.

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. The relationships describing the input and output power of the motor are given by Equations 3.6 and 3.7.

$$P_{input} = V_t(I_a + I_f) \quad (3.6)$$

$$P_{output} = \frac{2\pi n}{60} \times \tau \quad (3.7)$$

### Shunt DC motor nameplate

The name plate of the shunt dc motor at our lab is shown in Figure 3.5.

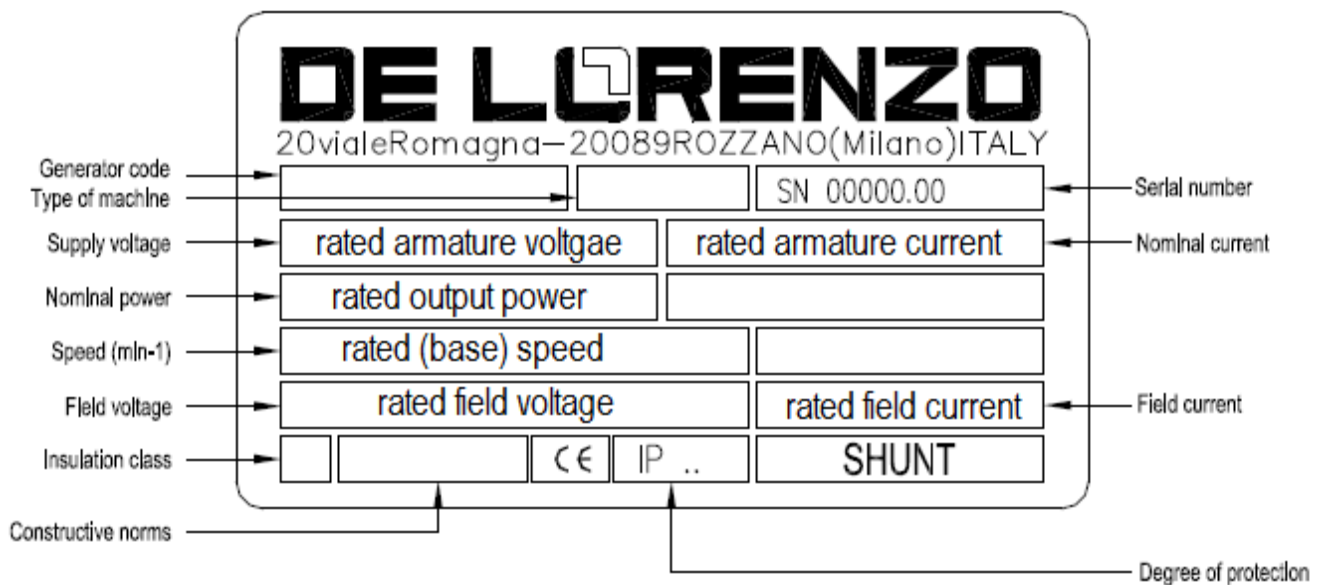


Figure 3.5: Shunt Dc Motor Name Plate

When applying the **rated terminal voltage**, a rated load of  $\tau_{rated}$  can be applied to the shaft that can run at speeds up to the base speed, this region is called the **constant torque region** where the load is constant and speed is controlled between zero till base speed. After the base speed is exceeded, the motor enters the **constant power region** where increasing the speed further means that the load on the shaft must be decreased (lighter loads should be mounted on the shaft) because further increase in the torque means increase in the current which means increase in the terminal voltage which is already on its rated value. The characteristics are shown by Figure 3.6.

$$\tau_{rated} = \frac{P_{rated}}{\omega_{rated}} \quad (3.8)$$

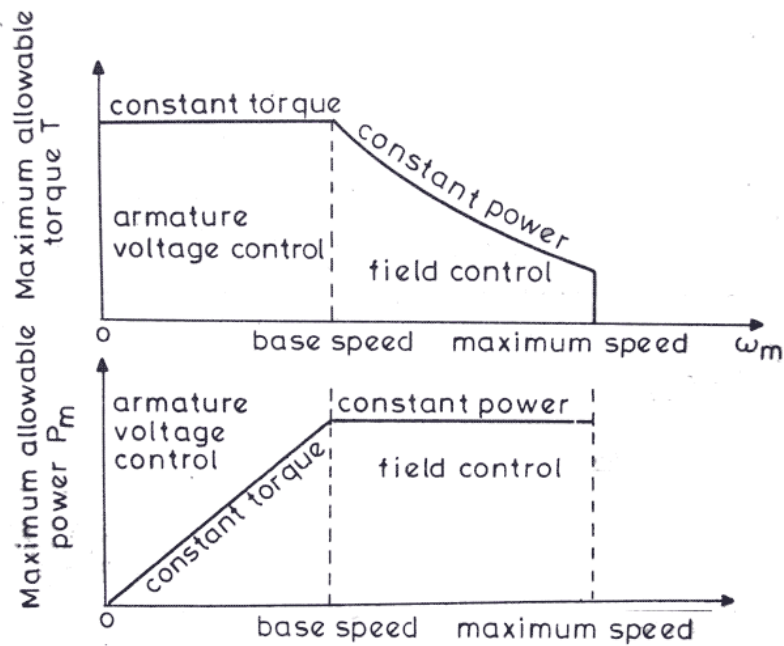


Figure 3.6: Motor Characteristics

Any torque higher than the rated torque will cause the shaft to stand still (get locked) and may break the shaft.

What is the maximum speed?

This speed is determined by the thermal capacity of the motor, determining what the maximum speed is and for how long the motor can run at this speed. It may be up to 30% of the maximum speed. Higher speeds cause the rotor to experience high centrifugal forces and the shaft can break apart.

### Speed Control of Shunt DC motors

Based on equation 3.5, there are three ways the speed of a shunt dc motor can be controlled:

1. Armature voltage  $V_a$ , as shown by Figure 3.7

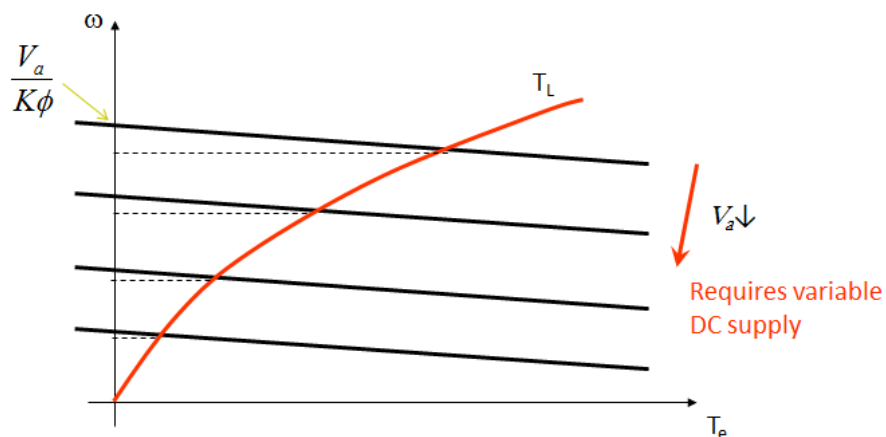


Figure 3.7: Armature Voltage- Controlled Shunt Dc Motor

**Advantages for the armature voltage method:**

- 1) Doesn't change speed regulation
- 2) Speed is controlled from zero till base speed

**Disadvantages for the armature voltage method:**

- 1) Cost is higher because of using power electronic controllers.
2. Field flux  $\phi$  (by changing field resistance  $R_f$ ), as shown by Figure 3.8

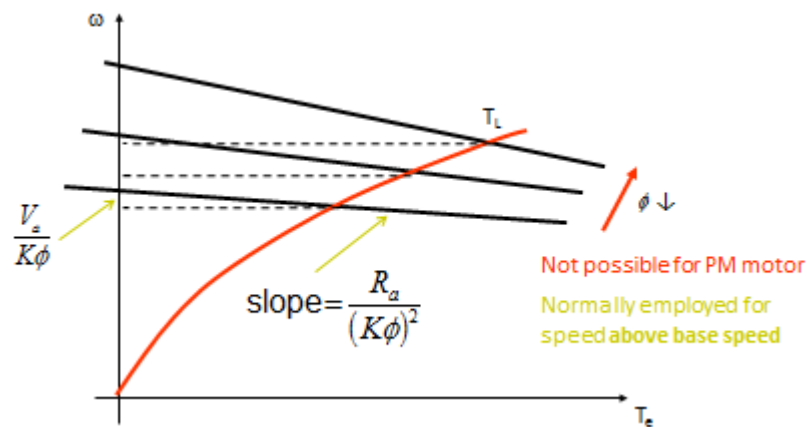


Figure 3.8: Flux- Controlled Shunt Dc Motor

**Advantages for flux control method:**

- 1) Speed control above base speed
- 2) The cost of rheostat is small because  $R_f$  has small value

**Disadvantages for flux control method:**

- 1) Speed regulation is poor
- 2) At high speeds flux is small thus causes the speed to become unstable
3. Armature resistance  $R_a$ , as shown by Figure 3.9

**Advantages for armature resistor method:**

- 1) Starting and speed control functions may be combined in one rheostat
- 2) The speed range begins at zero speed.
- 3) Cost is less for the same speed range than other methods.

4) Simple method

**Disadvantages for armature resistor method:**

- 1) Introduce power loss in rheostat thus low efficiency
- 2) Speed regulation is poor (causes difference between the loaded and unloaded cases.)

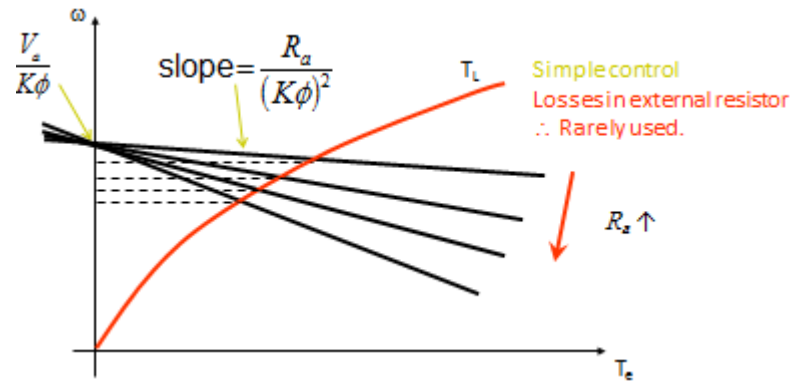


Figure 3.9: Armature Resistance- Controlled Shunt Dc Motor

The first two are commonly used, but the third is less common because it reduces the efficiency of the motor. Where the armature voltage method controls speeds below the base speed while the field method controls speeds above the base speed as shown by Figure 3.10.

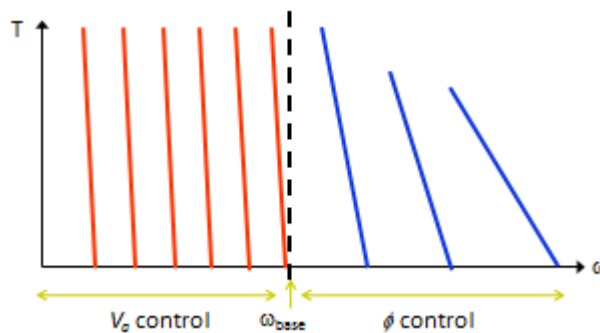


Figure 3.10: Speed Control Strategy

**Modes of Operation**

Modes of operation of a separately excited dc motor are shown by Figure 3.11.

**Reversal of Direction of rotation of Shunt DC motor**

To reverse the direction of rotation of the shunt dc motor, reverse the polarity of the armature circuit or reverse the polarity of the field circuit.

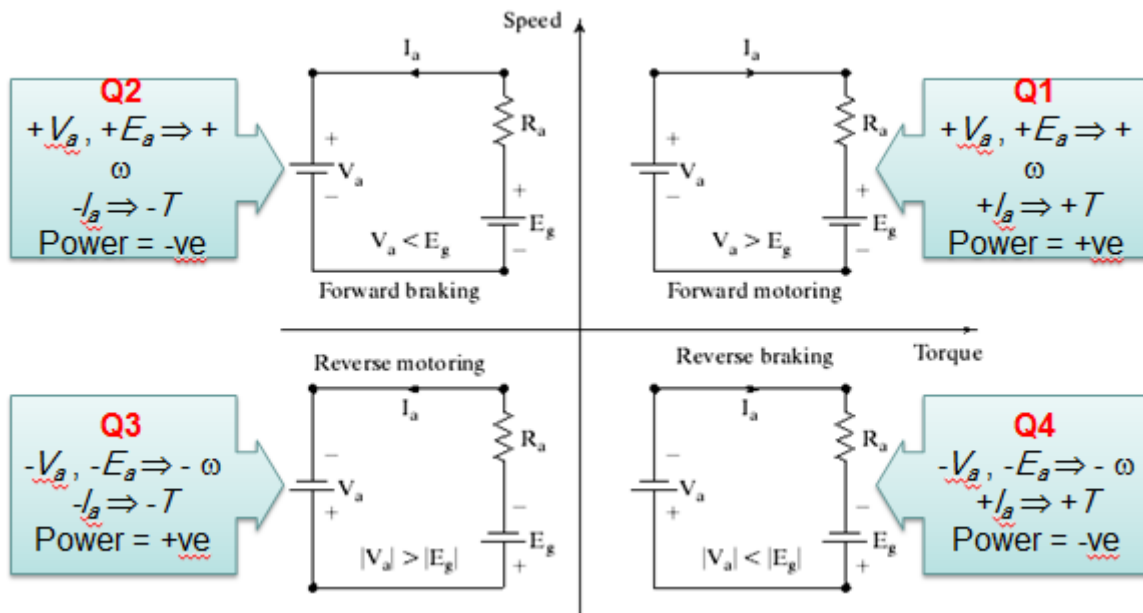


Figure 3.11: Modes of Operation of a Separately Excited Dc Motor

### Procedure:

Using the lab equipment in Figure 3.1, make the appropriate wiring and follow the procedure.

The connection that will be used through the experiment procedure is shown in Figure 3.12. A resistor is inserted in series with armature circuit for starting and speed control. Another resistor is inserted in series with the field circuit for speed control and to meet the ratings of the motor field circuit.

#### Part 1: Torque-Speed characteristics

1. Connect the circuit shown in Figure 3.3.c.
2. Set the inserted armature resistance to its maximum value.
3. Set the inserted field resistance to its proper value.
4. Switch on the variable dc voltage power supply and set the terminal voltage to 220 V.
5. Slowly turn off the inserted armature resistance and observe how the speed increases.
6. Change the motor load using the electromagnetic break so that its current does not exceed 0.5 A.
7. Complete Table 3.1.

Table 3.1: Torque-Speed Characteristics Data

$I_f$ [A]	$I_a$ [A]	$\tau$ [N.m]	$n$ [rpm]	$P_{in}$ [W]	$P_{out}$ [W]	$\eta$
0.28						

Part 2: Altering the Field Resistance

1. Set the inserted armature resistance to its maximum value.
2. Set the inserted field resistance to its proper value.
3. Set the terminal voltage to 220 V using the variable dc power supply.
4. Slowly turn off the inserted armature resistance.
5. Slowly increase the inserted field resistance to vary the field current such that it will be below the rated current. What do you note on the motor speed?
6. At a certain field resistor value, vary the motor's load using the electromagnetic break to obtain various armature current values. You can compare these results to the results obtained in part1.
7. Complete Table 3.2.

Table 3.2: Data for Speed Control of a Shunt Dc Motor Using Alternating Field Resistor

$I_f$ [A]	$I_a$ [A]	$\tau$ [N.m]	$n$ [rpm]	$P_{in}$ [W]	$P_{out}$ [W]	$\eta$

Part 3: Altering the Armature Voltage

1. Set the inserted armature resistance to its maximum value.
2. Set the inserted field resistance to its proper value.
3. Set the terminal voltage to 220 V using the variable dc power supply.
4. Slowly turn off the inserted armature resistance.
5. Decrease the terminal voltage (compensate for the field current using the inserted resistor). What do you note on the motor speed?



6. At a certain terminal voltage value, vary the motor's load using the electromagnetic break to obtain various armature current values. You can compare these results to the results obtained in part1.
7. Complete Table 3.3.

**Note:** You should maintain the value of the field current to 0.22 A (to maintain the value of the flux constant). You can do that by decreasing the inserted field resistance when the terminal voltage is decreased.

Table 3.3: Data for Speed Control of a Shunt Dc Motor Using Alternating Armature Voltage

$I_f$ [A]	$V_t$ [V]	$I_a$ [A]	$\tau$ [N.m]	$n$ [rpm]	$P_{in}$ [W]	$P_{out}$ [W]	$\eta$
0.22							

Part 4: Inserting a Series Resistor in the Armature Circuit

1. Set the inserted armature resistance to its maximum value.
2. Set the inserted field resistance to its proper value.
3. Set the terminal voltage to 220 V using the variable dc power supply.
4. Slowly decrease the inserted armature resistance. What do you note on the motor speed?
5. At a certain armature resistor value, vary the motor's load using the electromagnetic break to obtain various armature current values. You can compare these results to the results obtained in part1.
6. Complete Table 3.4.

Table 3.4: Data for Speed Control of a Shunt Dc Motor Using Alternating Armature Resistance

$I_f$ [A]	$R_a$ [ $\Omega$ ]	$I_a$ [A]	$\tau$ [N.m]	$n$ [rpm]	$P_{in}$ [W]	$P_{out}$ [W]	$\eta$
0.22							

Part 5: Reversal of direction of shunt motor

Follow the instruction of your lab supervisor to reverse the direction of motor.

