King Fahd University of Petroleum & Minerals

Electrical Engineering Department

EE-462

Electric Machines

Laboratory Manual

Table of Contents

Safety Guidelines……………………………………………………………….. …

Experiment 1: Parallel Operation of Three Phase Synchronous Generators…………………………………………………...…

Experiment 2: Slip Test for Determining Direct And Quadrature Axis Reactances of Synchronous Machines …………..…………….

Experiment 3: V-Curves Characteristics of A Synchronous Motor…… ….

Experiment 4: Effect of Rotor Resistance on Torque Speed Characteristics of Induction Motors …………………………

Experiment 5: Single Phase Induction Motors Characteristics ……………..

Experiment 6: Performance of Universal Motors …………………………...

Experiment 7: Parameter Identification of a Separately Excited DC Motor …………………………………………………....

Experiment 8: PI Speed Controller Design for a Separately Excited DC Motor …………………………………………………

Experiment 9: PI Controller Implementation of a Separately Excited DC Motor …………………………………………………

Appendix A: Quick Start with CASSY Lab

Appendix B: CASSY Lab Frequently Asked Questions

Appendix C: User's Instructions for Control Unit of Magnetic Powder Brake for the 1 kW Machines

Appendix D: Isolation Amplifier

Appendix E: Installation instruction of CASSY Lab

SAFETY GUIDELINES

To develop a healthy respect for electricity, it is important to understand how it acts, how it can be directed, what hazards it presents, and how these hazards can be minimized through safe laboratory procedures.

How Shock Occurs

Electricity can travel only in a closed or looped circuit. Normally, travel is through a conductor. Shock occurs when the body becomes a part of the electric circuit. The current must enter the body at one point and leave at another.

Shock may occur in one of three ways; the person must come in contact

1. With both wires of the electric circuit;
2. With one wire of an energized circuit and the ground or
3. With a metallic part that has become "hot" by itself being in contact with an energized wire, while the person is in contact with the circuit ground.

It is possible to receive a shock by touching only the energized wire, or an energized metallic part, and the ground because of the nature of an electric circuit. An electric circuit constitutes a completely continuous path. It starts at the generator, flows through wires (conductors) to the transformer, and back to the generator. In the transformer, the voltage is reduced (or increased) and flows into the building, where it is used to do useful work, and then back to the transformer. The generator and the transformer both have direct connections to the ground, and the current will use these paths if its normal path of return is broken and if it can get to the ground.

To receive a shock, a person must become part of an actual circuit; that is, the current must flow through his body as it would through a conductor. Under certain conditions, a person may be exposed to electricity but, unless his body becomes part of a circuit, no harm results. If, for instance, a person is standing on an insulating mat and touches only one wire of a 120-volt circuit, no

complete circuit is established and he will feel no shock. If, however, a person should touch both conductors of a circuit, even with the same finger, the finger becomes part of the circuit, current flowing through the finger from one side of the circuit to the other. For this reason, shock occurs when a finger is placed in a lamp socket (It is difficult to touch the base of the socket without also touching the side.)

Severity of The Shock

The severity of the shock received when a person becomes a part of an electrical circuit is affected by three primary factors. These factors are: (1) the rate of flow of current through the body, measured in amperes; (2) the path of the current through the body, and (3) the length of time the body is in the circuit. Other factors which may affect the degree of shock are: the frequency of the current phase of the heart cycle when shock occurs, and the physical and psychological condition of the person.

Remember that electric shock is no joke - for three reasons:

1. A shock, even a small one, is more harmful if it passes through the heart. Electrical leads should be handled with one hand only, while the other is safely out of the way.
2. Under certain conditions, electricity can produce a painful burn.
3. A sudden, unexpected shock causes a fast reaction and the reaction can result in injury, either to the person getting shocked, or a bystander. Be especially cautious when the circuit contains coils and capacitors. These can cause shocks after power has been turned off.

It is a good idea in any lab where electricity is used to learn where the master disconnects is in case of emergency. All students should be aware of elementary first aid and what to do if an accident occurs, either to themselves or another student.

Few suggestions are

- **DON’T** ever turn power on until the circuit is checked.
- **DO** be ready to turn the power off fast.
- **DON’T** ever clown around.
- **DO** make connections with one hand.
- **DO** turn the power off after every use.
- **DO** be prepared ahead.
- **DO** put everything carefully away after use.
- **DO** keep leads neat and area clean.
- **DO** follow instructions.
- Open and free wires shall be avoided before energizing the circuit.
- Do not energize any circuit until the instructor checks it.
- The supply voltage of the table is **220 VAC** only. Please check the voltage rating of any equipment before plugging into the table sockets. Use proper supply voltage for all the equipments in the lab. If a 110 VAC supply is needed then ask the technician to provide it
- The range of difference power equipments should be correctly selected in right time. **Do not overload any equipment / instrument**
- Seek help of your instructor for any doubt about the circuit connection.
- **Modification to the circuit may only be performed when the system is switched off (zero voltage/ zero current)**
- Always use the coupling and shaft end guards to protect against contact to rotating parts.
- **After finishing the experiment, turn off all the supply and bring them back to zero reading before dismantling the circuit. The first connections to be removed during dismantling the circuit are connections from all the voltage supplies.**
- Normally it is not required to open the device’s housing. However, if necessary to open the housing then it must be performed by lab technician

and under the condition only when the mains plug and all connecting leads have been disconnected.