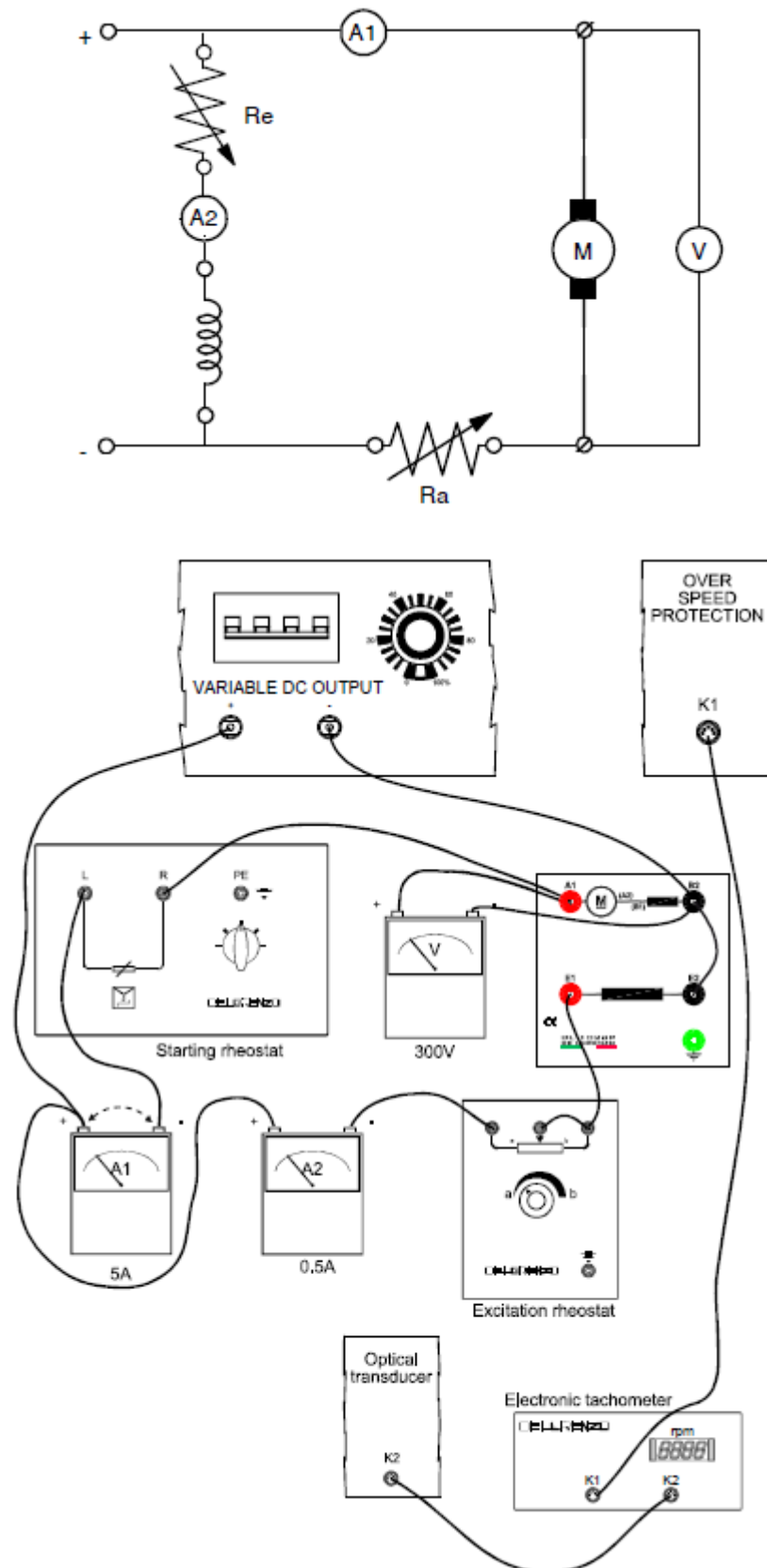


Figure 3.12: Schematic and wiring diagram for the shunt dc motor.

**Discussion and Analysis:**

1. Plot the motor speed versus torque for the two inserted armature resistance values on the same curve and use clear legend to point out each curve.. Explain the nature of the curve.
2. Plot the motor's efficiency versus armature current for each case on the same graph. Use clear legend to point out each curve. Explain the nature of the curve.
3. What happens to the motor speed when its inserted armature resistance is decreased?
4. Does the change of the inserted armature resistance have a great effect on the efficiency of the motor compared to its effect on speed? Why?
5. Show sample of calculation for each of the following quantities:

$P_{in}$ ,  $P_{out}$ ,  $\eta$ .

6. Why inserting a series resistor in the armature circuit ( $R_a$ ) is the most wasteful method of speed control.
7. Plot the motor speed versus torque for the two armature voltage values on the same curve and use clear legend to point out each curve. Explain the nature of the curve.
8. Plot the motor's efficiency versus armature current for each case on the same graph. Use clear legend to point out each curve. Explain the nature of the curve.
9. What happens to the motor speed when its armature voltage is decreased?
10. Does the change of the terminal voltage have a great effect on the efficiency of the motor compared to its effect on speed?
11. What is the advantage of using this type of speed control?
12. Plot the motor speed versus torque for the two field current values on the same curve and use clear legend to point out each curve. Explain the nature of the curve.
13. Plot the motor's efficiency versus armature current for each case on the same graph. Use clear legend to point out each curve. Explain the nature of the curves.
14. What happens to the motor speed when the inserted field resistance is decreased?
15. Does the change of the inserted field resistance have a great effect on the efficiency of the motor compared to its effect on speed?
16. What is the advantage of using this type of speed control? What is the disadvantage?
17. Plot speed versus torque curve. Explain the nature of the curve.

18. Plot torque versus armature current. Explain the nature of the curve.
19. Plot efficiency versus armature current. Explain the nature of the curve.
20. If the direction of the current through the field winding is changed, what would happen? Prove that using mathematical equations.
21. If the direction of the current through the armature winding is changed, what would happen? Prove that using mathematical equations.
22. If the direction of the current through both the armature and field windings is changed, what would happen? Explain why?
23. What wiring changes do you have to do in Figure 3.12 to reverse the direction of rotation of the motor shaft? Implement suggested changes and see what happens?
24. Show sample of calculation for  $P_{in}$ ,  $P_{out}$ , and  $\eta$ .

## Experiment 4

# Series DC Motor

### Objectives:

- To determine the torque-speed characteristic curve.
- To find out how to reverse the direction of rotation of a series dc motor.
- To control the speed of a loaded series dc motor by changing armature voltage.
- To control the speed of a loaded series dc motor by shunting the armature circuit.
- To control the speed of a loaded series dc motor by shunting the field circuit.

### Apparatus:

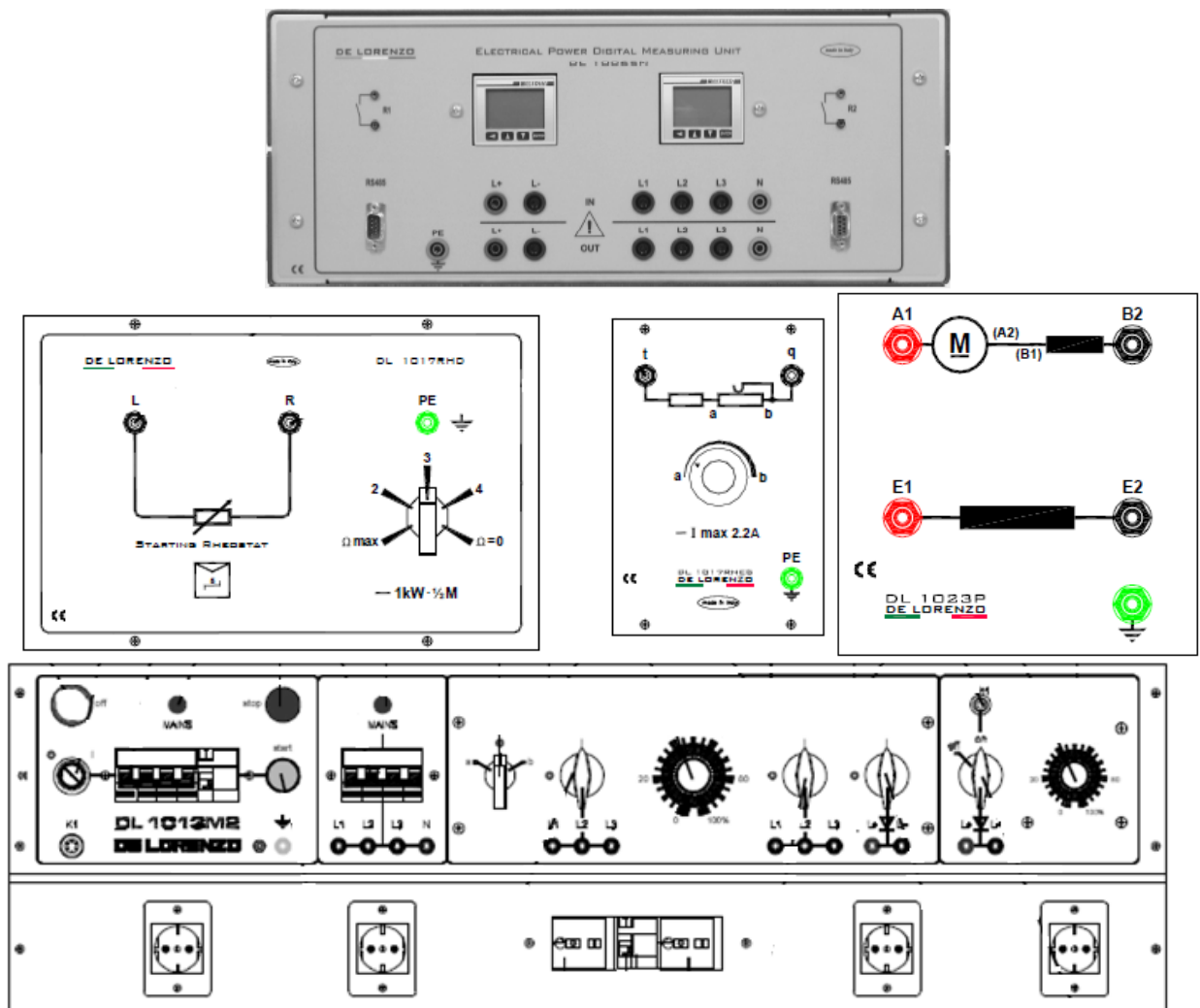


Figure 4.1: System Apparatus

**Theoretical Background:**

A series dc motor is a motor whose field windings consists of a relatively few turns connected in series with the armature circuit. The equivalent circuit for a series dc motor is shown in Figure 4.2.

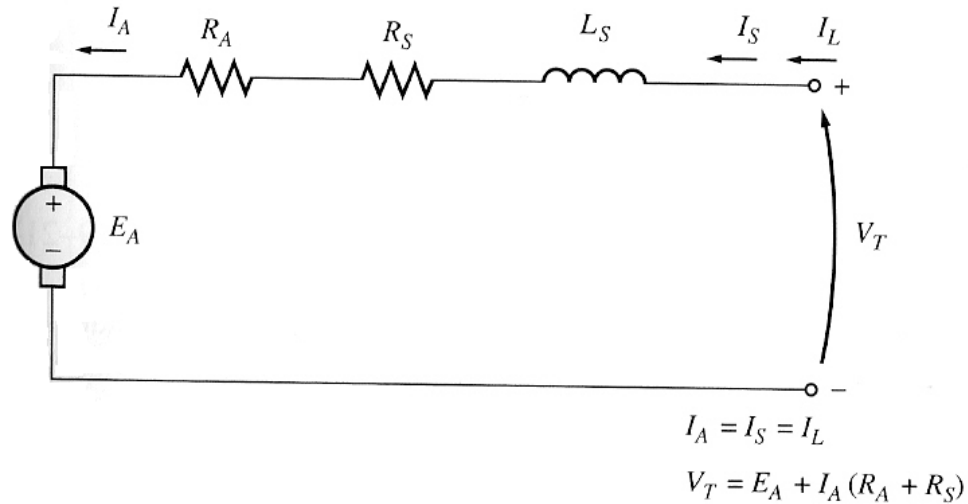


Figure 4.2: Equivalent Circuit of a Series Connected Dc Motor

In a series dc motor, the armature current, the field current, and the line current are all the same. The Kirchhoff's voltage law equation for this motor is

$$V_T = E_A + I_A(R_A + R_S) \tag{4.1}$$

**Induced Torque in a Series DC motor**

The terminal characteristics of a series dc motor is very different from that of the shunt dc motor. The basic behavior of a series dc motor is due to the fact that the flux is directly proportional to the armature current, at least until saturation is reached. As the load on the motor increases, its flux increases too. As seen earlier, an increase in the flux in the motor causes a decrease in its speed. The result is that a series dc motor has a sharply drooping torque-speed characteristic.

The induced torque in this machine is given by

$$\tau_{ind} = K_m \phi I_A \tag{4.2}$$

The flux in this machine is directly proportional to its armature current (at least until the metal saturation). Therefore, the flux in the machine can be given by

$$\phi = c I_A \tag{4.3}$$

Where  $c$  is a constant of proportionality. The induced torque in this machine is thus given by

$$\tau_{ind} = K_m \phi I_A \phi = K_m c I_A^2 \quad (4.4)$$

In other words, the torque in the motor is proportional to the square of its armature current. As a result of this relationship, it is easy to see that a series motor gives more torque per ampere than any other dc motor. It is therefore used in applications requiring very high torques. Examples of such applications are the starter motors in cars, elevator motors, and tractor motors in locomotives.

### The Terminal Characteristic of a Series DC Motor

To determine the terminal characteristic of a series dc motor, any analysis will be based on the assumption of linear magnetization curve, and then the effects of saturation will be considered in a graphical analysis. The assumption of a linear magnetization curve implies that the flux in the motor will be given equation 4.3 above. This equation will be used to derive the torque-speed characteristic curve for the series dc motor. The derivation of a series motor's torque-speed characteristic starts with Kirchhoff's voltage law:

$$V_T = E_A + I_A (R_A + R_S) \quad (4.5)$$

From equation 4.4, the armature current can be expressed as

$$I_A = \sqrt{\frac{\tau_{ind}}{K_m c}} \quad (4.6)$$

Also,  $E_A = K_b \phi \omega$ . Substituting these expressions in equation 4.1 yields

$$V_T = K_b \phi \omega + \sqrt{\frac{\tau_{ind}}{K_m c}} (R_A + R_S) \quad (4.7)$$

If the flux can be eliminated from this expression, it will directly relate the torque of a motor to its speed. To eliminate the flux from the expression, notice that

$$I_A = \frac{\phi}{c} \quad (4.8)$$

And the induced torque equation can be written as

$$\tau_{ind} = \frac{K_m}{c} \phi^2 \quad (4.9)$$

Therefore, the flux in the motor can be represented as

$$\phi = \sqrt{\frac{c}{K_m}} \sqrt{\tau_{ind}} \quad (4.10)$$

Substituting Equation 4.10 into equation 4.7, assuming  $K_m = K_b = K$  and solving for speed yields

$$\omega = \frac{V_T}{\sqrt{Kc}} \frac{1}{\sqrt{\tau_{ind}}} - \frac{R_A + R_S}{Kc} \quad (4.11)$$

Notice that for an unsaturated series dc motor, the speed of the motor varies as the reciprocal of the square root of the torque. That is quite an unusual relationship! This ideal torque-speed characteristic is plotted in Figure 4.3.

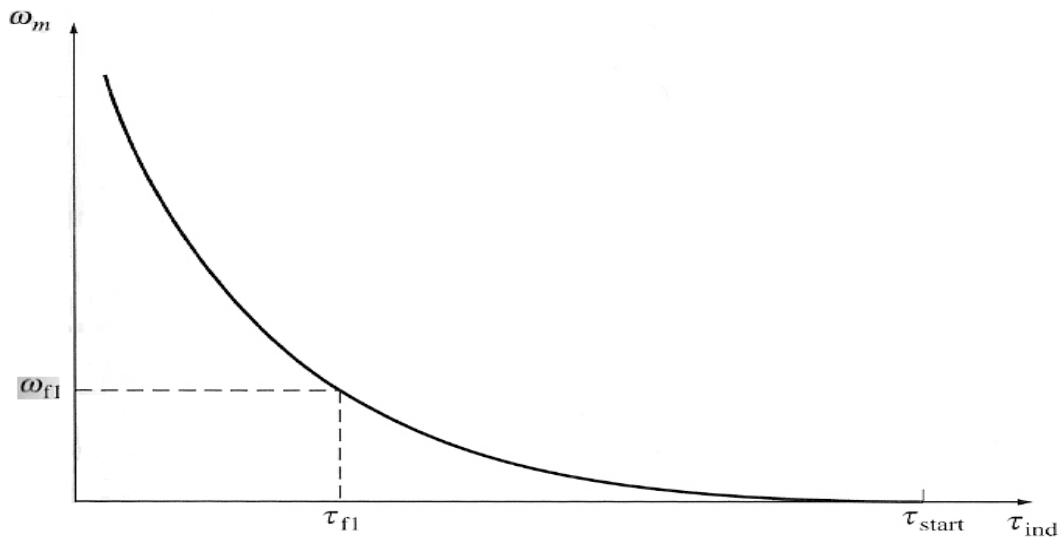


Figure 4.3: Torque-Speed Characteristic for a Series Dc Motor.

One disadvantage of the series motors can be seen immediately from Equation 4.11. When the torque on the motor goes to zero, its speed goes to infinity. In practice, the torque can never go entirely to zero because of the mechanical, core, and stray losses that must be overcome. However, if no other load is connected to the motor, it can turn fast enough to seriously damage itself. Never completely unload a series dc motor, and never connect one to a load by a belt or other mechanism that could break. If that were to happen and the motor were to become unloaded while running, the results could be serious.



### Series dc motor nameplate

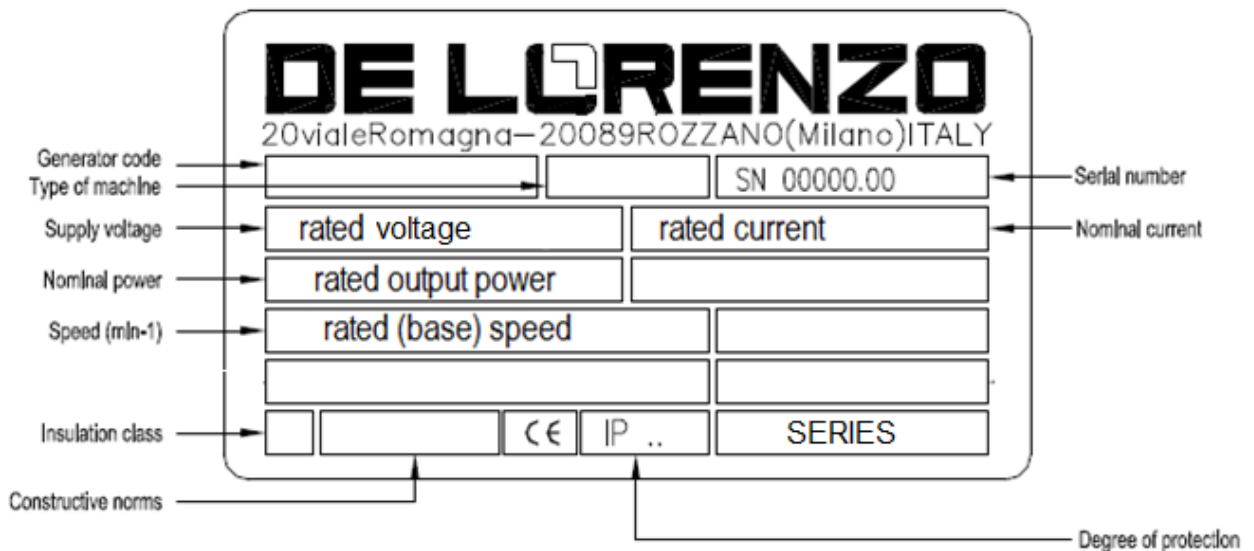


Figure 4.4: Series Dc Motor Name Plate

### Speed Control of Series DC Motors

Unlike with the shunt dc motor, there is only one efficient way to change the speed a series dc motor. That method is to change the terminal voltage of the motor. If the terminal voltage is increased, the first term in equation 4.10 is increased, resulting in a higher speed for any given torque. The speed of series dc motors can also be controlled by the insertion of a series resistor into the motor circuit, but this technique is very wasteful of power and is used only for intermittent periods during the start up of some motors.

#### 1. Flux Control Methods

- Field divertor

A veritable resistance is connected parallel to the series field as shown in Figure 4.5 (a). This variable resistor is called as divertor, as the desired amount of current can be diverted through this resistor and hence current through field coil can be decreased. Hence, flux can be decreased to the desired amount and speed can be increased above its previous values before the divertor. Further increase in the resistance means that the speed will decrease back to its previous value.

- Armature divertor

Divertor is connected across the armature as in Figure 4.5 (b). For a given constant load torque, if armature current is reduced then flux must increase. As,  $T_a \propto \Phi I_a$  This will result in an increase in current taken from the supply and hence flux  $\Phi$  will increase and subsequently speed of the motor will decrease.

### - Tapped field control

As shown in Figure 4.5 (c) field coil is tapped dividing number of turns. Thus we can select different value of  $\Phi$  by selecting different number of turns.

### - Paralleling field coils

In this method, several speeds can be obtained by regrouping coils as shown in Figure 4.5 (d).

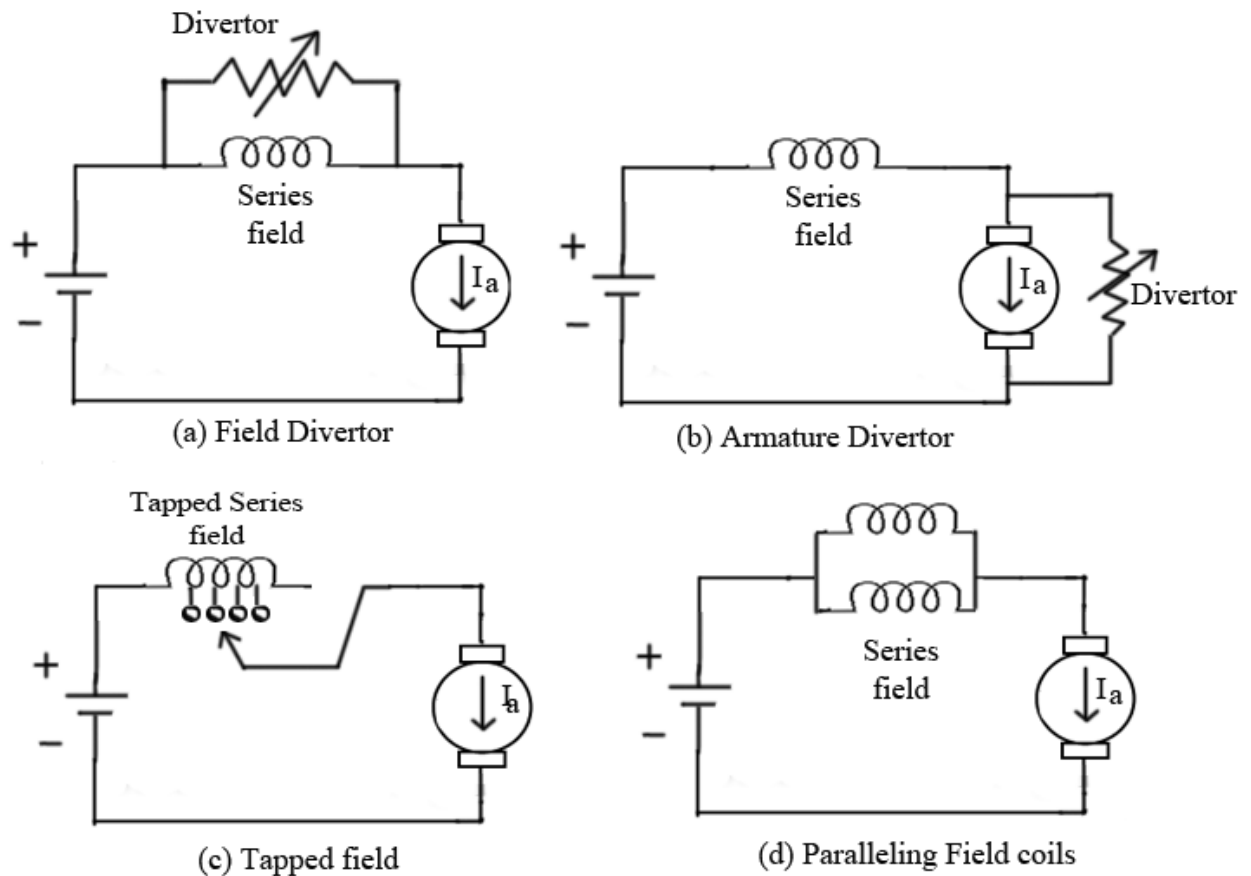


Figure 4.5: Field Control Methods

## 2. Variable Resistance in Series with Armature

By introducing a resistance in series with the armature, voltage across the armature can be reduced. And, hence, speed reduces in proportion with it.

## 3. Varying the armature voltage

Reducing voltage across the armature reduces speed in proportion with it.

**Procedure:**

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

**Part 1: Torque speed characteristics of series dc motor**

1. Connect the circuit shown in Figure 4.6
2. Connect the dc power supply to the electromagnetic break and increase the voltage till the break current reaches 0.15 A.
3. Set the inserted armature resistor to its maximum.
4. Switch on the variable dc voltage power supply and then set the terminal voltage to 220 V.
5. Slowly turn off the inserted armature resistance and observe the speed increases.
6. Change the motor load using the electromagnetic brake so that its current does not exceed 0.5 A or torque does not go below 2 N.m.
7. Complete Table 4.1.

Table 4.1: Series Motor Data.

$I_T$ [A]	$P_{in}$ [W]	$n$ [RPM]	$\tau$ [N.M]	$P_{out}$ [W]	$\eta$
$I_{rated}$					

**Part 2: Speed control by changing terminal voltage**

1. Connect the circuit shown in Figure 4.6
2. Connect the dc power supply to the electromagnetic break and increase the voltage till the break current reaches 0.15 A.
3. Set the inserted armature resistor to its maximum.
4. Switch on the variable dc voltage power supply and then set the terminal voltage to 220 V.
5. Slowly turn off the inserted armature resistance and observe the speed increases.
6. Decrease the terminal voltage.

7. For a certain value of the terminal voltage, change the motor load using the electromagnetic brake so that its current does not exceed 0.5 A or torque does not go below 2 N.m. Compare to the case in part 1.
8. Complete Table 4.2.

Table 4.2: Series Motor Data with Changing Terminal Voltage

$I_T$ [A]	$P_{in}$ [W]	$n$ [RPM]	$\tau$ [N.M]	$P_{out}$ [W]	$\eta$

**Part 3: Speed control by shunting the field circuit**

1. Connect the circuit shown in Figure 4.6, Add a resistor in parallel with the field circuit.
2. Connect the dc power supply to the electromagnetic break and increase the voltage till the break current reaches 0.15 A.
3. Set the inserted armature resistor to its maximum.
4. Switch on the variable dc voltage power supply and then set the terminal voltage to 220 V.
5. Slowly turn off the inserted armature resistance and observe the speed increases.
6. Change the value of the shunting resistor.
7. For a certain value of the field current, change the motor load using the electromagnetic brake so that its current does not exceed 0.5 A or torque does not go below 2 N.m. Compare to the case in part 1.
8. Complete Table 4.3.

Table 4.3: Series Motor Data with Shunting Field Resistor

$I_T$ [A]	$P_{in}$ [W]	$n$ [RPM]	$\tau$ [N.M]	$P_{out}$ [W]	$\eta$

**Part 4: Speed control by shunting the armature circuit**

1. Connect the circuit shown in Figure 4.6, add a resistor in parallel with the armature circuit.
2. Connect the dc power supply to the electromagnetic break and increase the voltage till the break current reaches 0.15 A.
3. Set the inserted armature resistor to its maximum.
4. Switch on the variable dc voltage power supply and then set the terminal voltage to 220 V.
5. Slowly turn off the inserted armature resistance and observe the speed increases.
6. Change the value of the shunting resistor.
7. For a certain value of the field current, change the motor load using the electromagnetic brake so that its current does not exceed 0.5 A or torque does not go below 2 N.m. Compare to the case in part 1.
8. Complete Table 4.4.

Table 4.4: Series Motor Data with a Shunting Armature Resistor

$I_T$ [A]	$P_{in}$ [W]	$n$ [RPM]	$\tau$ [N.M]	$P_{out}$ [W]	$\eta$

**Part 5: Reversal of direction of series dc motor**

Follow the instructions of your lab supervisor in order to reverse the direction of rotation of motor.

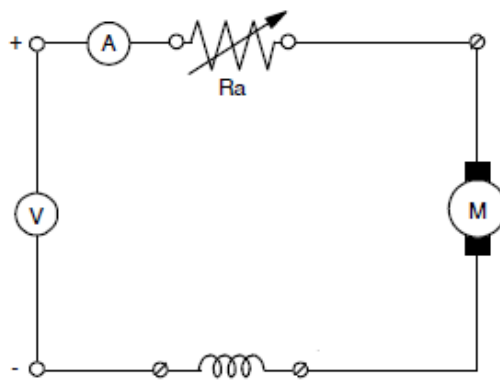


Figure 4.6: Series Motor Schematic Diagram.

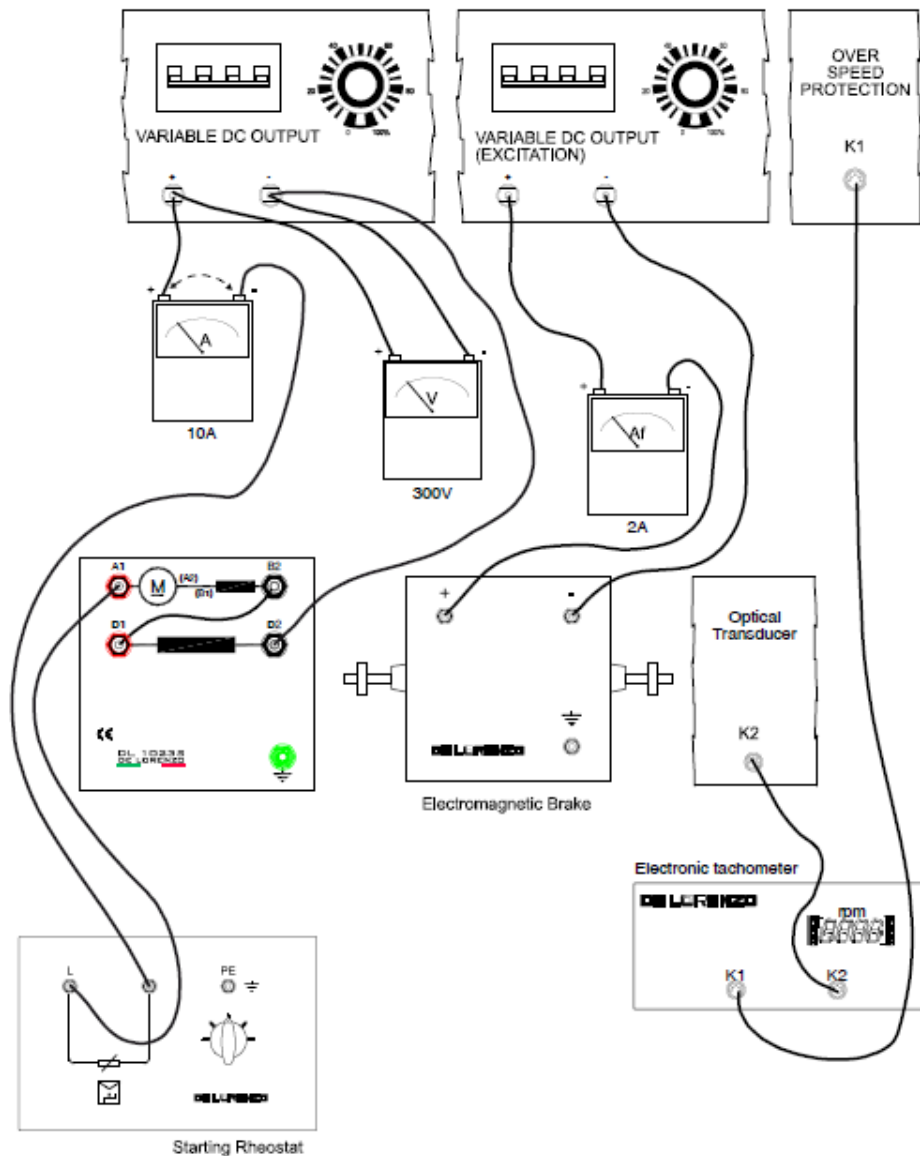


Figure 4.7: Series Motor Wiring Diagram.

**Discussion and Analysis:**

1. Plot speed–torque characteristic curve from Table 4.1. Explain the nature of the curve.
2. Plot the motor efficiency versus the load current. Explain the nature of the curve.
3. Plot torque versus armature current curve. Explain the nature of the curve.
4. If the direction of the current through the field winding is changed, what would happen?
5. If the direction of the current through the armature winding is changed, what would happen?
6. If the direction of the current through both the armature and field windings is changed, what would happen? Explain why?

7. What wiring changes do you have to do in Figure 4.6 to reverse the direction of rotation of the motor shaft? Implement suggested changes and see what happens?
8. Show sample of calculation for  $P_{in}$ ,  $P_{out}$ , and  $\eta$ .
9. Plot the speed versus voltage curve. Explain the nature of the curve.
10. Plot the efficiency versus voltage curve. Explain the nature of the curve.
11. From the plots in question 9 and 10, how the speed range compares to the efficiency range while varying the armature voltage. Use the following equation to calculate the efficiency and the speed ranges:

$$n_{range} = \frac{n_{max} - n_{min}}{n_{max}}, \quad \eta_{range} = \frac{\eta_{max} - \eta_{min}}{\eta_{max}}$$

12. Is this method used to control the speed of the motor above or below the base speed (rated speed specified on the motor tag)?
13. Plot the speed versus armature current curve. Explain the nature of the curve.
14. Plot the efficiency versus armature current curve. Explain the nature of the curve.
15. From the plots in question 13 and 14, how the speed range compares to the efficiency range while varying the parallel armature resistor value.
16. Is this method used to control the speed of the motor above or below the base speed?
17. Plot the speed versus field current curve. Explain the nature of the curve.
18. Plot the efficiency versus field current curve. Explain the nature of the curve.
19. From the plots in question 17 and 18, how the speed range compares to the efficiency range while varying the parallel field resistor value.
20. Is this method used to control the speed of the motor above or below the base speed?
21. Compare the range of change of speed with the range of efficiencies from the plots you have made for each of the three speed control method. What can you conclude from the results?
22. If a resistor was inserted in series with armature circuit, do you expect it to control the speed above or below the base speed.

## References

1. <http://www.electricaleasy.com/2014/01/speed-control-methods-of-dc-motor.html>

## Experiment 5 Three-Phase Induction Motor

### Objectives:

- To determine the parameter values of the equivalent circuit of a three-phase induction motor.
- To determine the speed-torque characteristics three-phase induction motor.
- To know how to reverse the direction of rotation of a three-phase induction motor.

### Apparatus:

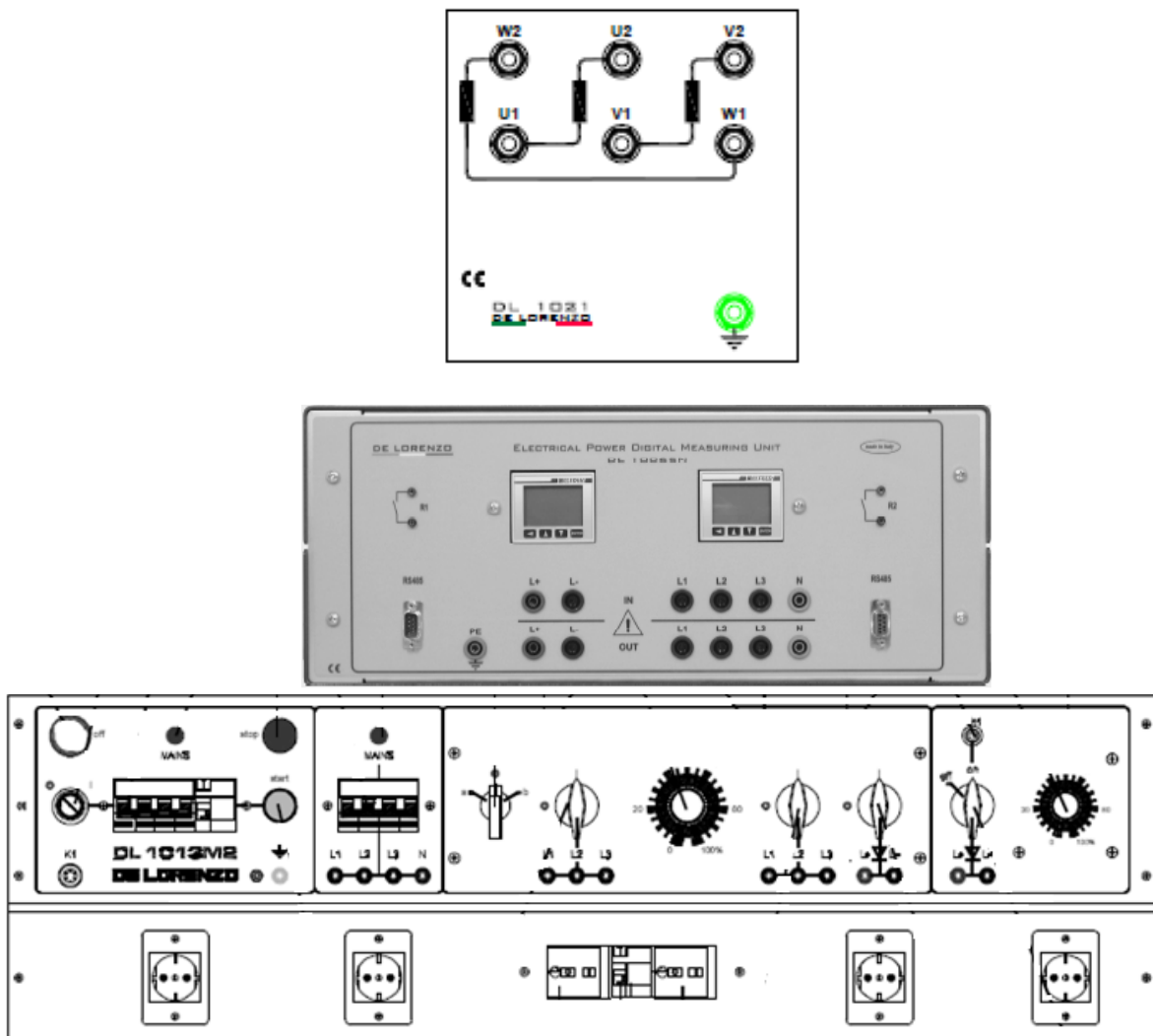


Figure 5.1: System Apparatus



### Theoretical Background:

The three phase induction motor essentially consists of two parts: stator and rotor. The stator is always connected to a three phase power supply. Due to the phase shift of  $120^\circ$  between each successive phases, a rotating magnetic field is produced and its speed is governed by the following expression

$$n_{sync} = \frac{120f}{P} \quad (5.1)$$

Where  $f$  is the system frequency,  $P$  is the number of poles and  $n_{sync}$  is the speed of the magnetic field's rotation.

The produced rotating magnetic field passes over the rotor bars and induces a voltage in them and that's why this machine is called an induction motor.

There are two different types of induction motor rotors *which can be placed inside the stator*. One is called a *squirrel-cage rotor* or simply a *cage rotor*, while the other is called a *wound rotor*.