- Attention should be given to the proper routing of the cables related to experiment when connecting the rotating machines. **Cables should never have a chance to come into contact with rotating components**
- Machines are to be positioned immediately adjacent to one another with their base please securely bolted together
- **Connect the thermal switch of the motor to the "TEMP CONTROL" on the control unit.**
- **Connect all the "PE" or ground connections present on the motor, generator and the tacho generator panels to the "PE "connection of the supply.**
- **Ground all the ground connections of isolation amplifier, CASSY and profi-CASSY units.**
- When a DC motor is removed from its power source then subsequently driven by at the cradle dynamometer it ca go into generator operation, thus producing voltage which will continue to be present at its terminals.
- Safety of working shall be strictly observed and maintained by one of the group member throughout the experiment time.
- **Push the emergency button "RED BUTTON" present on the experiment table in case of any emergency or safety related events.**

EE-Power Lab Regulations:

- Please adhere to the lab timings.
- **Safety shoes and clothing** is strictly enforced for any activities in the lab
- Keep good house keeping while working in the lab and place the wires and other accessories at their specified locations after finishing the work.

EXPERMINAT # 1:	**PARALLEL OPERATION OF THREE PHASE SYNCHRONOUS GENERATORS**

Objectives:

- To study the conditions necessary to connect a three-phase alternators in parallel with the utility.
- To set up synchronizing circuit and understanding the synchronization process.
- To analyze the performance of the synchronous generator before and after synchronization.

Apparatus:

- AC Main supply (utility), 3-phase, 400 V , 60 HZ
- AC multifunction machine
- DC multifunction machine
- DC supply, 40-250 V / 10 A
- DC supply , 0-250 V / 2.5 A
- Tacho generator
- Synchronization indicator
- Three Phase ON/OFF switch
- Variable resistance (Rheostat)
- Multifunction meter
- AC Ammeter, 0 – 10 A
- 2 AC Voltmeters, 0 – 400 V
- 2 Analog frequency meters
- Couplings guards
- Isolation Amplifier, CASSY unit, Profi- CASSY unit and PC

Theory:

Using an isolated synchronous generator to supply its own load independently is very rare (such a situation is found only a few out-of-the –way applications such as emergency generators). For all usual generator applications, there is more than one generator operating in parallel to supply the power demanded by the load.

There are several advantages of connecting the synchronous generator in parallel. Some of the advantages are:

1. Several generators can supply a bigger load than one machine by itself.
2. Having many generators increase the reliability of the power system, since the failure of any one of them dose not cause a total power loss to the load.
3. Having many generators operating in parallel allows one or more of them to be removed for shutdown and preventive maintenance.
4. If only one generator is used and it is not operating at near full load, then it will be relatively inefficient. But with several smaller machines it is possible to operate only a fraction of them. The ones that do operate are operating near full load and thus more efficiency.

It is possible to connect a synchronous generator, which has already been excited and is being driven at its nominal speed, to three-phase power lines. To accomplish this, there are three conditions that must be met:

1. The magnitude and phase angle of generated voltage must be equal to voltage and phase of the main power line.
2. The frequency of the voltage generated by the generator must be equal or slightly higher than the frequency of the main power line.
3. The phase sequence of both the generated voltage and the power line must be the same.

These paralleling conditions required some explanations. Condition 1 is obvious, in order for two sets of voltage to be identical; they must have the same RMS magnitude of voltage. The voltage in phase “ A ” and “ A' ” will be completely identical at all times if both their magnitudes and their angles are the same, which explains condition 3.

Condition 2 ensures that the sequence in which the phase voltage peak in the generator and the power line is the same. If the phase sequence is different, then even though one pair of voltages (the ‘A’ phases) are in phase, the other two pairs of voltages are 120º out of phase. If the three phase switch is connected in this manner, there would be no problem with phase ‘A’, but huge current would flow in phase ‘B’ and ‘C’, damaging the machine. To correct the phase sequence problem, simply swap the connection on any two of the three phases on the generator or utility side.

If the frequencies are not very nearly equal at the time of synchronization, large power transient will occur until the generator stabilizes at a common frequency. The frequencies must be very nearly equal, but they cannot be exactly equal. They must differ by a small amount so that the phase angles of the oncoming machine will change slowly with respect to the phase angles of the running system. In that way, the angles between the voltages can be observed and the synchronization switch can be closed when the systems are in phase.

The simplest way to match the power lines and the generated voltage is done with the help of special synchronizing lamp placed between the power lines and the generator. Since it is possible that during the synchronizing process an unfavorable phase relationship may exist between power lines and generator that could place as much as twice the phase voltage across the lamps, two lamps are connected in series to form a pair. In the “dark-lamp circuit” method, lamps are placed between the same phase of the power lines and the generator. The machine can be connected to the power lines at the time when all lights are

simultaneously off. The parallel connection may be made only if the illumination rotation stops and the lamps are dark.

Procedure:

Please follow the following steps carefully

1. Note the rated values of current, voltage and speed of the synchronous generator as well as the motor that will drive the generator and enter it into the table 1.

Table 1: Machine ratings

DC Multifunction Machine		AC Multifunction Machine	
Model No.		Model No.	
Rated Voltage		Rated Voltage	
Rated Current		Rated Current	
Rated Power		Rated Power	
Rated Speed		Rated Speed	
		Power Factor	
		Frequency	

2. Connect the circuit shown in Fig. 1.
3. Connect all the "PE" or ground connections present on the motor, generator and the Tacho generator terminals to the "PE "connection of the supply.
4. Switch ON the Isolation Amplifier and Profi-CASSY. Note that the channel A measures the utility voltage E_u and the channel B measures the generator voltage E_G.
5. Adjust the scale of the channels A & B of isolation amplifier at "1/100" settings.
6. From the PC, run the CASSY lab software

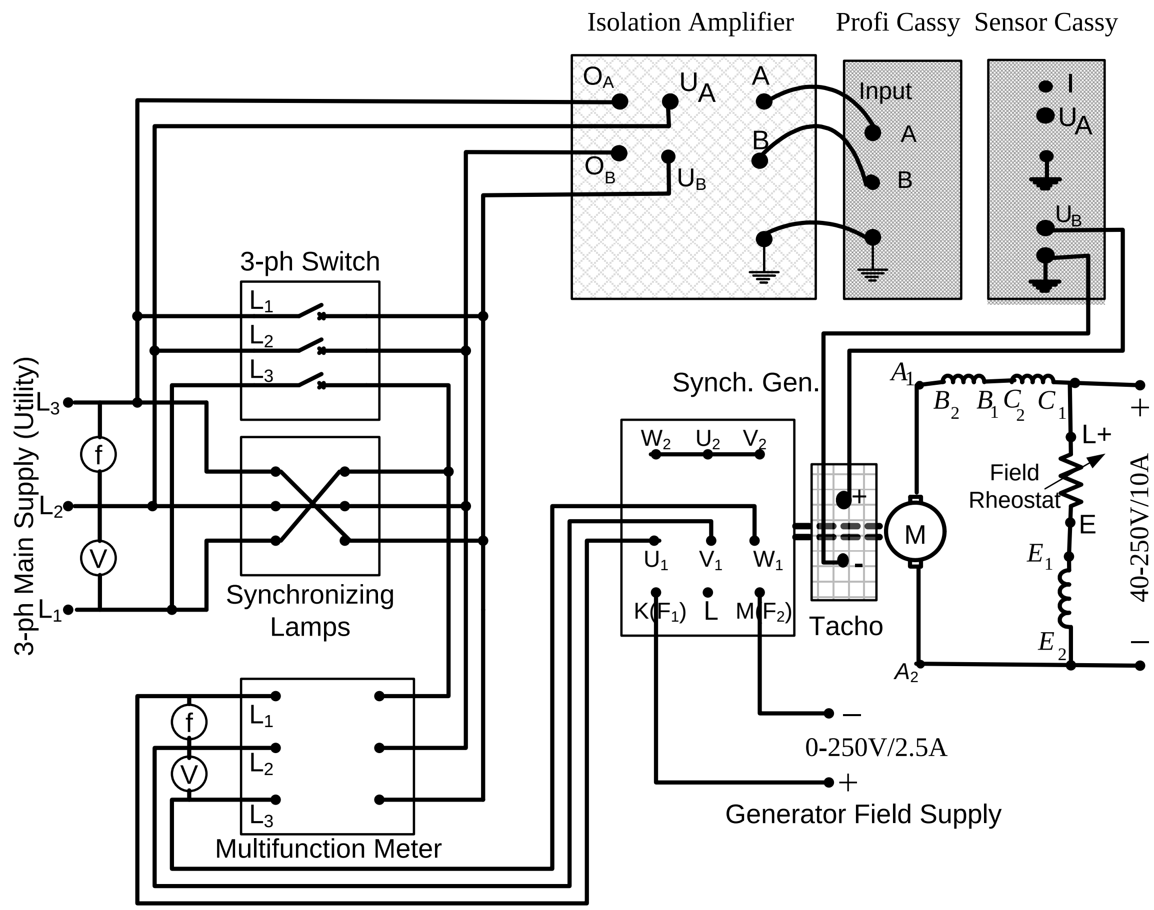

Fig. 1: Connection diagram of synchronous generator with the utility

7. From the “CASSY”, activate channels UA1 and UB1. Select “ RMS” value option for both channels
8. From the “CASSY”, activate channel UB2. Select “ Average” value option for this channel
9. From “Parameter / Formula / FFT” option, use new quantity to define the utility voltage E_u as (UA1* 100) from the formula option. Accordingly adjust the symbol, unit, and the range (0 – 400 V).
10. Repeat the above step to define the generator voltage E_G as (UB1*100) with a range of (0 – 400 V) and the speed N as (UB2*1000) with a range of (0 – 2000 rpm).

11. From “Parameter / Formula / FFT” option, use new quantity to define the generator frequency f_G as (N/30), why? Accordingly adjust the symbol, unit, and the range (55 – 65 Hz).
12. Double click on the “setting” icon to select the measuring parameters. Check the “ Automatic Recording” option.
13. From the “Display” option, select time t as x-axis and $E_{u,}$ E_G and f_G as y-axis. Switch off all other signals.
14. **Ask the instructor to check your connections and CASSY lab settings. Do not proceed to next stage unless your connections and settings are completely examined by the instructor.**
15. Make sure that the 3-phase ON/OFF switch is at OFF position.
16. Make sure that all the variable DC supplies in the circuit are at zero position.
17. Turn on the main 400 V AC supply. Check the readings of voltmeter and the frequency meter in the utility side.
18. Start recording of the data in the CASSY lab software by clicking “F9”
19. Turn on the motor variable DC supply and set it at 200 V.
20. Turn on the field supply of the generator and increase it slowly up to 15 V so that the generator will build up voltage.
21. Adjust the field voltage of the generator to get the generated voltage equal to the main supply voltage
22. Adjust the motor field rheostat to get the motor speed equal to the synchronous speed of the generator, i.e. 1800 RPM. This ensures the frequency of the generation is equal to the frequency of the utility (60 Hz).
23. From the multifunction meter, read and record for the Line-Line and Line-Neutral voltages in all the three lines, real and reactive powers

generated, frequency and power factor of the generator. Enter these values in table 2.