A squirrel-cage induction motor rotor consists of a series of conducting bars laid into slots carved in the face of the rotor and shorted at either end by large shorting rings. A wound rotor has a complete set of three-phase windings that are mirror images of the windings on the stator. The three phases of the rotor windings are usually Y-connected, and the ends of the three rotor wires are tied to slip rings on the rotor's shaft. The rotor windings are shorted through brushes riding on the slip rings. Wound rotor induction motors therefore have their rotor currents accessible at the stator brushes, where that can be examined and where extra resistance can be inserted into the rotor circuit.

### The Concept of Rotor Slip

The voltage induced in a rotor bar of an induction motor depends on the speed of the rotor relative to the magnetic fields. Since the behavior of an induction motor depends on the rotor's voltage and current, it is often more logical to talk about this relative speed. Two terms are commonly used to define the relative motion of the rotor and the magnetic fields. One of them is slip speed. Slip speed is defined as the difference between synchronous speed and rotor speed:

$$n_{slip} = n_{sync} - n_m \quad (5.2)$$

where

$n_{slip}$  = slip speed of the motor

$n_{sync}$  = speed of magnetic fields

$n_m$  = mechanical shaft speed of rotor

The other term used to describe the relative motion is slip. Slip is the relative speed expressed on a per-unit or a percent basis. That is, slip is defined as

$$s = \frac{n_{slip}}{n_{sync}} \times 100\% \quad (5.3)$$

$$s = \frac{n_{sync} - n_m}{n_{sync}} \times 100\% \quad (5.4)$$

This equation can also be expressed in terms of angular velocity  $\omega$  (radians per second) as

$$s = \frac{\omega_{sync} - \omega_m}{\omega_{sync}} \times 100\% \quad (5.5)$$

Notice that, if the rotor turns at synchronous speed,  $s = 0$ , while if the rotor is stationary,  $s = 1$ . All normal motor speeds fall somewhere between those two limits. It is possible to express the mechanical speed of the rotor shaft in terms of synchronous speed and slip. Solving equations 5.4 and 5.5 for mechanical speed yields

$$n_m = (1 - s)n_{sync} \quad (5.6)$$

or

$$\omega_m = (1 - s)\omega_{sync} \quad (5.7)$$

These equations are useful in the derivation of induction motor torque and power relationships.

### The Electrical Frequency on the rotor

An induction motor works by inducing voltages and currents in the rotor of the machine, and for that reason has sometimes been called a rotating transformer. Like a transformer, the primary (stator) induces a voltage in the secondary (rotor), but unlike a transformer, the secondary frequency is not necessarily the same as the primary frequency.

If the rotor of a motor is locked so that it can not move, then the rotor will have the same frequency as the stator. On the other hand, if the rotor turns at synchronous speed, the frequency on the rotor will be zero. What will the rotor frequency be for any arbitrary rate of rotor rotation?

At  $n_m = 0$  rev/min, the rotor frequency  $f_r = f_e$  and the slip  $s = 1$ . At  $n_m = n_{sync}$ , the rotor frequency  $f_r = 0$  Hz and the slip  $s = 0$ . For any speed in between,

$$f_r = sf_e \quad (5.8)$$

An induction motor may be operated in one of two configurations: delta or star connections as shown in Figure 5.2 and 5.3 respectively.

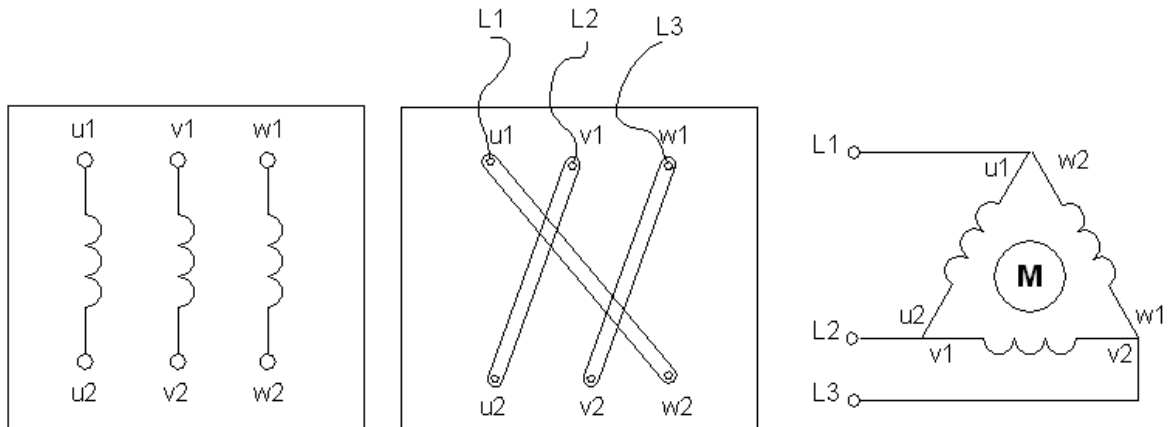


Figure 5.2: Delta Connection.

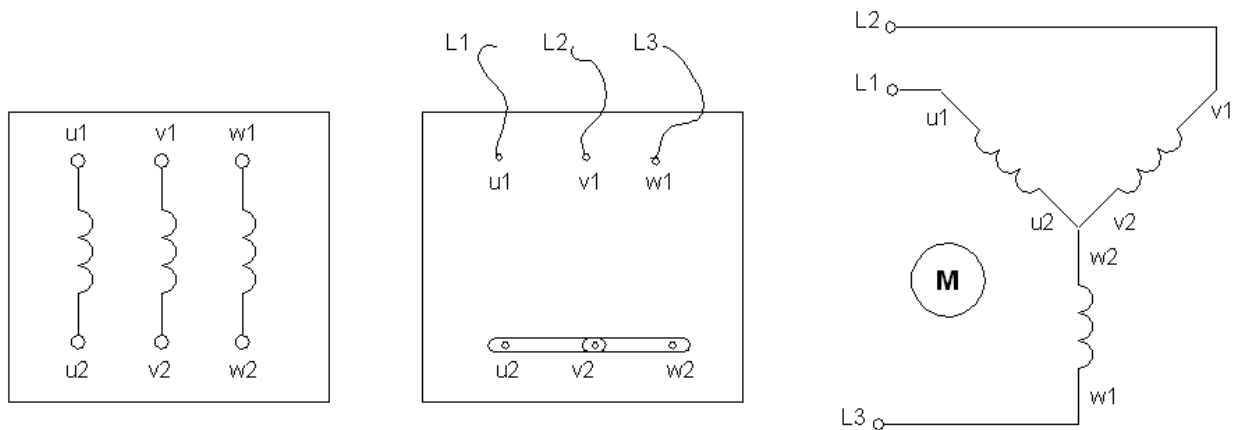


Figure 5.3: Star Connection.

The three phase induction motor per-phase equivalent circuit shown in Figure 5.4 **models the losses** that occurs in the induction motor:

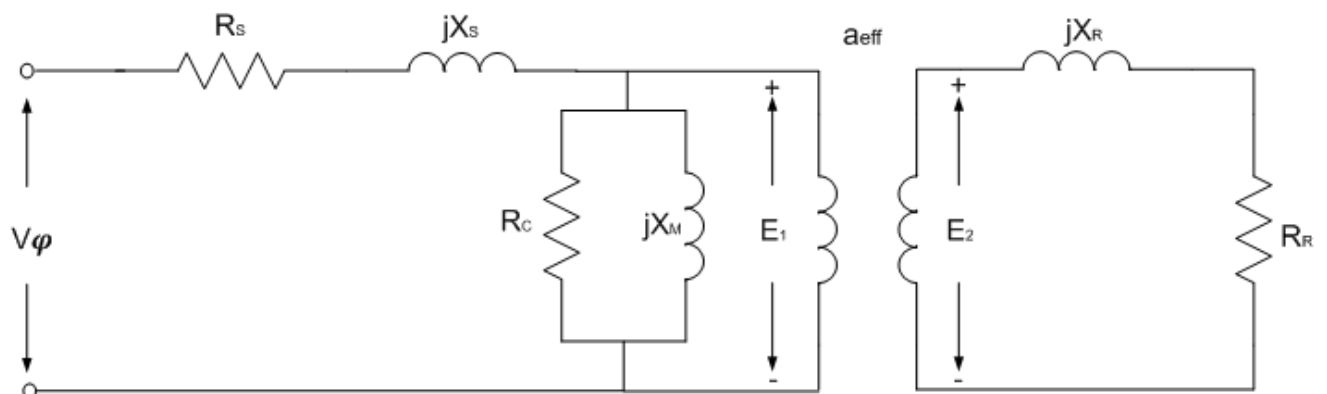


Figure 5.4: Three Phase Induction Motor Per-Phase Equivalent Circuit.

### Torque speed characteristics

Based on the per-phase equivalent circuit, the equation relating the torque produced by the motor and its rotating speed can be derived and is given by:

$$\tau = KsE_2^2 \frac{R_2}{\sqrt{R_2^2 + (sX_2)^2}}, K = \frac{3}{2\pi m_s} \quad (5.9)$$

Figure 5.4 shows the curve of the torque speed characteristics in its operation modes.

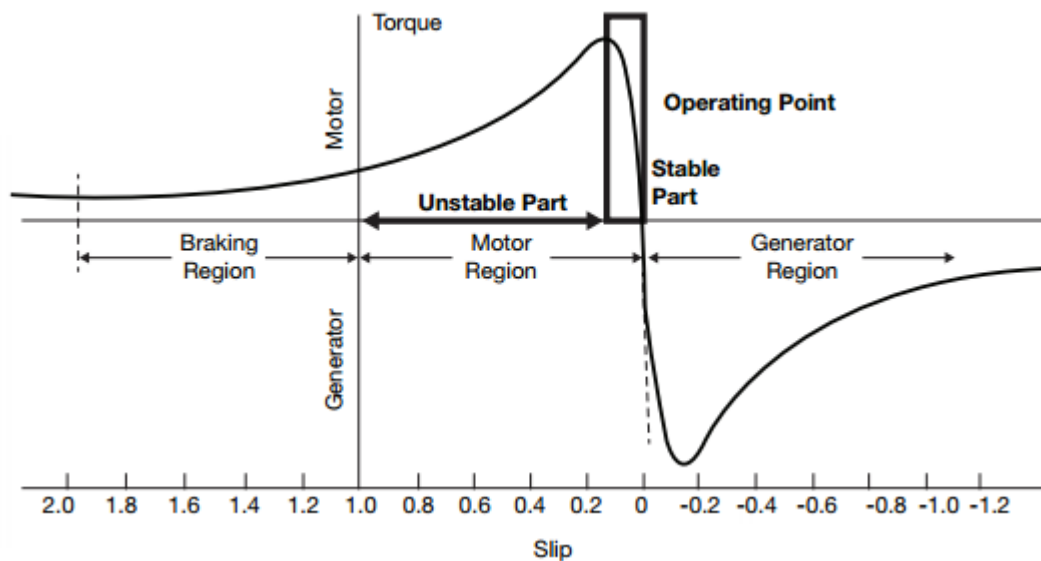


Figure 5.4: Torque Speed Characteristics and Regions of Operation

### Operating Regions

The torque-speed curve breaks down into three operating regions:

1. Braking,  $n_m < 0, s > 1$

Torque is positive whilst speed is negative. If the power converted is negative (from  $P = \tau\omega$ ) then the airgap power is positive. i.e. the power is flowing from the stator to the rotor and also into the rotor from the mechanical system. This operation is also called *plugging*.

This mode of operation can be used to quickly stop a machine. If a motor is travelling forwards it can be stopped by interchanging the connections to two of the three phases. Switching two phases has the result of changing the direction of motion of the stator magnetic field, effectively putting the machine into braking mode in the opposite direction.

2. Motoring,  $0 < n_m < n_s, 0 < s < 1$

Torque and motion are in the same direction. This is the most common mode of operation.

### 3. Generating, $n_m > n_s$ , $s < 0$

In this mode, again torque is positive whilst speed is negative. However, unlike plugging, if the power converted is negative, so is the air gap power. In this case, power flows from the mechanical system, to the rotor circuit, then across the air gap to the stator circuit and external electrical system.

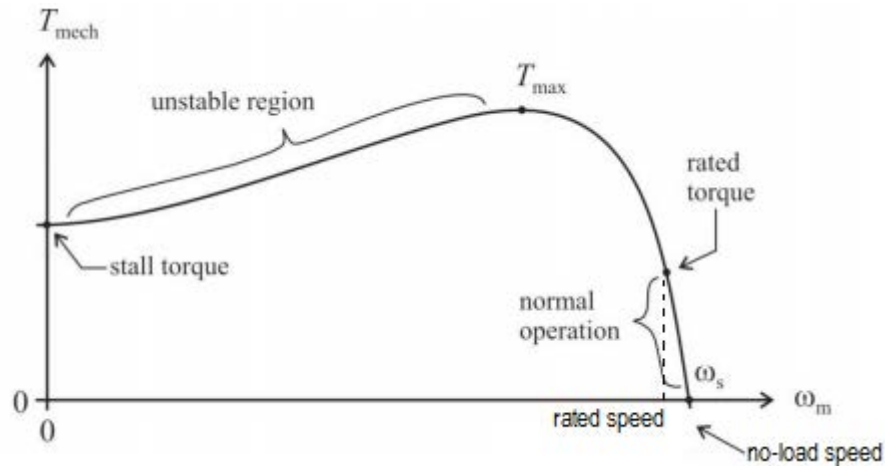


Figure 5.6: Torque Speed Characteristics of Three Phase Induction Motor in the Motoring Mode

With no mechanical load, the induction motor operates at synchronous speed. In practice, there will be some load due to bearing and load friction. As the load on the machine is increased, the machine slows down; at first operating the normal operation region shown in Figure 5.6. If the motor is overloaded, it will reach a maximum torque that the machine is capable of producing. When the motor is loaded beyond this, the slope of the torque characteristic changes and the motor provides less torque when speed is reduced. For most mechanical loads, this is an unstable operating mode and the motor speed will decrease to zero. This point is labeled as the stall torque in Figure 5.6. Incidentally, this is also the amount of torque the machine has available at starting.

### Induction motor tests

Three tests are used to determine the perimeters of the induction motor model.

#### 1) DC Test

This test is carried out in the laboratory by applying a variable dc voltage to two terminals of the stator winding as shown in Figure 5.7. The dc voltage should be increased so that the current flowing in the stator winding reaches the rated current (but not exceeding it) of the induction machine in an attempt to heat the winding to the same temperature they would have during normal operation. Because the current flowing is a dc current, there will be no induced voltage in the rotor circuit and the stator reactance will behave as a short circuit. Therefore, the only quantity limiting current flow in the machine is the stator internal resistance, which can be determined using Ohm's law as follows

For delta connection:

$$R_s = \frac{3}{2} \times \frac{V_{DC}}{I_{DC}} \quad (5.10)$$

For star connection:

$$R_s = \frac{1}{2} \times \frac{V_{DC}}{I_{DC}} \quad (5.11)$$

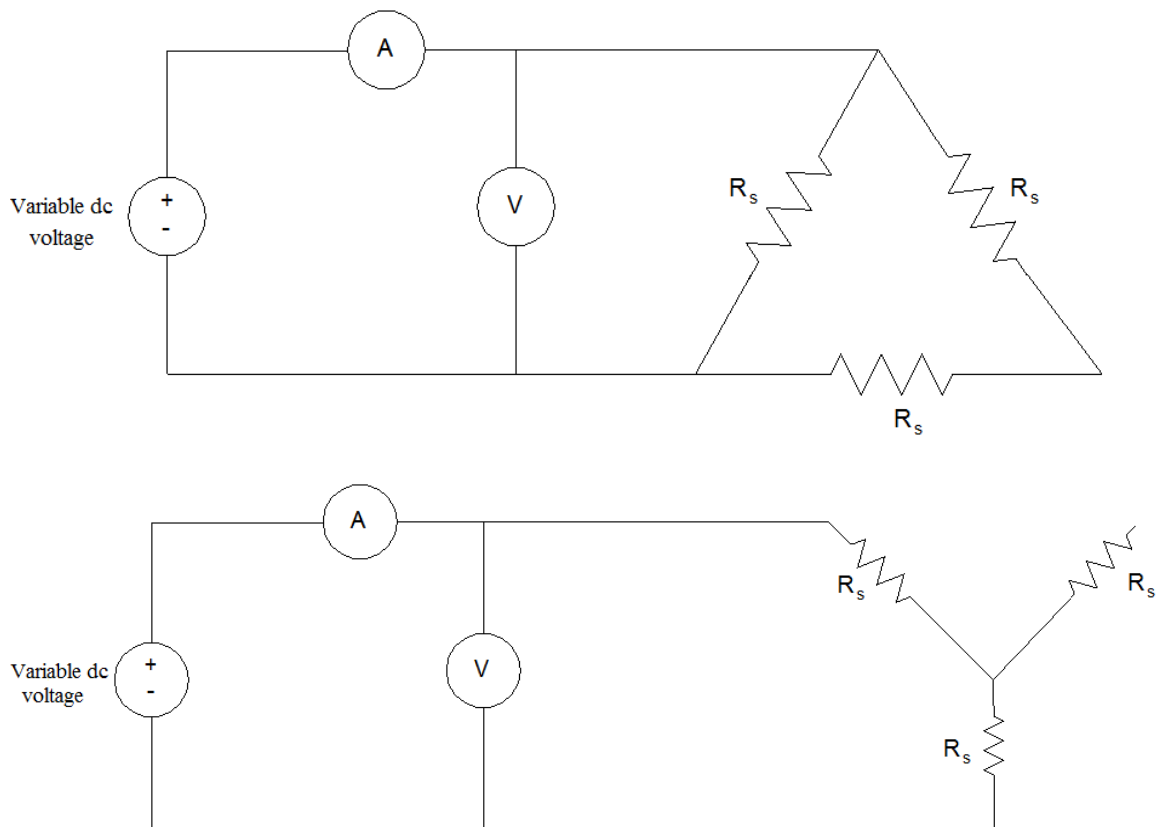


Figure 5.7: Circuit Configurations For The Dc Test.

## 2) No Load Test

During this test, the induction machine is operated as a motor and is run at synchronous speed (slip  $\rightarrow 0$ ). Therefore, all input power to the motor will be consumed as losses: stator copper losses ( $I_\phi^2 R_s$ ), core losses and mechanical rotational losses (friction and windage losses). Because the slip is too small, the rotor impedance becomes too high compared to the parallel impedance ( $Z_p = R_c // jX_M$ ) and hence no current will flow in the rotor impedance. In addition, the resistance  $R_c$  can be neglected because it is much greater than  $X_M$ . The equivalent circuit for this test is shown in Figure 5.8. **This test is carried out with a delta connected stator.**

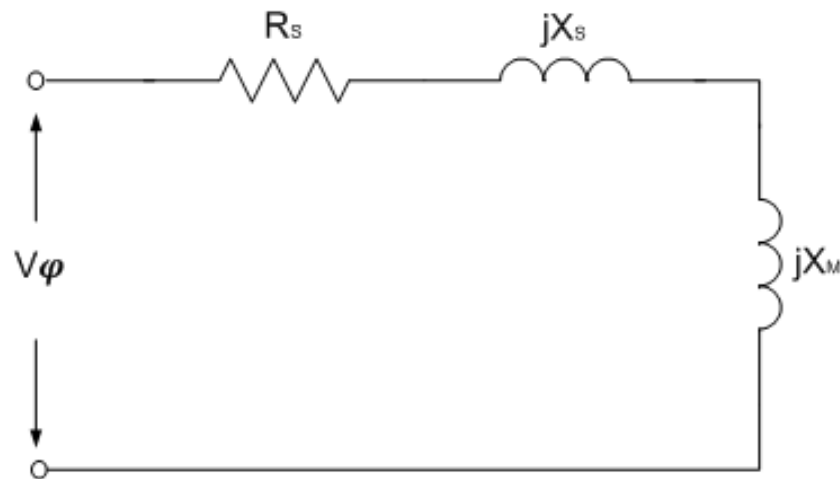


Figure 5.8: Induction Machine Equivalent Circuit Under No Load Test.

Using the measured data, the machine's losses and its magnetization reactance  $X_M$ , at rated input voltage with rated frequency, can be computed using equations 5.12 and 5.13, respectively.

$$P_{rot.} = P_{in,NL} - P_{CU,S} = P_{in,NL} - 3I_{\phi}^2 R_S \quad (5.12)$$

$$X_M = \frac{V_{\phi}}{I_{\phi}} \sin \theta - X_S \quad (5.13)$$

### 3) Locked Rotor Test

In the blocked rotor test, it should be kept in mind that the applied voltage on the stator terminals should be low otherwise normal voltage could damage the winding of the stator. In block rotor test, the low voltage is applied so that the rotor does not rotate and its speed becomes zero and full load current passes through the stator winding. The slip is unity related to zero speed of rotor hence the load resistance becomes zero. Now, slowly increase the voltage in the stator winding so that current reaches to its rated value. At this point, note down the readings of the voltmeter, wattmeter and ammeter to know the values of voltage, power and current. **This test is carried out with a star connected stator.**

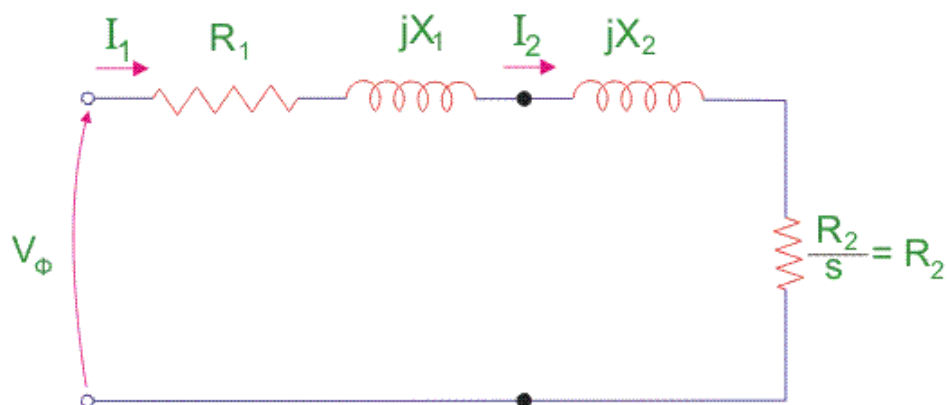


Figure 5.9: Locked Rotor Test Equivalent Circuit

The power losses in an induction motor is given by the following diagram

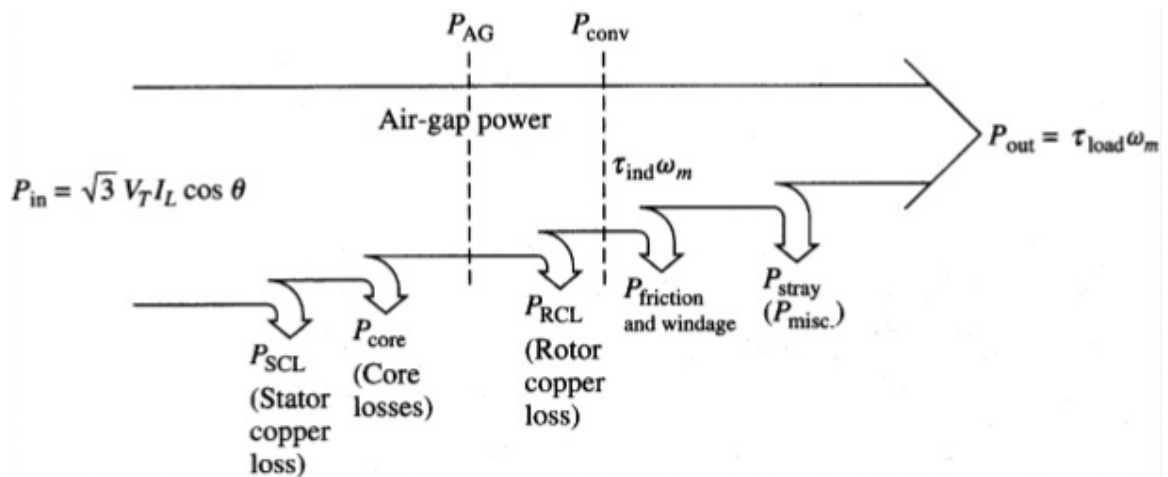


Figure 5.10: Power flow diagram for the induction motor losses.

### Induction Motor Name Plate

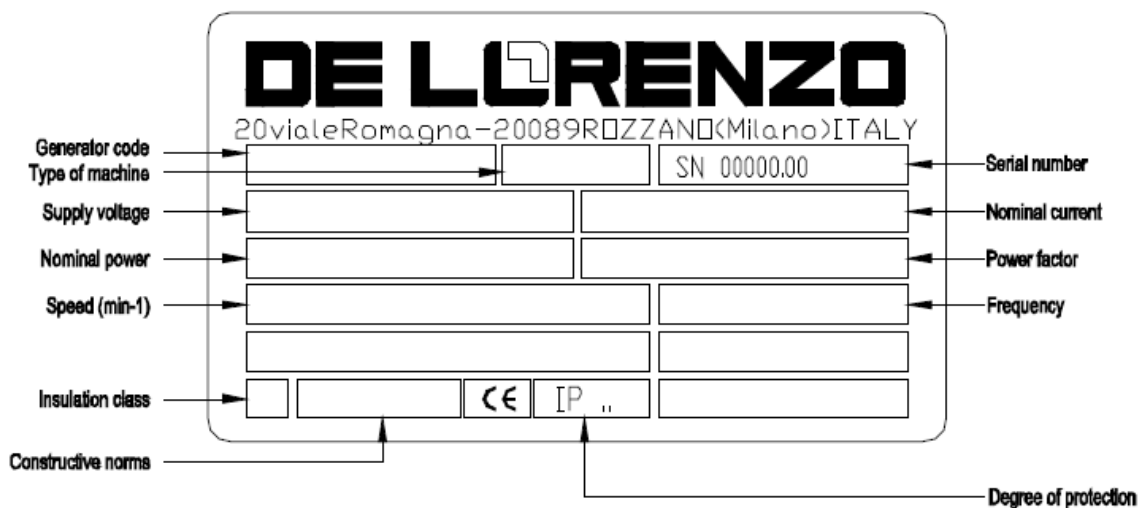


Figure 5.11: Induction Motor Nameplate

### Procedure:

#### a) DC Test

1. Connect the circuit in Figure 5.12.
2. Calculate  $R_s$  from the measurement of applied dc voltage ( $V_{DC}$ ) and dc current ( $I_{DC}$ ).

Table 5.1: DC test results

$V_{DC}$ [V]	$I_{DC}$ [A]	$R_s$ [ $\Omega$ ]



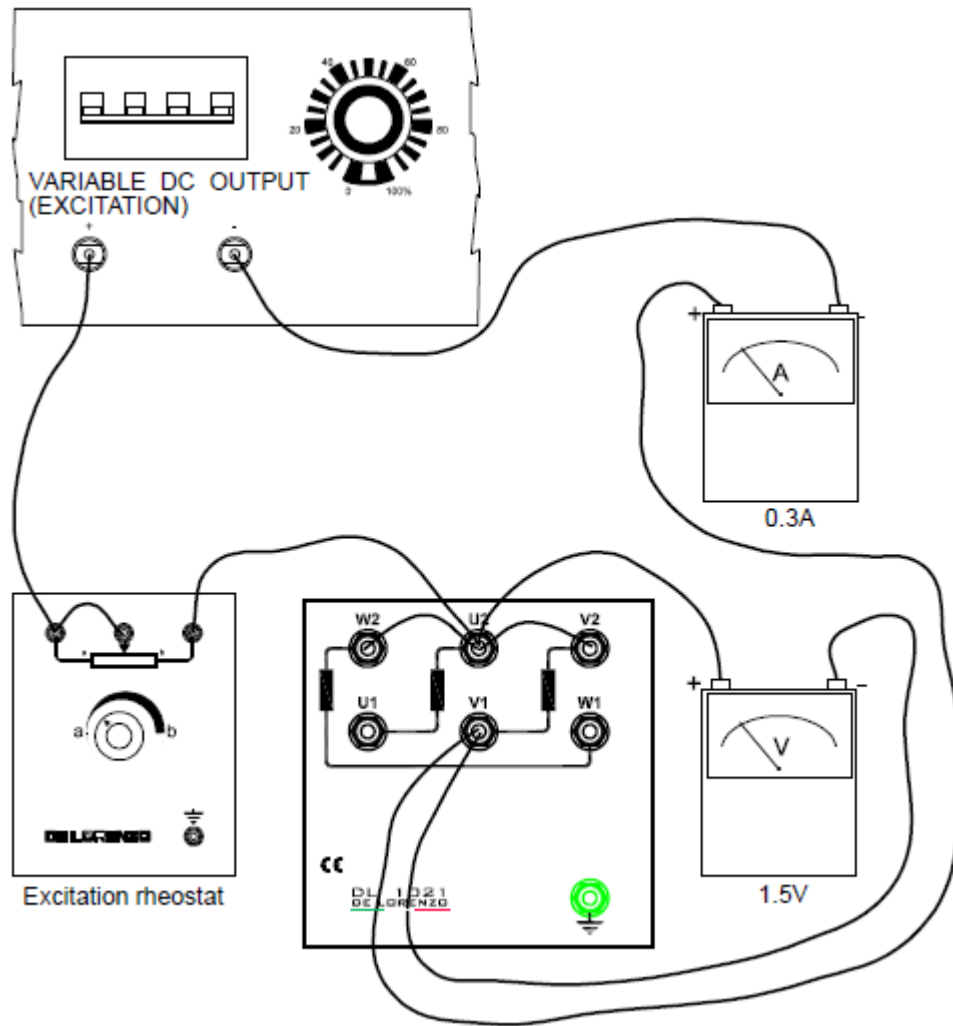


Figure 5.12: DC Test Wiring Diagram

**b) No load Test**

1. Connect the motor such as it is **delta** as shown by Figure 5.13.
2. Set the load on minimum torque (0 N.m).
3. Turn the power on and increase the line voltage to 220V.
4. Complete Table 5.2.

Table 5.2: No-Load Test Data

$V_{L-L}$ [V]	$I_L$ [A]	Ptot[W]	$n_m$ [rpm]
220			

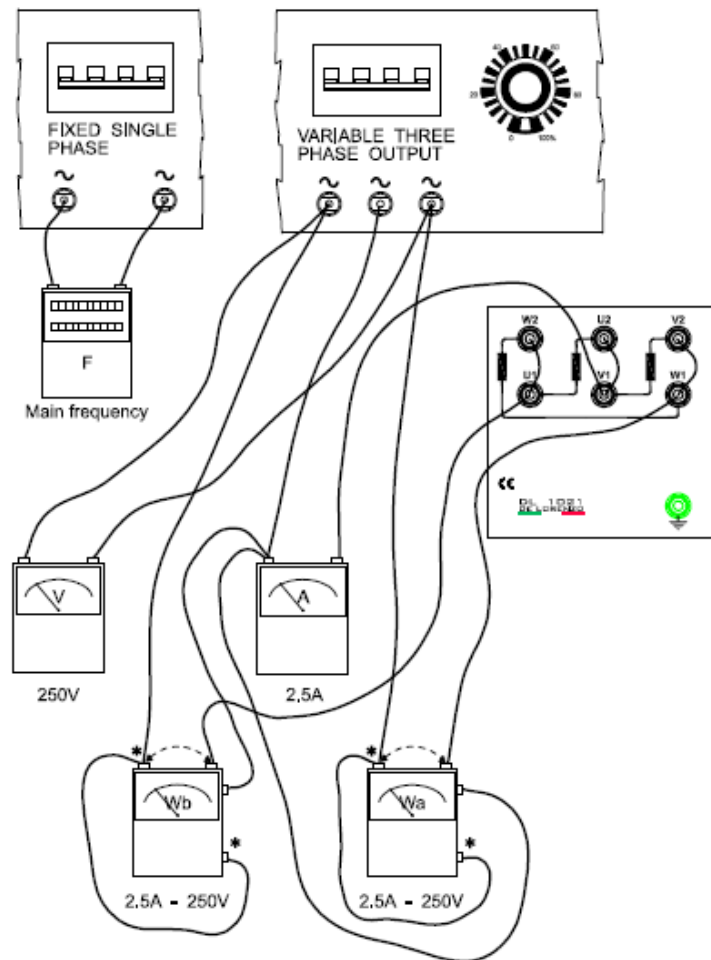


Figure 5.13: No Load Test Wiring

c) **Locked Rotor Test**

1. Connect the motor such as it is **star** as shown by Figure 5.14.
2. Hold the motor shaft with your hands or use the locking mechanism in the lab.
3. Turn the power on and increase the line voltage slowly until the motor current reaches its rated value.
4. Complete Table 5.3.

Table 5.3: Locked Rotor Test Data

$V_{L-L}$ [V]	$I_L$ [A]	Ptot[W]	$n_m$ [rpm]
	Irated		

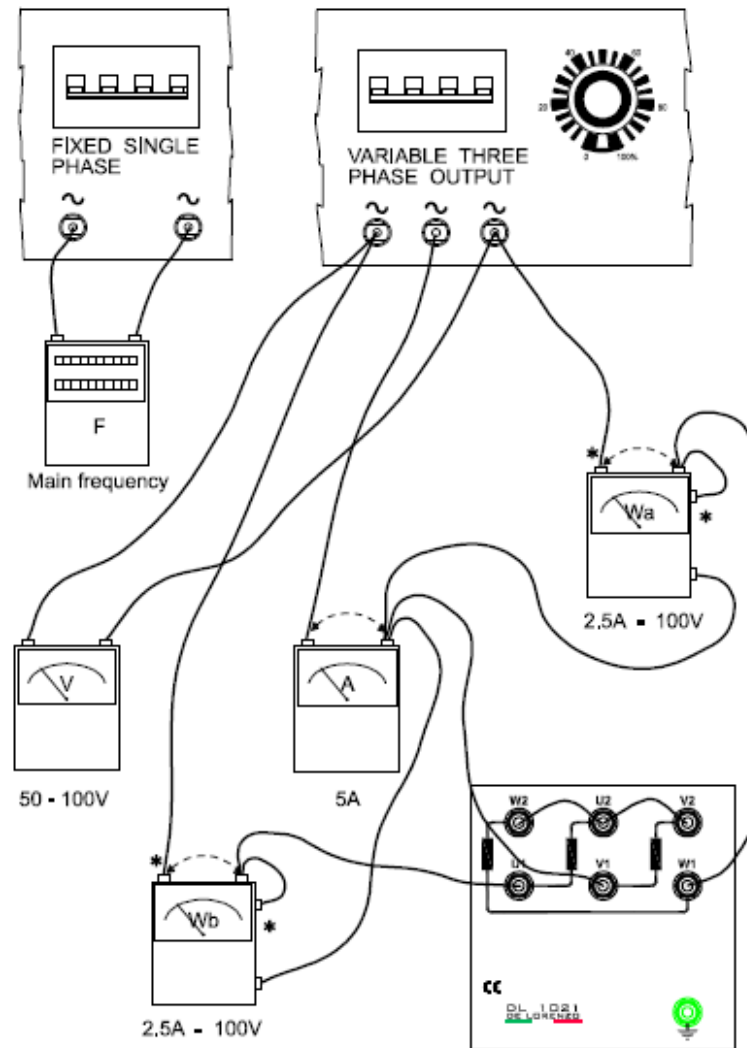


Figure 5.14: Blocked Rotor Test

#### d) Load Test

This test is carried out to study the torque-speed characteristics of the three phase induction motor and its efficiency. At a fixed value for the supply voltage (of 220V), vary the load torque and complete Table 5.4. ***Make sure not to exceed the rated current of the motor.***

1. Connect the motor such as it starts as star and run as delta.
2. Set the load on minimum torque (0 N.m).
3. Turn the power on and increase the line voltage to 220V.
4. Start increasing the load torque for the values given in Table 5.4.
5. Complete Table 5.4.

Table 5.4: Load Test Data

$V_{L-L}$ [V]	$I_L$ [A]	$P_{L-L}$ [W]	$\tau$ [N.m]	$n_m$ [rpm]	$P_{out}$ [W]	Slip	PF	$\eta$
220								
220								
220								
220								
220								

**e) Reversal of a Three-Phase Induction Motor**

By the help of your lab supervisor prepare the connection to reverse the direction of rotation of the motor.

**Discussion and Analysis:**

1. Calculate the synchronous speed of the motor using Equation 9.1 and the ratings on the three-phase induction motor name plate.
2. Compute:  $P_{rot}$  from the No-Load Test. (Use the stator resistor value calculated in the dc test).
3. Calculate the efficiency of the motor showing a sample of calculation.
4. Show sample of calculation for the slip.
5. Plot the torque versus speed curve from the load test. Explain the nature of the curve.
6. Plot the torque versus rotor current. Explain the nature of the curve.
7. Plot the efficiency versus rotor current. Explain the nature of the curve. Where was the efficiency maximum?
8. Why the induction motor is started with star connection and operated with delta connection?
9. If two of the three phases are reversed, what would happen?
10. If three phases are reversed, what would happen?

## Experiment 6 Starting and Speed Control of Three-Phase Induction Motor

### Objectives:

- To study the methods of starting three phase induction motors.
- To study methods of speed control of three phase induction motors.
- To study the operation and advantages of variable frequency drive.