24. Check the phase sequence of the generated voltage and the main supply by observing the ON-OFF sequence of the lamps. If the lamps illuminate and go out ***alternatively*** then phase rotation of the generator mismatches with that of the main power supply. Any two leads of the generator stator terminal should be swapped to correct the phase sequence. **Make sure that the lamps are flashing all together**.
25. With the lamps flashing together, adjust the speed of generator until the flashing has stopped and the lamps are dark (Dark-Lamp Method).
26. **At the moment where the lamps are completely dark**, turn ON the three-phase switch to connect the synchronous generator in parallel with the utility.
27. Stop recording of the data in the CASSY software by clicking "F9" and save your file.
28. From the multifunction meter, read and record for the Line-Line and Line-Neutral voltages in all the three lines, real and reactive powers generated, frequency and power factor of the generator. Enter these values in table 2.
29. After synchronization, observe the change in the real power, reactive power and the power factor by increasing motor supply voltage.
30. Repeat and observe the change in the real power, reactive power and the power factor by varying of the field voltage of the generator.
31. Turn OFF the 3-phase switch to disconnect the generator from utility.
32. Decrease the motor voltage to zero.
33. Decrease the generator field voltage to zero.
34. Switch OFF all power supplies.

Table 2: Wattmeter readings before and after synchronization

Wattmeter readings	**Before synchronization**	**After synchronization**
$\mathbf{V_{L1-N}}$		
$\mathbf{V_{L2-N}}$		
$\mathbf{V_{L3-N}}$		
$\mathbf{V_{L1-L2}}$		
$\mathbf{V_{L2-L3}}$		
$\mathbf{V_{L3-L1}}$		
P		
Q		
cosφ		
Frequency		

Report:

1. Complete table 1.
2. Complete table 2. Comment on the results obtained before and after synchronization
3. Copy the plots obtained during the experiment and put it in the report. Identify the instant of synchronization from the computer plots obtained.
4. Comment on the difference in wattmeter readings before and after synchronization
5. What happen if after synchronization, the motor field supply is varied?
6. What happen if after synchronization, the generator field supply is varied?

EXPERIMENT # 2:	**SLIP TEST FOR DETERMINING DIRECT AND QUADRATURE AXIS REACTANCES OF SYNCHRONOUS MACHINES**

Objectives:

To determine the direct axis (X_d) and quadrature axis (X_q) reactances of a 3-phase salient pole and cylindrical synchronous machine.

Apparatus:

- 1 Variable AC power supply 0- 400V / 2.5A.
- 1 AC multifunction machine
- 1 DC multifunction machine
- 1 Variable DC supply , 40-250 V / 10 A
- 1 Tacho generator
- 2 Couplings with coupling guards
- 3 Shaft end guards
- Isolation Amplifier, CASSY unit, Profi- CASSY unit and PC
- Sufficient quantity of safety cables

Theory:

Because of saliency, the reactance measured at the terminals of a salient-pole synchronous machine as opposed to a cylindrical-rotor machine varies as a function of the rotor position. The effects of saliency are taken into account by the two-reactance theory. The armature current I_a is resolved into two

components: I_d in time quadrature with, and I_q in time phase with the excitation voltage E_f, Figures 1-a and 1-b, in which δ is the torque angle or the power angle, ϕ is the power factor angle, and $(\delta + \phi)$ is the internal power angle ψ.

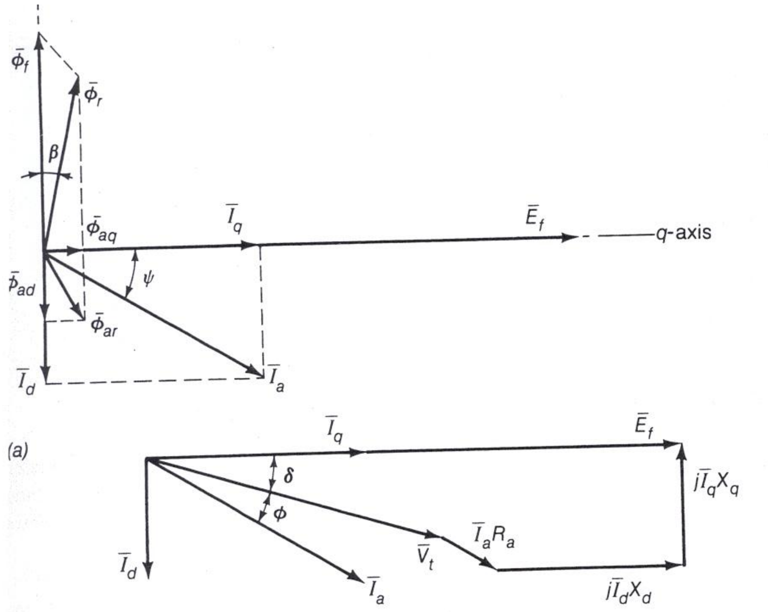

Fig. 1: Phasor diagram of an unsaturated salient pole synchronous generator operating at lagging power factor.