### Apparatus:

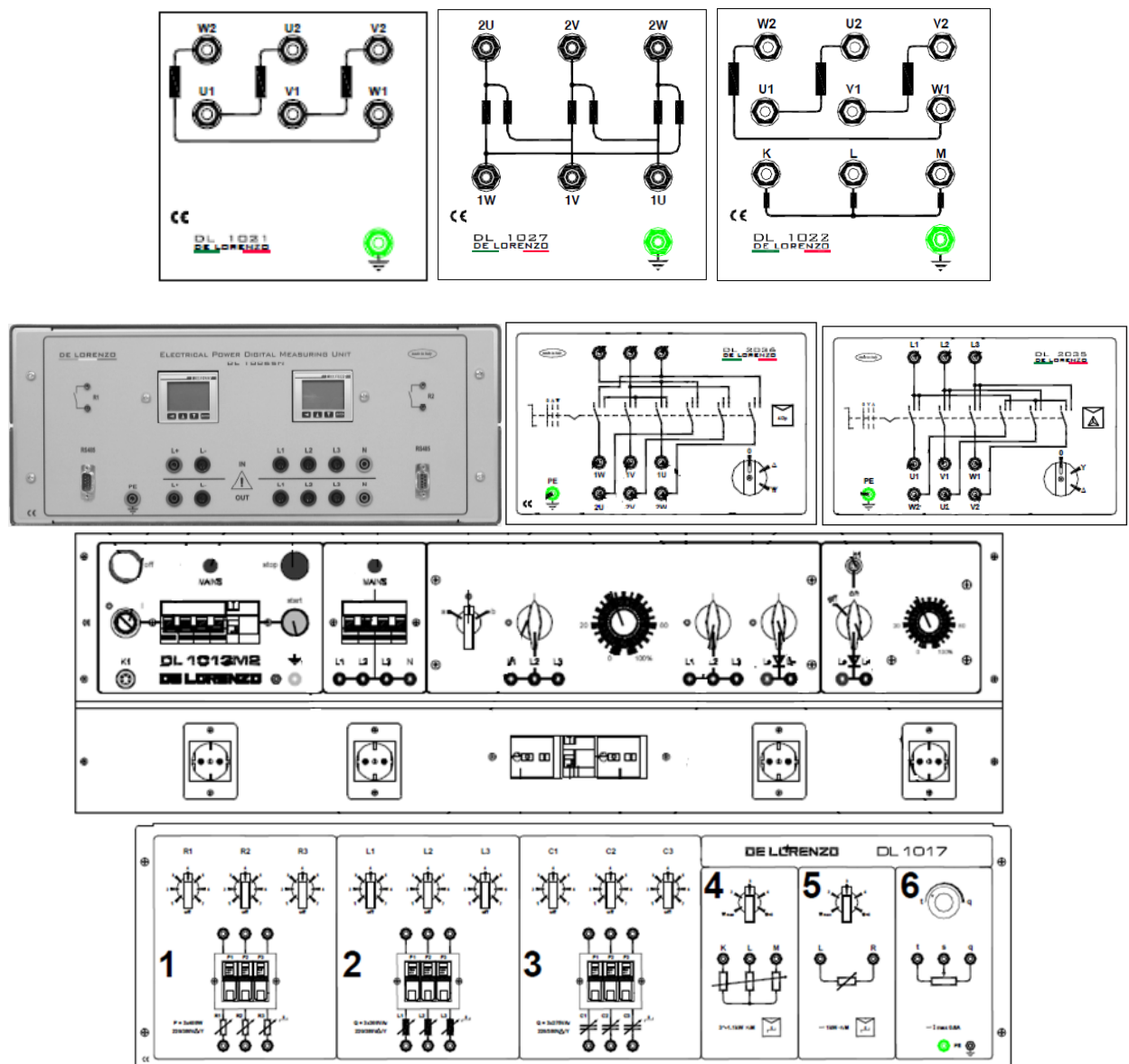


Figure 6.1: System Apparatus

### **Theoretical Background:**

Motor When typical induction motors become energized directly from the supply, a much larger amount of current (5 to 7 times its full load current and develops a torque which is only 1.5 to 2.5 times the full load torque) than normal operating current rushes into the motor to set up the magnetic field surrounding the motor and to overcome the lack of angular momentum of the motor and its load. As the motor increases to slip speed, the current drawn subsides to match (1) the current required at the supplied voltage to supply the load and (2) losses to windage and friction in the motor and in the load and transmission system. A motor operating at slip speed and supplying nameplate horsepower as the load should draw the current printed on the nameplate, and that current should satisfy the equation:

$$\text{Horsepower} = (\text{voltage} \times \text{current} \times \text{power factor} \times \text{motor efficiency} \times \sqrt{3}) / 746$$

If we look at the equivalent circuit of the three phase induction motor at the time of starting, we can see the motor behaves like an electrical transformer with short circuited secondary winding, because at the time of starting, the rotor is stationary and the back emf due to the rotation is not developed yet hence the motor draws the high starting current. So the reason of using the starter is clear here. We use starters in order to limit the high starting current. We use different starters for both the type of three phase induction motors.

### **Starting Methods of Squirrel Cage Induction Motor**

We classify starting methods for squirrel cage induction motor into two types on the basis of voltage. The two types are

- (i) Full voltage starting method
- (ii) Reduced voltage method for starting squirrel cage induction motor.

#### **Full voltage starting method**

In this type we have only one method of starting.

#### **Direct on Line Starting Method**

This method is also known as the **DOL method for starting the three phase squirrel cage induction motor**. In this method we directly switch the stator of the three phase squirrel cage induction motor on to the supply mains. The motor at the time of starting draws very high starting current (about 5 to 7 times the full load current) for the very short duration. The amount of current drawn by the motor depends upon its design and size. But such a high value of current does not harm the motor because of rugged construction of the squirrel cage induction motor. Such a high value of current causes sudden undesirable voltage drop in the supply voltage. A live example of this sudden drop of voltage is the dimming of the tube lights and bulbs in our homes at the instant of starting of refrigerator motor.

**Reduced voltage method for starting squirrel cage induction motor**

In reduced voltage method we have three different type of starting method:

**1. Stator Resistor Starting Method**

Given below is the figure for the starting resistor method:

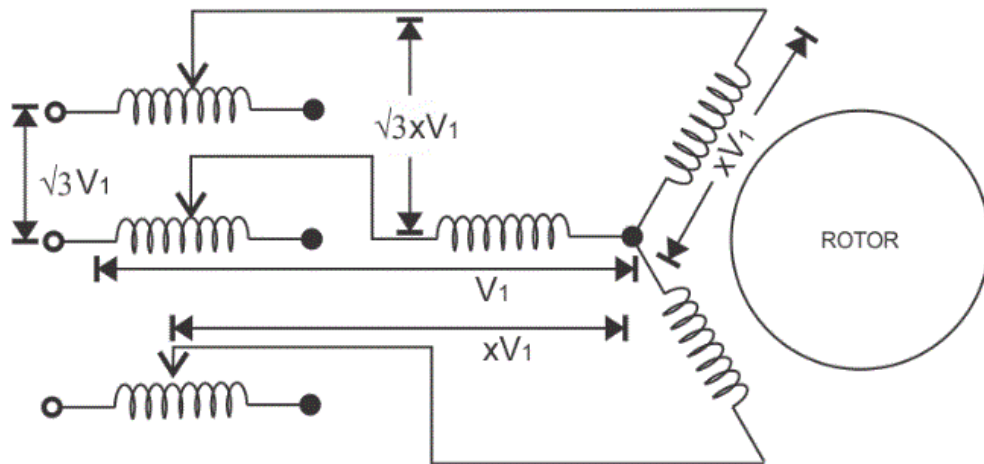


Figure 6.2: Inserting a Starting Stator Resistor

Obviously, the purpose of primary resistors is to drop some voltage and apply a reduced voltage to the stator. Consider, the starting voltage is reduced by 50%. From the torque equation of a three phase induction motor, the starting torque is approximately proportional to the square of the applied voltage. That means, if the applied voltage is 50% of the rated value, the starting torque will be only 25% of its normal voltage value. This method is generally used for a **smooth starting of small induction motors**. It is not recommended to use primary resistors type of starting method for motors with high starting torque requirements.

Resistors are generally selected so that 70% of the rated voltage can be applied to the motor. At the time of starting, full resistance is connected in the series with the stator winding and it is gradually decreased as the motor speeds up. When the motor reaches an appropriate speed, the resistances are disconnected from the circuit and the stator phases are directly connected to the supply lines.

Now there are some considerations regarding this method. If we add series resistor then the energy losses are increased so it's better to use series reactor in place of resistor because it is more effective in reducing the voltage however series reactor is more costly than the series resistance.

### 2. Auto Transformer Starting Method

As the name suggests in this method we connect auto transformer in between the three phase power supply and the induction motor as shown by Figure 6.3.

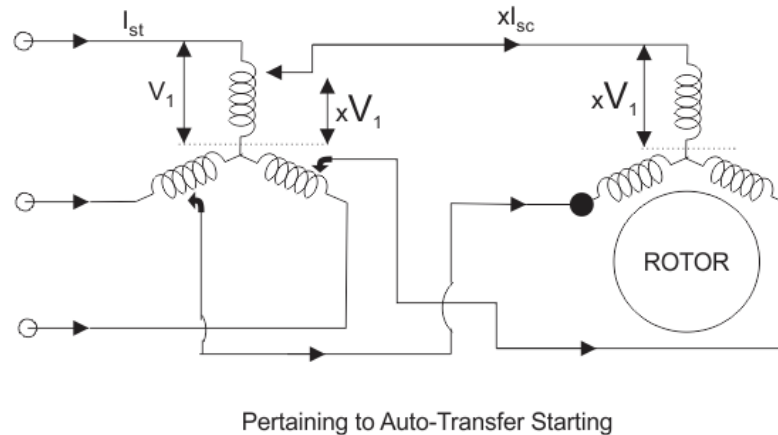


Figure 6.3: Using Autotransformer for Starting the Motor

Auto-transformers are also known as auto-starters. They can be used for both star connected and delta connected squirrel cage motors. It is basically a three phase step down transformer with different taps provided that permit the user to start the motor at, say, 50%, 65% or 80% of line voltage. With auto-transformer starting, the current drawn from supply line is always less than the motor current by an amount equal to the transformation ratio. For example, when a motor is started on a 65% tap, the applied voltage to the motor will be 65% of the line voltage and the applied current will be 65% of the line voltage starting value, while the line current will be 65% of 65% (i.e. 42%) of the line voltage starting value. This difference between the line current and the motor current is due to transformer action. The internal connections of an auto-starter are as shown in the figure. At starting, switch is at "start" position, and a reduced voltage (which is selected using a tap) is applied across the stator. When the motor gathers an appropriate speed, say up to 80% of its rated speed, the auto-transformer automatically gets disconnected from the circuit as the switch goes to "run" position.

### 3. Star-Delta Starting Method

This is a starting method that reduces the starting current and starting torque. At starting the Induction motor is star connected after it reached the approximate operational speed it is switch to delta. The motor must be delta connected during a normal run, in order to be able to use this starting method.

This starting method only works when the application is light loaded during the start. If the motor is too heavily loaded, there will not be enough torque to accelerate the motor up to speed before switching over to the delta position.



The induction motor must be built to run normally with a mesh-connected stator winding. At starting, the winding is connected temporarily in star. The phase voltage is thus reduced to  $1/\sqrt{3} = 0.58$  of normal, and the motor behaves as if the auto-transformer were employed with a ratio  $x = 0.58$ . The starting current per phase is  $I_s = 0.58I_x$ , the line current is  $(0.58)2I_x = 0.33I_x$ , the starting torque is one-third of short-circuit value.

The method is cheap and effective, so long as the starting torque is not required to exceed about 50 percent of full load torque. It can therefore be used for machine-tools, pumps, motor generators etc. The method is unsuitable for motors at voltages exceeding 3000 V. because of the excessive number of stator turns needed for delta running. Where induction motors are required to run for considerable periods on small loads, a star-delta switch permits the machine to be star-connected during these periods, with reduction of magnetizing current and increase in efficiency.

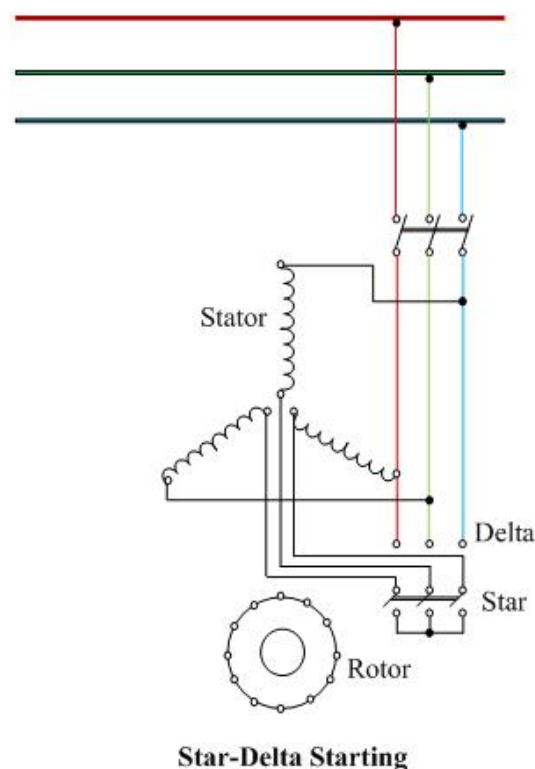


Figure 6.4: Star Delta Starting of Induction Motor

### Starting Methods of Wound Rotor Motors

We can employ all the methods that we have discussed for starting of the squirrel cage induction motor in order to start the wound rotor motors. We will discuss the cheapest method of starting the wound rotors motor here.

### Addition of External Resistances in Rotor Circuit

This will decrease the starting current, increases the starting torque and also improves the power factor. The circuit diagram is shown below: In the circuit diagram, the three slip rings shown are connected to the rotor terminals of the wound rotor motor. At the time of starting of the motor,

the entire external resistance is added in the rotor circuit. Then the external rotor resistance is decreased in steps as the rotor speeds up, however the motor torque remain maximum during the acceleration period of the motor. Under normal condition when the motor develops load torque the external resistance is removed.

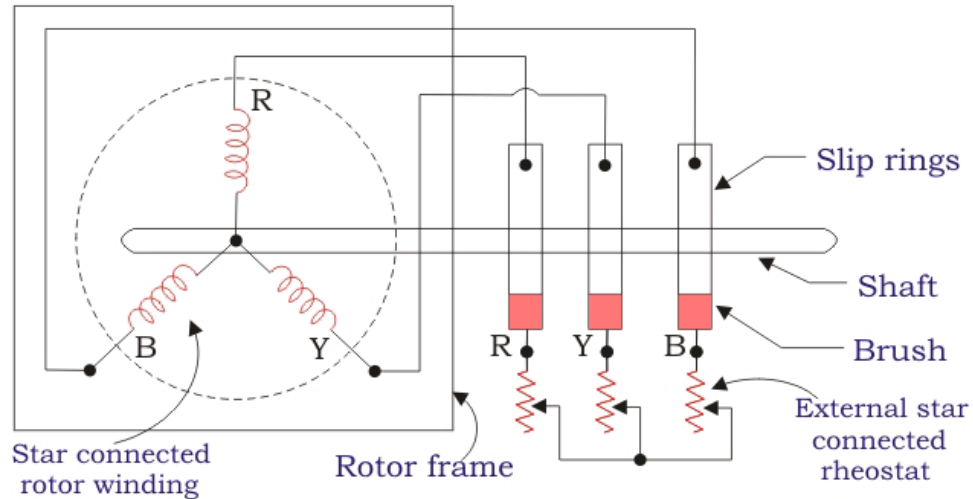


Figure 6.5: Rotor Starting Resistor for Slip Ring Induction Motor

### Speed Control Methods for Induction Motor

An induction motor is practically a constant speed motor that means for the entire loading range, change in speed of the motor is quite small. Speed of a DC shunt motor can be varied very easily with good efficiency, but in case of Induction motors, speed reduction is accompanied by a corresponding loss of efficiency and poor power factor. As induction motors are widely being used, their speed control may be required in many applications. **Different speed control methods of induction motor** maybe used:

#### 1. By changing the applied voltage:

From the torque equation of induction motor,

$$T = \frac{k_1 s E_2^2 R_2}{\sqrt{(R_2^2 + (s X_2)^2)}} = \frac{3}{2\pi N_s} \frac{s E_2^2 R_2}{\sqrt{(R_2^2 + (s X_2)^2)}} \quad (6.1)$$

Rotor resistance  $R_2$  is constant and if slip  $s$  is small then  $(sX_2)^2$  is so small that it can be neglected. Therefore,  $T \propto sE_2^2$  where  $E_2$  is rotor induced emf and  $E_2 \propto V$ . Thus,  $T \propto sV^2$ , which means, if supplied voltage is decreased, the developed torque decreases. Hence, for providing the same load torque, the slip increases with decrease in voltage, and consequently, the speed decreases. This method is the easiest and cheapest, still rarely used, because

1. Large change in supply voltage is required for relatively small change in speed.

2. Large change in supply voltage will result in a large change in flux density; hence, this will disturb the magnetic conditions of the motor.

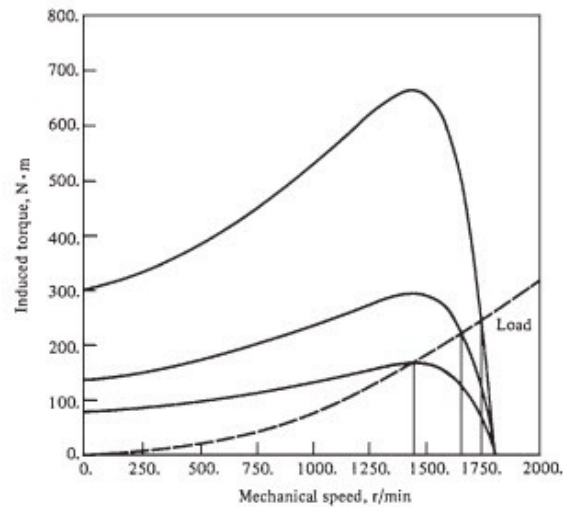


Figure 6.6: Variable Line Drive Speed Control

## 2. By changing the applied frequency

Synchronous speed of the rotating magnetic field of an induction motor is given by,

$$N_s = \frac{120 f}{P} \quad (\text{RPM}) \quad (6.2)$$

where,  $f$  = frequency of the supply and  $P$  = number of stator poles. Hence, the synchronous speed changes with change in supply frequency. Actual speed of an induction motor is given as  $N = N_s (1 - s)$ . However, this method is not widely used. It may be used where the induction motor is supplied by a dedicated generator (so that frequency can be easily varied by changing the speed of prime mover). Also, at lower frequency, the motor current may become too high due to decreased reactance. And if the frequency is increased beyond the rated value, the maximum torque developed falls while the speed rises.

This curve is obtained while derating the applied terminal voltage linearly with decrease in frequency otherwise the steel in the core will saturate.

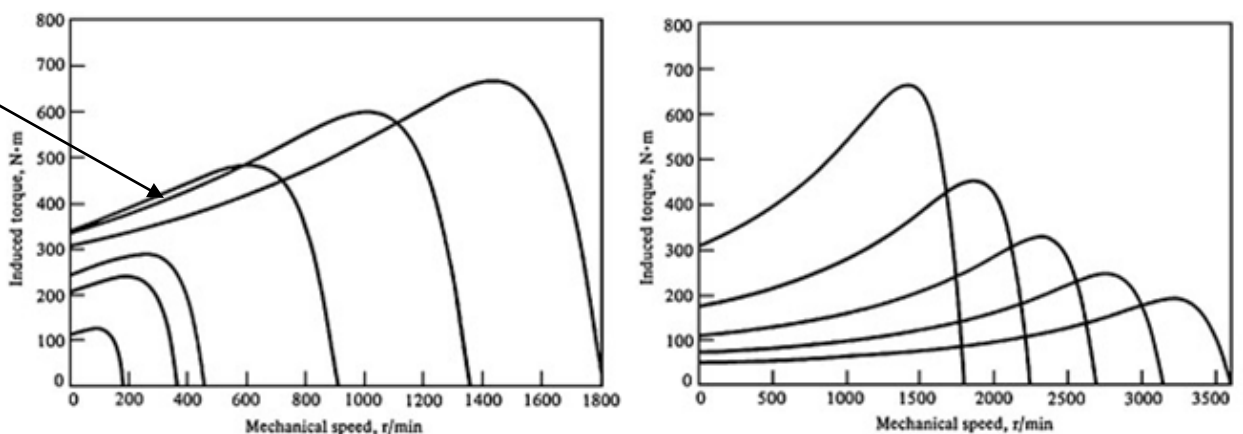


Figure 6.7: Speed Control by Adjusting Frequency below the Base Speed (Left) and above the base speed (right)

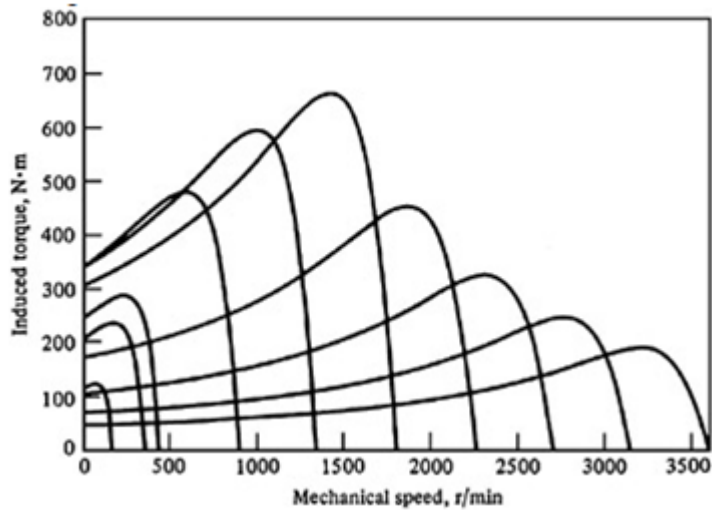


Figure 6.8: Speed Control by Adjusting Frequency for All Ranges

### 3. Changing the number of stator poles

From the above equation of synchronous speed, it can be seen that synchronous speed (and hence, running speed) can be changed by changing the number of stator poles. This method is generally used for squirrel cage induction motors, as squirrel cage rotor adapts itself for any number of stator poles. Change in stator poles is achieved by two or more independent stator windings wound for different number of poles in same slots. For example, a stator is wound with two 3phase windings, one for 4 poles and other for 6 poles. For supply frequency of 50 Hz

- 1) Synchronous speed when 4 pole winding is connected,  $N_s = 120 \cdot 50 / 4 = 1500$  RPM
- 2) Synchronous speed when 6 pole winding is connected,  $N_s = 120 \cdot 50 / 6 = 1000$  RPM

### 4. Adding external resistance on rotor side

In this method of speed control of three phase induction motor external resistance are added on rotor side. The equation of torque for three phase induction motor is

$$T \propto \frac{sE_2^2 R_2}{R_2^2 + (sX_2)^2} \quad (6.3)$$

The three phase induction motor operates in low slip region. In low slip region term  $(sX_2)^2$  becomes very very small as compared to  $R_2$  so it can be neglected and also  $E_2$  is constant. So the equation of torque after simplification becomes,

$$T \propto \frac{s}{R_2} \quad (6.4)$$

Now if we increase rotor resistance,  $R_2$  torque decreases but to supply the same load torque must remain constant. So we increase slip, which will further results in decrease in rotor speed. Thus by adding additional resistance in rotor circuit we can decrease the speed of three phase

induction motor. The main advantage of this method is that with addition of external resistance starting torque increases but this method of speed control of three phase induction motor also suffers from some disadvantages:

- 1) The speed above the normal value is not possible.
- 2) Large speed change requires large value of resistance and if such large value of resistance is added in the circuit it will cause large copper loss and hence reduction in efficiency.
- 3) Presence of resistance causes more losses.
- 4) This method cannot be used for squirrel cage induction motor.

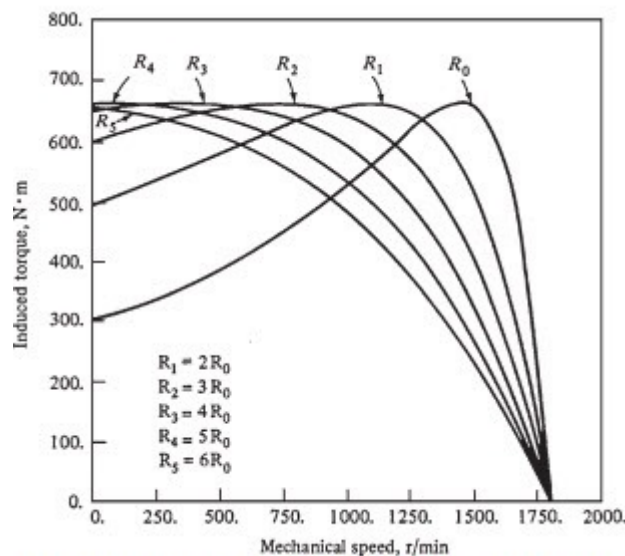


Figure 6.9: Speed Control by Varying the Rotor Resistance of a Wound Rotor Induction Motor

### 5. Constant V/F control of induction motor

This is the most popular method for controlling the speed of an induction motor. As in above method, if the supply frequency is reduced keeping the rated supply voltage, the air gap flux will tend to saturate. This will cause excessive stator current and distortion of the stator flux wave. Therefore, the stator voltage should also be reduced in proportional to the frequency so as to maintain the air-gap flux constant. The magnitude of the stator flux is proportional to the ratio of the stator voltage and the frequency. Hence, if the ratio of voltage to frequency is kept constant, the flux remains constant. Also, by keeping V/F constant, the developed torque remains approximately constant. This method gives higher run-time efficiency. Therefore, majority of AC speed drives employ constant V/F method (or variable voltage, variable frequency method) for the speed control. Along with wide range of speed control, this method also offers 'soft start' capability.

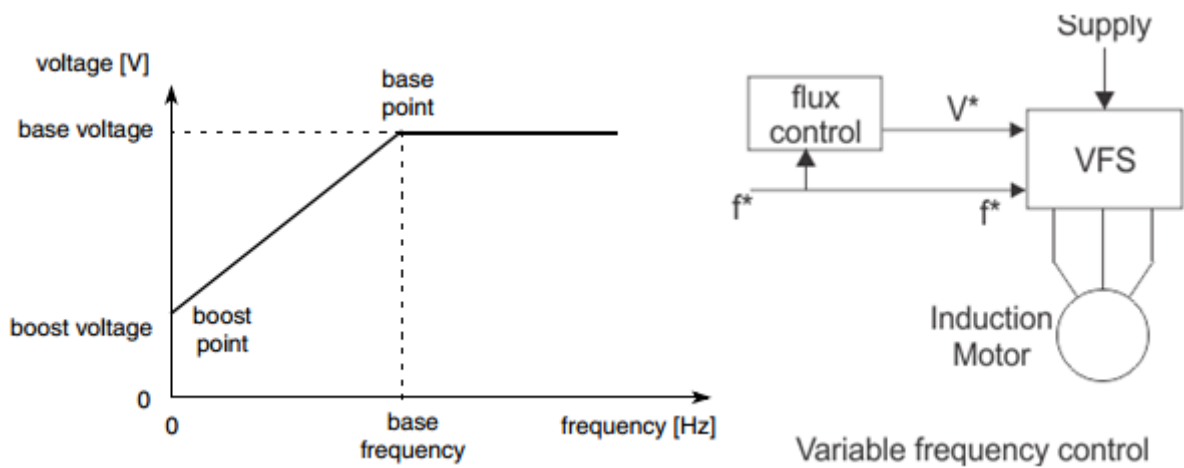


Figure 6.10: Speed Control Using V/F Constant Method

### Voltage boosting

At low frequencies (typically less than about one quarter of the base frequency), the voltage drop that occurs at the internal resistance of the stator winding becomes significant causing flux weakening. The stator supply voltage can be boosted to maintain the magnetizing voltage and hence maintain rated flux in the machine. Using this approach, it is possible to accelerate a motor from zero speed to rated speed smoothly and without the high inrush currents normally associated with induction machine starting.

### Operating Regions

A variable voltage, variable frequency drive is capable of operating over a wide speed range. There are three distinct operating modes, illustrated in the diagrams below.

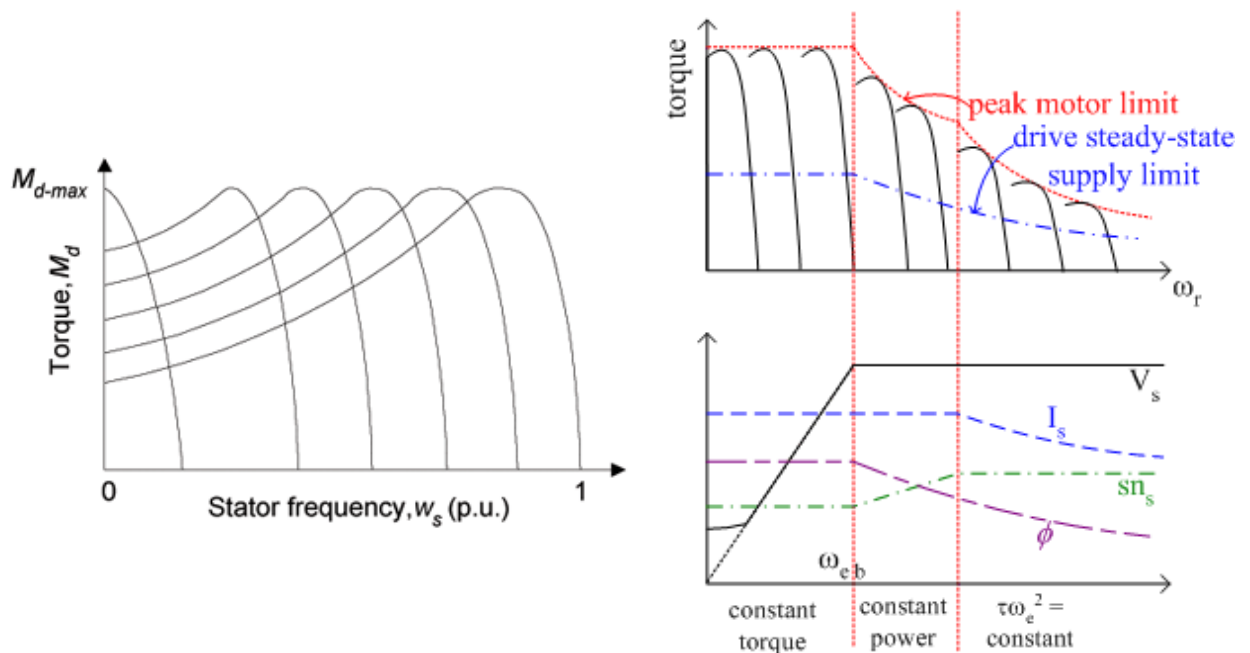


Figure 6.11: Operation Regions Using V/F Constant Method

1. Below base speed. This is the constant torque region where V/f control can be applied, with low frequency **voltage boosting**.
2. Constant power. Above base frequency there is a region where slip speed can be increased without exceeding rated currents and without coming too close to pull-out torque. Voltage must remain at the rated value, so this is a field weakening region.
3. Field weakening, constant slip speed. As the field is weakened, a point is reached where slip speed cannot be increased any further. In this region,  $\tau\omega_e^2$  is constant

### Variable Frequency Drives

The VFD controller is a solid-state power electronics conversion system consisting of three distinct sub-systems: a rectifier bridge converter, a direct current (DC) link, and an inverter as shown by Figure 6.12.

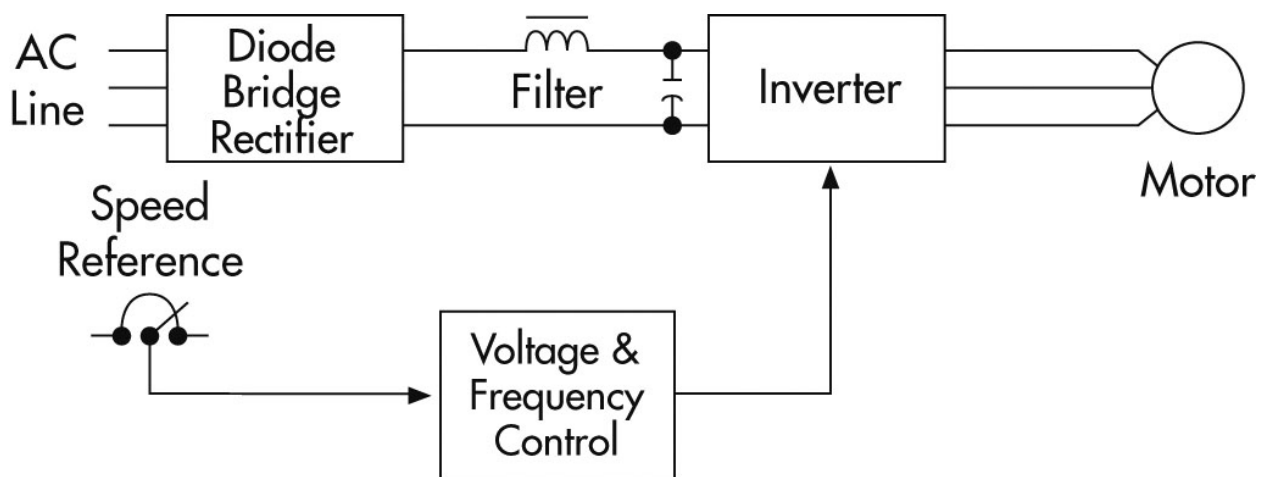


Figure 6.12: Variable Frequency Drive Stages

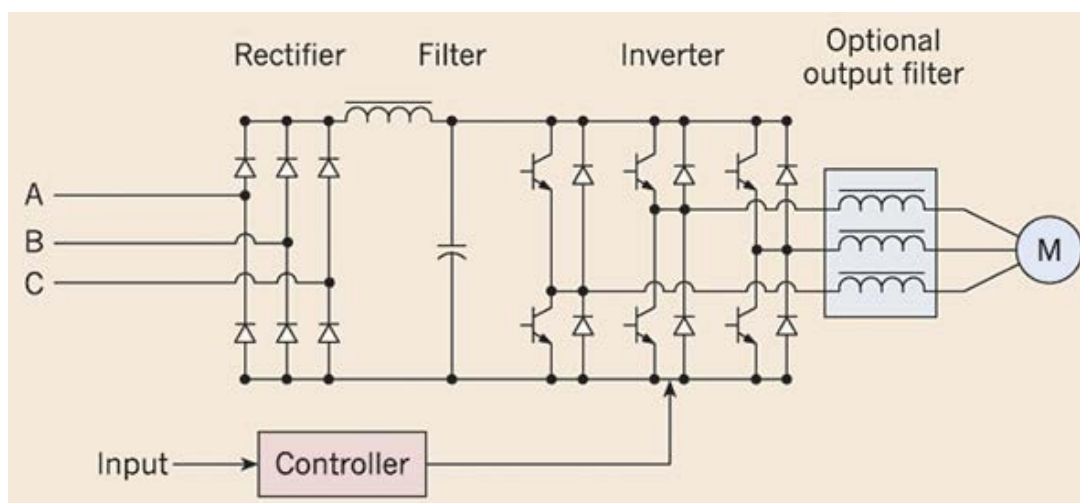


Figure 6.13: Variable Frequency Drive Implementation



The most basic rectifier converter for the VSI drive is configured as a three-phase, six-pulse, full-wave diode bridge. In a VSI drive, the DC link consists of a capacitor which smooths out the converter's DC output ripple and provides a stiff input to the inverter. This filtered DC voltage is converted to quasi-sinusoidal AC voltage output using the inverter's active switching elements.

In variable-torque applications suited for Volts-per-Hertz (V/Hz) drive control, AC motor characteristics require that the voltage magnitude of the inverter's output to the motor be adjusted to match the required load torque in a linear V/Hz relationship.

The two other drive control platforms, vector control and direct torque control (DTC), adjust the motor voltage magnitude, angle from reference, and frequency so as to precisely control the motor's magnetic flux and mechanical torque.

In starting a motor, a VFD initially applies a low frequency and voltage, thus avoiding high inrush current associated with direct-on-line starting. After the start of the VFD, the applied frequency and voltage are increased at a controlled rate or ramped up to accelerate the load. This starting method typically allows a motor to develop 150% of its rated torque while the VFD is drawing less than 50% of its rated current from the mains in the low-speed range. A VFD can be adjusted to produce a steady 150% starting torque from standstill right up to full speed.

With a VFD, the stopping sequence is just the opposite as the starting sequence. The frequency and voltage applied to the motor are ramped down at a controlled rate. When the frequency approaches zero, the motor is shut off. A small amount of braking torque is available to help decelerate the load a little faster than it would stop if the motor were simply switched off and allowed to coast. Additional braking torque can be obtained by adding a braking circuit (resistor controlled by a transistor) to dissipate the braking energy.

### You can get lots of benefits from Variable Frequency Drives

1. Smooth starting reducing risk of motor damage during start up and stop
2. Smooth acceleration & deceleration time
3. Stopping methods
4. Reversal of motor
5. Reduce harmonics and power line disturbances
6. Increase power factor
7. Energy savings ( motor must not all the time at rated power)
8. Elimination of expensive mechanical drive components (like gears to reduce speed and increase torque)
9. Increased motor longevity



Figure 6.14 shows a photo of the VFD unit used in the lab, with its block diagram shown by Figure 6.15.