Referring to figure 1-b, the terminal current I_a may be expressed as follows, while taking the terminal voltage V_t as a reference:

$$\vec{I_a} = V_t \frac{X_d + X_q}{2X_d X_q} e^{j\Pi/2} + V_t \frac{X_d - X_q}{2X_d X_q} e^{j(2\delta - \Pi/2)} + \frac{E_f}{X_d} e^{j(\delta - \Pi/2)} \quad (1)$$

Thus the salient-pole synchronous machine delivers three components of current to the bus. The second term on the right side of equation 1 vanishes for a round-rotor synchronous machine, because X_d equals X_q. Even for no excitation (E_f=0), as for a salient-pole synchronous machine, it can be seen that the

current has an active component. With sufficient excitation, the current can be made equal to zero. For example, at no-load, for δ =0 and $E_f = V_t$, I_a becomes zero. Further, it can be seen that, for $E_f = 0$,

$$I_a = I_{max} = \frac{V_t}{X_q} \quad \text{for } \delta = \frac{\Pi}{2} \qquad (2)$$

and

$$I_a = I_{min} = \frac{V_t}{X_d} \quad \text{for } \delta = 0 \qquad (3)$$

The current wave is an amplitude-modulated wave, provided δ is varied slowly. This analysis suggests a method of determining the direct-axis and quadrature-axis steady state (or synchronous) reactances of a synchronous machine by a test known as the ***slip test***. The machine is unexcited, and balanced voltages are applied at the armature terminals. The rotor is driven at a speed differing slightly from synchronous speed (which is calculated from the frequency of the applied voltage and the number of poles of the machine). The armature currents are then modulated at slip frequency by the machine, having maximum amplitude when the quadrature axis is in line with the mmf wave and minimum amplitude when the direct axis aligns with the mmf wave. The armature voltages are also usually modulated at slip frequency because of impedences in the supply lines, the amplitude being greatest when the current is smallest, and vice versa. Such variations of voltage and current are illustrated in the oscillograms of Figure 2. The maximum and minimum values of the voltage and current can also be read on a voltmeter and an ammeter, provided the slip is small. The field winding should be kept open in the slip test so that the slip-frequency current is not induced in it.

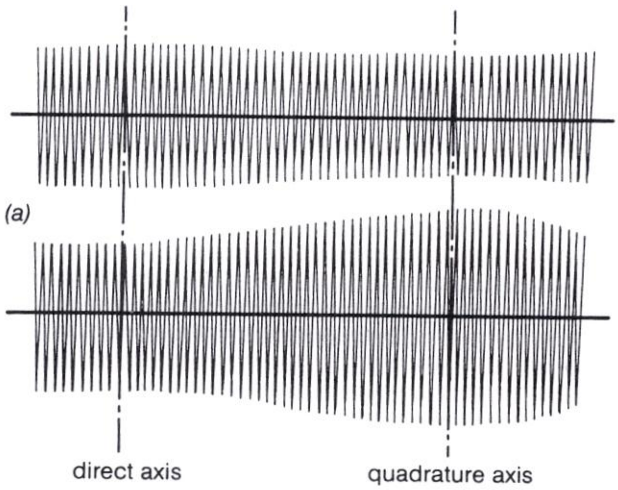

Fig.2: Slip test oscillogram. (a) Armature voltage variation. (b) Armature current variation

The direct axis reactance X_d can now be calculated from the ratio of maximum voltage to minimum current:

$$X_d = \frac{V_{max} / \sqrt{3}}{I_{min}} \quad (4)$$

On the other hand, the quadrature axis reactance X_q is given by the ratio of minimum voltage to maximum current.

$$X_q = \frac{V_{min} / \sqrt{3}}{I_{max}} \quad (5)$$

Procedure:

Note the rated values of current, voltage and speed of the synchronous machine as well as the DC motor and enter it into the Table 1.

Table 1: Machine ratings

DC Multifunction Machine		AC Multifunction Machine	
Model No.		Model No.	
Rated Voltage		Rated Voltage	
Rated Current		Rated Current	
Rated Power		Rated Power	
Rated Speed		Rated Speed	
		Power Factor	
		Frequency	

(a) For cylindrical rotor synchronous machines

1. Connect the circuit as shown in the wiring diagram of Figure 3. Make sure that the switch S_1 is open.
2. Set the "**Isolation Amplifier**" as follows: in case of current measurement, set the Switch to "1 V/A"; and in the case of voltage measurement, set the Switch to "/100".
3. From the PC, run the CASSY lab Software. Activate channels (UA1), (UB1) and (UB2). Select "RMS" value option for UA1, UB1, and average value for UB2.
4. Click on **Tool Box Button** and click on the "**Parameter/Formula/FFT**" option. Define the voltage as UA1*100 with a scale of -100 to 100, the current as UB1 with a scale of -0.2 to 0.2 , and the speed as UB2*1000 with a scale of 0 to 2000 rpm.
5. Double click on the **Tool Box Button** and set the measuring parameters as follows: Meas. Interv: 500 μs, x Number: 1000 and = Meas. Time : 500 ms.

6. From the "**Display Button**", select the x-axis as time and the y-axis as voltage and current. Switch off all other channels.

7. **Ask your instructor to check your connections and CASSY Lab settings. Do not proceed to the next stage unless your connections and settings are completely examined by the instructor.**
8. Using the DC motor as a prime mover, adjust the variable DC power supply connected to the DC motor to a value of 40 V. Make sure that the direction of rotation is clockwise. If not, exchange the field connection E_1 and E_2.
9. Switch off the DC motor by reducing the variable DC power supply to zero value.
10. Short circuit the multifunction AC machine slip rings KLM.
11. Increase the output line voltage of the variable AC power supply until the machine rotates.
12. Observe the direction of rotation and make sure it is rotating clockwise. If not, exchange any two phases of the supply.
13. Reduce the AC power supply to zero.
14. Remove the short circuit on KLM of the multifunction AC machine.
15. Run the DC prime mover to a speed between 1700 and 1750 rpm and increase the AC line-to line voltage to a value of 70V.
16. Using CASSYLab software, start recording the results by pressing F9. Record the maximum and minimum values of voltage and current in Table 2.
17. Save the file with a proper name.
18. Repeat steps 15 to 17 at a speed of 1800 rpm. To get the speed of 1800 rpm, you need to increase the DC prime mover voltage.

(b) For salient pole rotor synchronous machine

1. Replace the cylindrical rotor machine by the salient pole Hampdon Synchronous machine.

2. Connect the DC prime mover as shown in Figure 4. Be sure of replacing the connections as follows: L1 to A, L2 to B, and L3 to C. **This is an important sequence.**

3. Repeat steps 15 to 18.

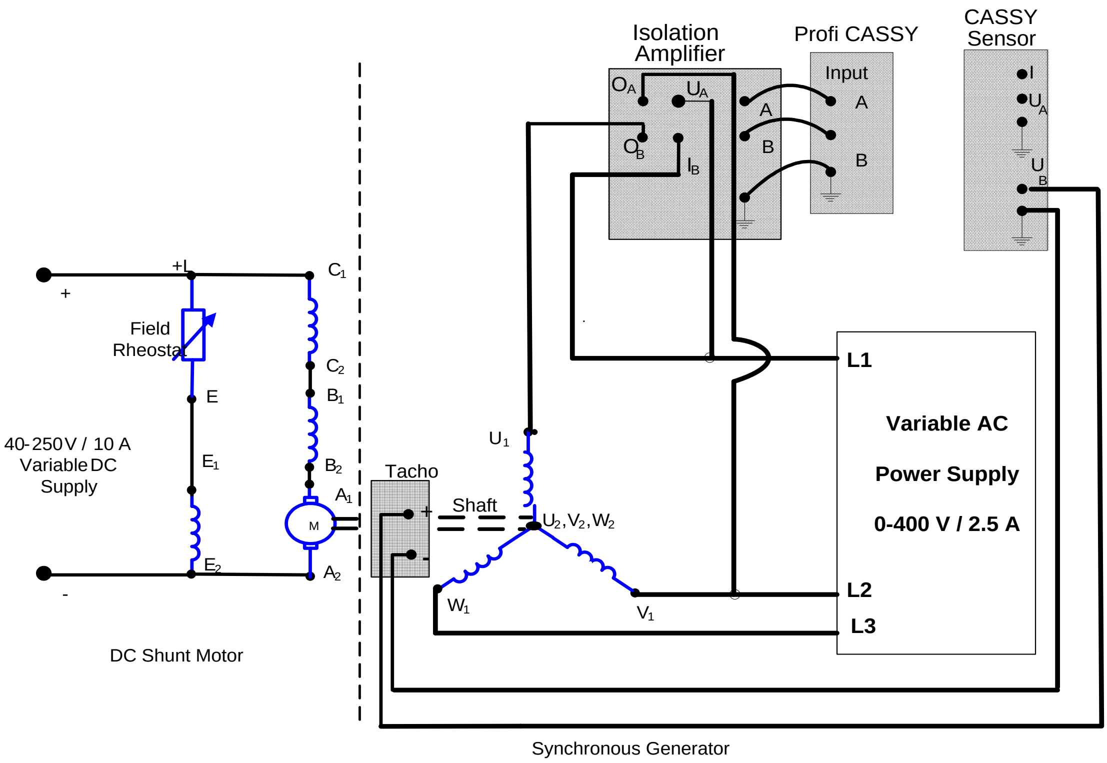

Fig. 3: Wiring diagram for the slip test

Table 2: Cylindrical Rotor Machine

Motor speed (rpm)	V_{max} (V)	V_{min} (V)	I_{max} (A)	I_{min} (A)	X_d (Ω)	X_q (Ω)
1700 -1750 N =						
1800						

Table 3: Salient-Pole Rotor Machine

Motor speed (rpm)	V_{max} (V)	V_{min} (V)	I_{max} (A)	I_{min} (A)	X_d (Ω)	X_q (Ω)
1700 -1750 N =						
1800						

<u>Report:</u>

1. Using the files obtained complete tables 2 and 3. Include all figures and measurement in your report.
2. For the cylindrical rotor machine and at a speed in the range 1700-1750 rpm, is their any difference in the values of X_d and X_q. Justify your answer.
3. Repeat step 2 for the salient pole machine.
4. For the cylindrical rotor machine and at speeds in the range 1700-1750 rpm and 1800 rpm, is their any difference in the values of X_d and X_q. Justify your answer.
5. Repeat step 2 for the salient pole machine.
6. Plot X_d and X_q at different speeds for both salient and cylindrical machines.
7. Write a formal report that includes all measurements and calculations.
8. Write a solid conclusion out of your findings.

EXPERMINAT # 3:	V-CURVES CHARACTERISITICS OF A SYNCHRONOUS MOTOR

Objectives:

- To study the starting process and operation of the synchronous motors.
- To study the synchronous motor V-Curves characteristics at different torque input.
- To locate the unity power factor, leading and lagging regions of the synchronous motor V-Curves characteristics.
- To investigate the major differences between the asynchronous (induction) motors and synchronous motors.