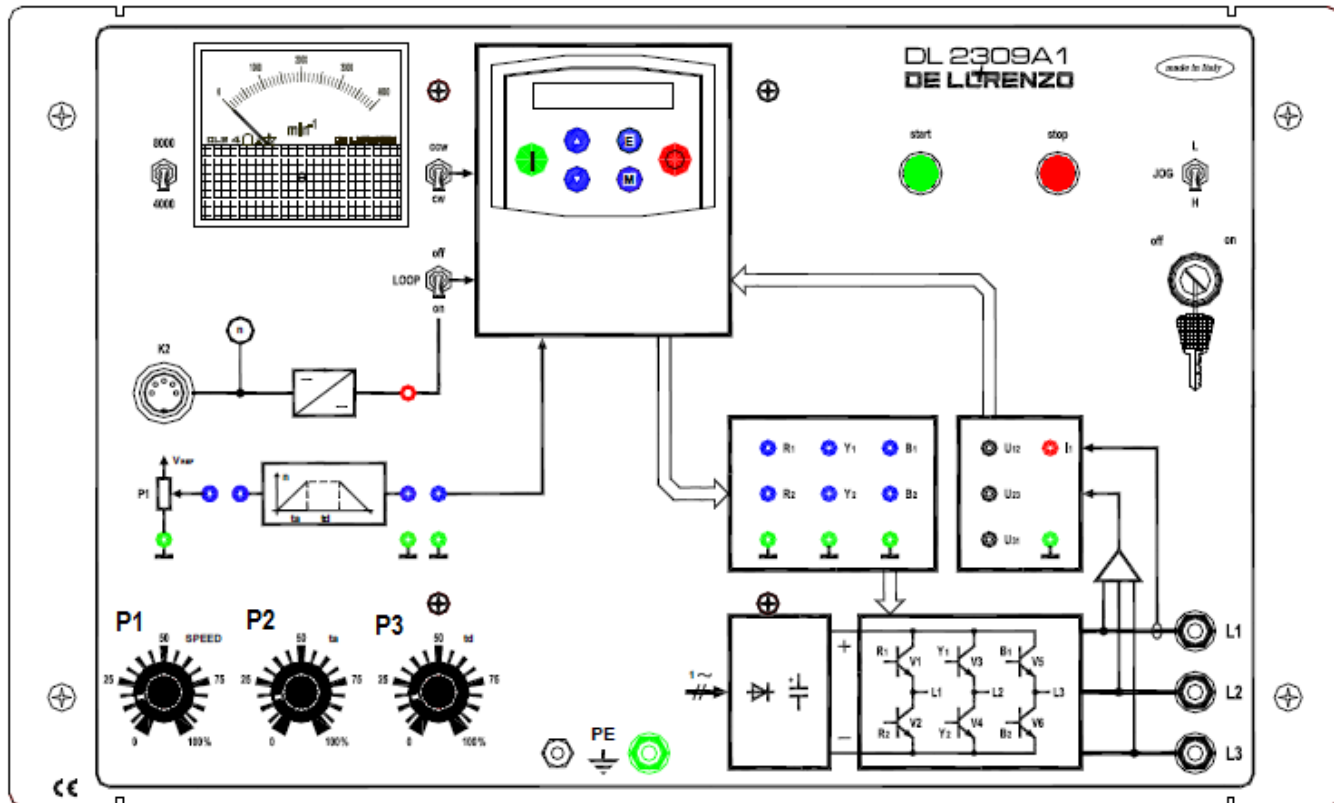


Figure 6.14: The VFD Used In the Lab

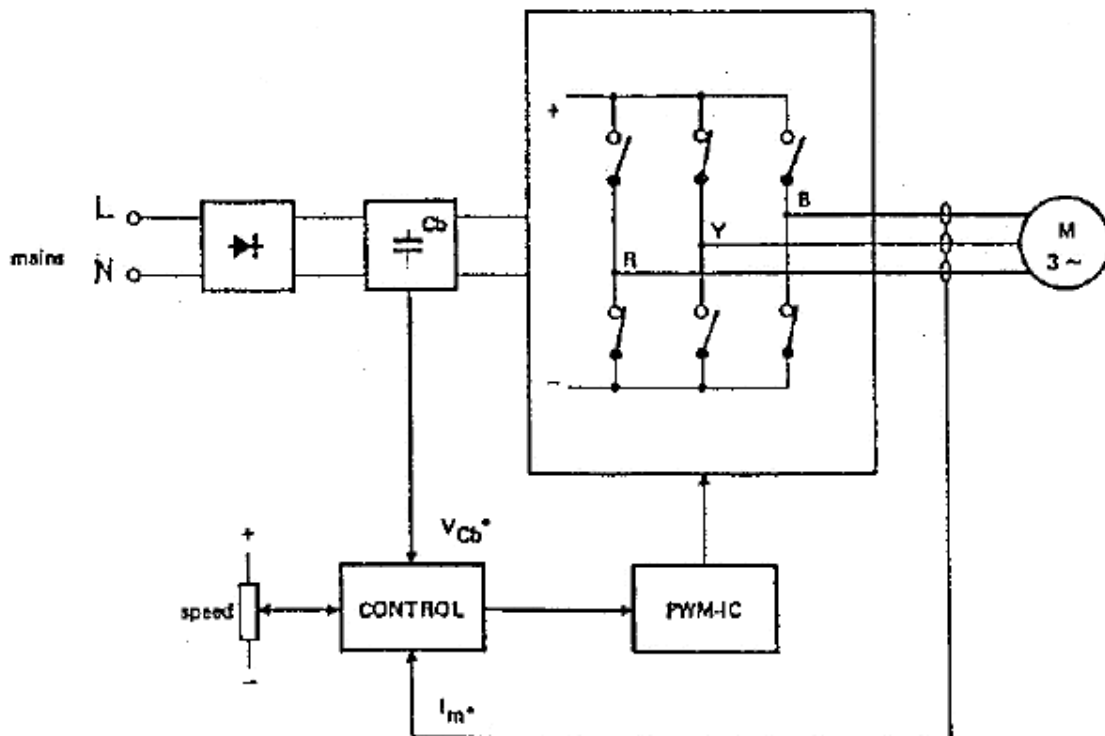


Figure 6.15: The VFD Block Diagram

The following illustrates the different parts of the unit.

- **Driving section**

1. *Key switch*; in the "on" position the green pilot lamp "start" lights and all the inverter driving controls are live.
2. *Push button "start"*: normally off when green pilot lamp is lit. Pressing the button the red pilot lamp "stop" lights and the inverter is operating.
3. *Push button "stop"*: normally closed contact. Pressing the button the red pilot lamp "stop" goes out, the green pilot lamp "start" lights and the inverter is inhibited.
4. *Switch "JOG"*: in the "H" position the drive will run at Jog speed. *Switch "cw/ccw"*: reverses the motor running direction.
5. If the reversing is performed with running motor, the following sequence is automatically carried out:
  6. The motor decelerates following the deceleration ramp to the minimum frequency; at the minimum speed the phase sequence is reversed;
  7. The motor starts again in the opposite direction and reaches the preset speed.
8. *Switch "LOOP"*: allows connecting the feedback from tachometric transducer connected to connector K2, ONLY WHEN THE MOTOR IS STANDSTILL.

- **Control section**

1. Potentiometer P1 "SPEED": allows to set the desired speed through an analog signal 0 to 10V.
2. Potentiometer P2 "ta": allows to set the acceleration time from 5 to 15 s approx.
3. Potentiometer P3 "td": allows to set the deceleration time from 5 to 15 s approx.
4. Display and keyboard: allow the inverter programming

- **Power section**

- ✓ Max motor power: 1.5 kW/2 hp.
- ✓ Rated output current: 7 A.
- ✓ Max output current: 12 A.
- ✓ Output voltage: 3 x 220/240 V.
- ✓ Output frequency: 0 to 240 Hz.
- ✓ Dc braking.
- ✓ Overload: 150%/30s.

**Procedure:**

Part 1: Slip Ring Induction Motor

- 1- With the help of your lab supervisor, connect the slip ring motor in Figure 5.1 and apply the suitable starting and speed control method on it.

Part 2: Dahlander Induction Motor

- 1- With the help of your lab supervisor, connect the Dahlander motor in Figure 5.1 and apply the suitable speed control method on it.

Part 3-1: Squirrel Cage Induction Motor

**The purpose of this part is to study the difference between the open loop and the closed loop configurations regarding speed regulation.**

1. Connect the motor as **delta**.
2. Connect the squirrel cage induction motor you used during the previous experiment to the drive unit as shown by Figure 6.15.
3. Set the base and maximum frequency of the VFD unit.
4. Fix the system frequency.
5. Use the system once in the open loop configuration and once in the close loop configuration.
6. Vary the load and fill in Table 6.1.

Table 6.1: Speed Regulation

	$V_{LL}$	$I_L$	$\tau$	$f$	$\omega$
<b>Open Loop</b>					
<b>Closed Loop</b>					

Part 3-2: Squirrel Cage Induction Motor

**The purpose of this part is to study the different regions (constant power and constant torque regions) of operation of the induction motor where frequency is varied between zero and base frequency then is increased above the base frequency.**

1. Connect the motor as **delta**.
2. Connect the squirrel cage induction motor you used during the previous experiment to the drive unit as shown by Figure 6.16.

3. Use the system in the open loop configuration or the close loop configuration.
4. Set the base and maximum frequency of the VFD unit.
5. Fix the applied torque.
6. Change the frequency and fill in Table 6.2.

Table 6.2: Variable Frequency Control

	$f$	$V_{LL}$	$I_L$	$\tau$	$\omega$	$P_o$	Slip	PF
<b>Below base frequency</b>								
<b>Above base frequency</b>								

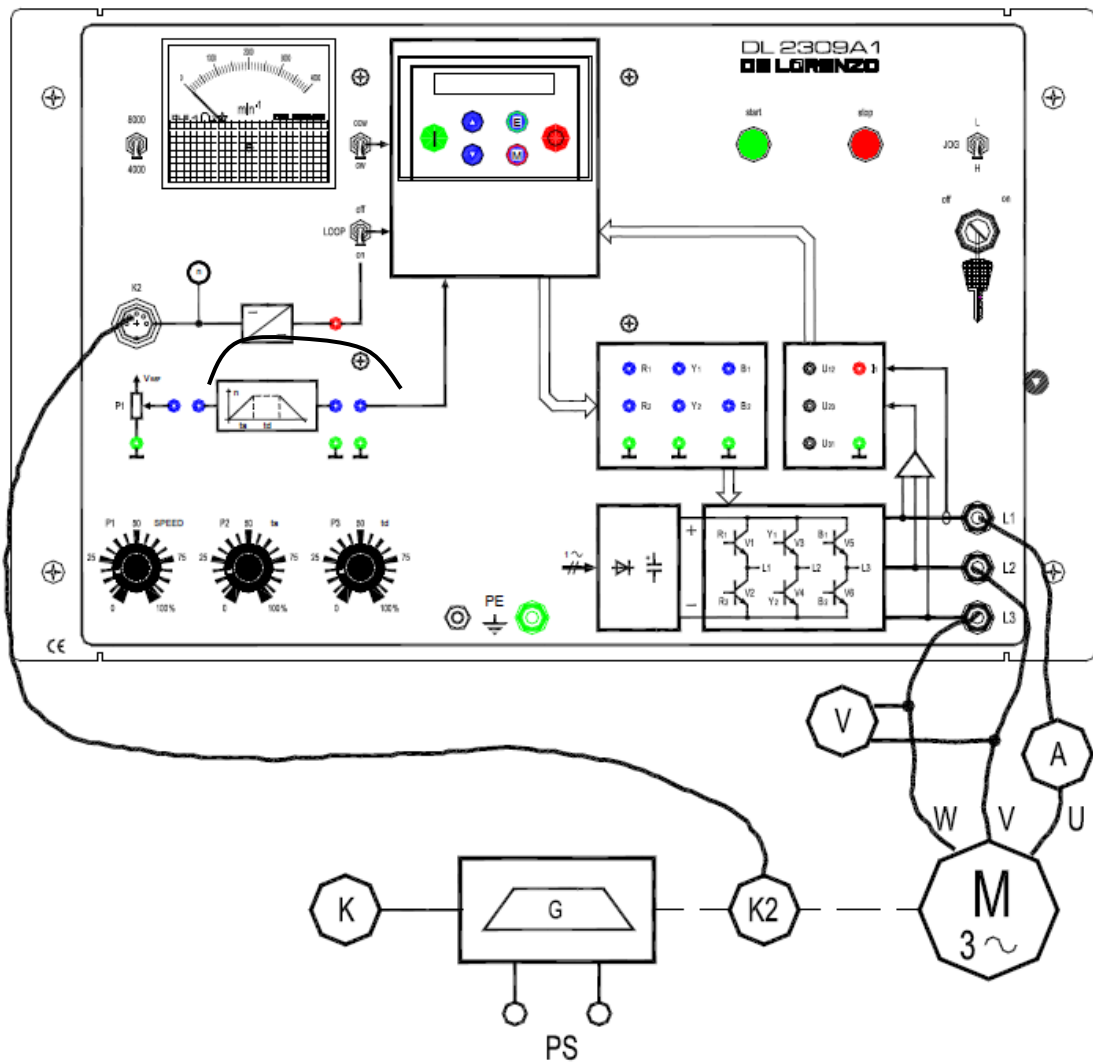


Figure 6.16: Wiring of VFD Unit.

**Discussion and Analysis:**

1. Why did you connect the motor as delta?
2. What is the difference between the base and the maximum frequency? What was the value of each frequency?
3. Plot the torque versus speed curve for both cases in Table 6.1 on the same graph.
4. What is the difference between the curves in the plot above?
5. What happens to the torque value as the speed changed below the base speed in part 2?
6. What happens to the torque value as the speed changed below the base speed in part 2?
7. What happens to the power value as the speed changed below the base speed in part 2?
8. What happens to the power value as the speed changed below the base speed in part 2?
9. Plot the torque versus speed curve from the data in Table 6.2. on the same figure, plot the power versus speed curve.
10. Explain the curve in the figure above.

**References:**

1. <http://powertips-elec.blogspot.com/2010/11/motor-starting-and-running-currents-and.html>
2. <http://www.electrical4u.com/starting-methods-for-polyphase-induction-machine/>
3. <http://iitg.vlab.co.in/?sub=61&brch=168&sim=939&cnt=1>
4. <http://www.electrical4u.com/2014/02/starting-of-three-phase-induction-motors.html>
5. <http://www.electrical4u.com/2014/02/speed-control-methods-of-induction-motor.html>
6. <http://www.electrical4u.com/speed-control-of-three-phase-induction-motor/>
7. <http://people.ucalgary.ca/~aknigh/vsd/ssim/sine/vvfvf.html>
8. [https://en.wikipedia.org/wiki/Variable-frequency\\_drive](https://en.wikipedia.org/wiki/Variable-frequency_drive)
9. <https://www.linkedin.com/pulse/20141125141141-230838542-variable-speed-drive-advantages-and-disadvantages>
10. <http://www.vfds.org/variable-frequency-drive-advantages-disadvantages-581363.html>

**Appendix 6.1:**

**Dahlender Motor (Double Speed Motors)**

These motors are designed specially to change speed by changing its number of poles. By changing the connection as shown by the figures below, two speeds can be obtained:

- 1- Low speed (half the rated speed).
- 2- High speed.

Two types of Dahlander are possible:

- 1- Star double star.
- 2- Delta double star.

The double star configuration is always the high speed configuration. While the delta or star is the low speed configuration. The Dahlander in our lab is a delta double star motor.

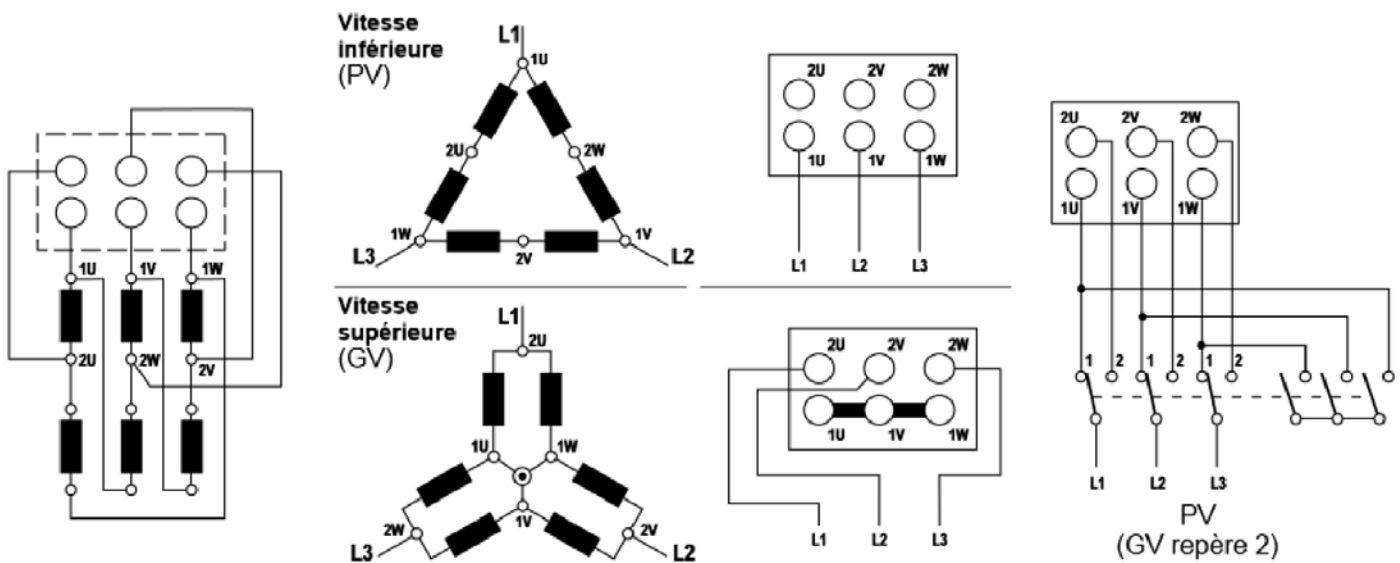


Figure 6.17: Delta Double Star Dahlander Motor

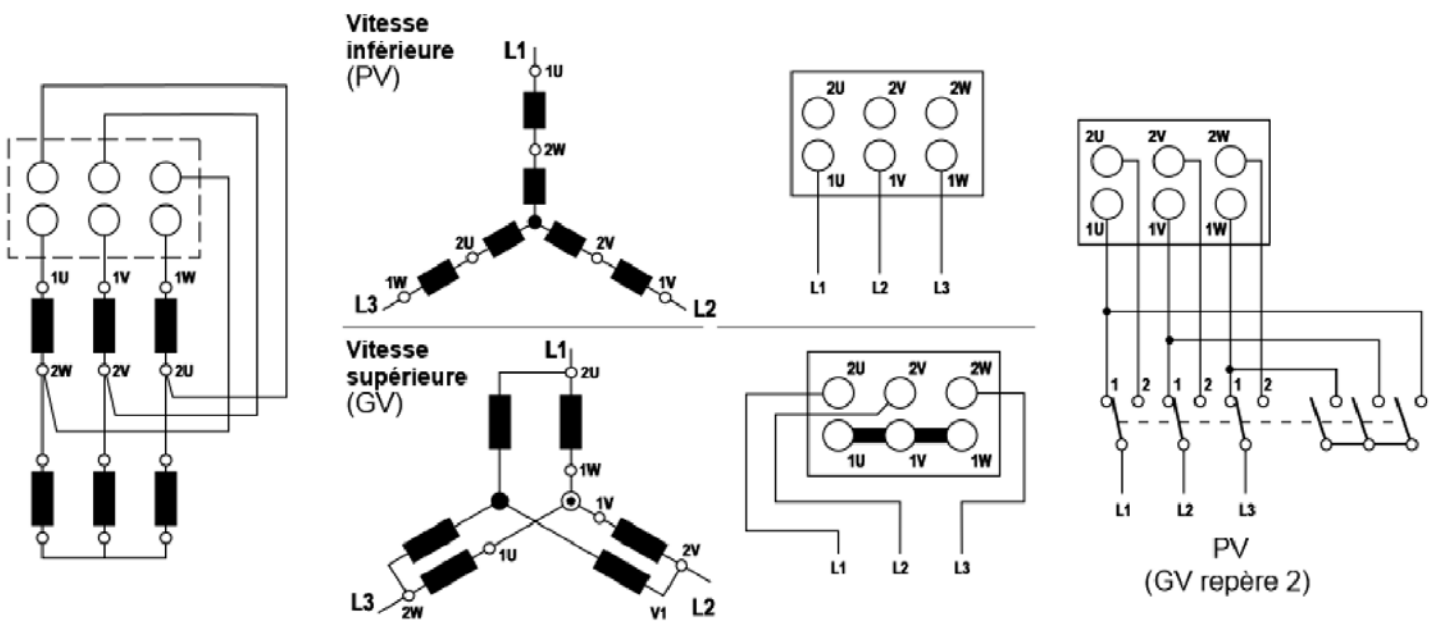


Figure 6.18: Star Double Star Dahlander Motor