Apparatus

- Variable AC power supply 0 – 400 V / 2.5 A
- Variable DC supply 0 – 24 V / 0 – 20 A
- AC multifunction machine
- Dynamic Brake arrangement
- Tacho generator
- Y-Δ switch
- Three phase ON / OFF switch
- Coupling with coupling guards
- Shaft end guard
- Control unit
- Isolation Amplifier, CASSY unit, Profi- CASSY unit and PC

Theory:

Synchronous motor is an AC motor. The synchronous motor is a rotating field machine which operates without slip. The rotor speed and the rotating field speed are exactly equal. Therefore, three-phase synchronous motors are mainly used where a constant speed operation is desired.

The synchronous motor consists of the stator and the rotor, also called armature. The three phase winding in the stator of the motor is excited by the three phase mains and produces a rotating magnetic field. In the rotor, a DC field is produced by the DC excited winding. The stator rotating field poles have an effect on the rotor DC field poles. Due to its inertia, the rotor, stationary at motor switch on, cannot follow the rotating stator field which rotates with synchronous frequency. The rotor poles experience a force from the stator poles but this force is constantly changing direction at a rapid-rate. It is only the rotor speed of the stator magnetic field that the rotor field is locked to the stator field. The rotor is then pulled into synchronization and rotates at the same speed as the stator field. The synchronous machine, therefore, cannot start independently. In order to start the synchronous motor, the three phase rotor windings is closed by connecting rotor terminals. The motor then starts as three-phase induction motor. When run-up has been achieved, the connection of the rotor terminals is opened again and the motor is then excited with a DC current. This pulls the motor into synchronization and the multi-function machine operates as synchronous motor. In this experiment, switchover is carried out using Y-Δ switch.

In a synchronous motor, the consumption from the three-phase mains is not only dependent on the load at the shaft i.e. on the required torque. It is also the case that the exciter current for the magnetic DC field in the rotor influences the stator field. When the exciter current is set so that at a certain load torque, power factor is 1, then the synchronous motor consumes the lowest stator

current for this load torque. This current is a purely active current. That means that in this case, the synchronous motor neither receives nor delivers reactive power to or from the three-phase mains.

If the rotor excitation is subsequently reduces at a constantly held load torque, then the current consumption from the three-phase mains increases. The synchronous motor now receives inductive reactive power from the three-phase mains. i.e. the motor is in under-excited mode.

If the rotor excitation is subsequently increased at a constantly held load torque, then the current consumption from the three-phase mains also increases. But this time, the synchronous motor now receives capacitive reactive power from the three-phase mains. i.e. the motor is in over-excited mode.

The current consumption from the three-phase mains as a function of the exciter current has V-shaped curve. As a result these curves are also called the V-characteristics of the synchronous motor.

If the exciter current drops too much then the pull-out torque of the synchronous motor sinks below the momentary load torque. The synchronous motor falls out of synchronization and comes to a stand still.

The synchronous motor offers very good possibilities of improving power factor. A synchronous motor is frequently used instead of capacitors in large systems as a dynamic phase shifter for the compensation of reactive power. Hereby, the synchronous motor is operated at no-load in over excitation mode. By altering the rotor excitation, the power factor can be brought to the desired value with any type of load in the mains.

Procedure:

Please follow the following steps carefully.

1. Note the rated values of current, voltage and speed of the synchronous motor and enter it into the table 1.

AC Multifunction Machine	
Model No.	
Rated Voltage	
Rated Current	
Rated Power	
Rated Speed	
Power Factor	
Frequency	

Table 1: Machine ratings

2. Use the following formula to get the nominal torque, T_N of the motor by substituting the values of nominal power P_N and nominal speed N present on the name plate of the motor.

$$T_N = \frac{P_N \ x \ 9.55}{N} \quad (1)$$

3. Connect the circuit given in Fig. 1.
4. Connect the thermal switch of the motor to the “TEMP CONTROL” on the control unit.
5. Connect all the “PE” or ground connections present on the motor, generator and the Tacho generator panels to the “PE “connection of the supply.
6. Switch ON the Isolation Amplifier and Profi-CASSY. Note that the channel A of the isolation amplifier measures the armature current I_L and channel B measures the field current I_F. Adjust the scale of the channel A of isolation amplifier at “1 V/ A” and channel B at 1/3 V/A settings.
7. From the PC, run the CASSY lab software.
8. From the “CASSY”, activate channel UA1. Select “RMS” value option.
9. From the “CASSY”, activate channel UA2, UB1 and UB2. Select “Average” value option for all.

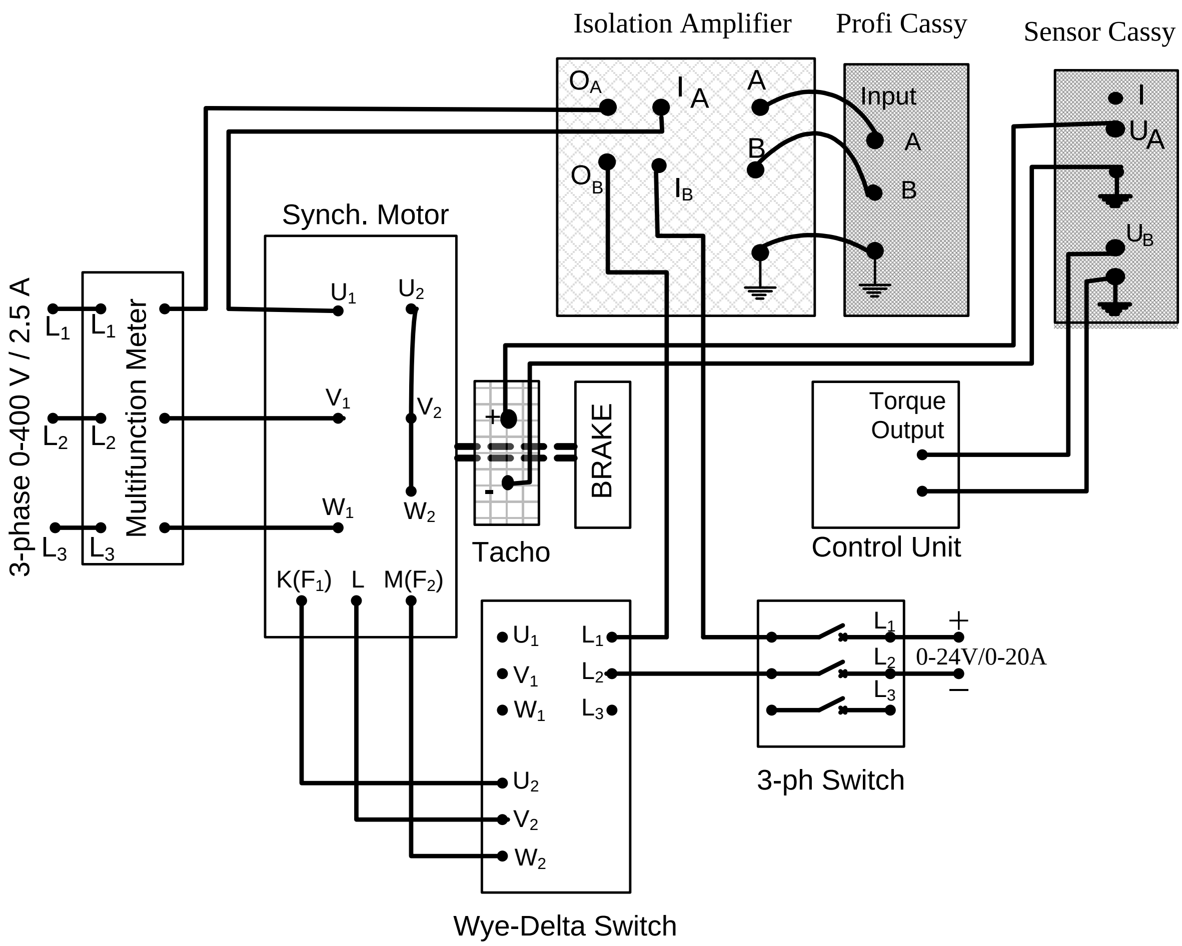

Fig. 1: Connection diagram for the V-characteristics of the synchronous motor

10. From "Parameter / Formula / FFT" option, use new quantity to define armature current I_L as (UA1) from the formula option. Accordingly adjust the symbol, unit, and the range (0 – 10 A).
11. Repeat above steps to define the field current I_F as (UB1*3) with a range of (0 – 20 A), the speed N as (UA2*1000) with a range of (0 – 2000 rpm) and the torque T as (UB2) with a range of (0 – 10 Nm).
12. From the "Display" option, select I_F as x-axis and I_L as y-axis. Switch off all other signals.
13. Double click on the "setting" icon to select the measuring parameters. Check the "Manual Recording" option.
14. Make sure that all supplies are at zero voltage position.

15. Set the Y-Δ switch at Y position and three phase switch at OFF position.
16. Adjust the torque to zero via the “BRAKE” in the control unit. Select a scale of 10 NM and “MAN” position 1. Set n_{min} to 10% and M_{max} to 60%.
17. **Ask the instructor to check your connections and CASSY lab settings. Do not proceed to next stage unless your connections and settings are completely examined by the instructor.**
18. Turn ON the variable DC supply and set it to some value e.g. 10 V.
19. Turn ON the three phase AC supply and increase the voltage to 400 V. The motor will start in induction mode. Check and record the motor speed from the CASSY.
20. From the multifunction meter, read and record the real power, reactive power, and power factor. Enter these values in table 2.
21. ***Simultaneously***, turn ON the three phase switch and moving the Y-Δ switch to the Δ position. The motor is now working in synchronous mode. Check and record the motor speed from the CASSY (the speed will reach to the synchronous speed i.e., 1800 RPM).
22. From the multifunction meter, read and record the real power, reactive power, and power factor. Enter these values in table 2.
23. Raise the DC power supply voltage to 20 Volt.
24. Press “F9” of the computer to record this value.
25. In 10 – 15 steps, reduce the DC supply voltage with a 2 V step to reduce the excitation current I_F. Press “F9” for recording after each step. As the motor starts hunting, increase the voltage to 20 V quickly.
26. Save the measurements in the CASSY software with a proper name.
27. Go to the CASSY lab software and double click on the “setting” icon to select the measuring parameters. Check the “Append New Meas. Series” recording option.
28. Increase the torque to 1.0 NM by rotating the “BRAKE” knob on the control panel.

29. Repeat steps 23 to 27 for 1 NM loading condition. This time while saving overwrite the file saved in step 26.
30. Repeat steps 23 to 27 for 2.0 NM and 3.0 NM loading conditions.
31. ***Simultaneously***, turn OFF the three phase switch and moving the Y-Δ switch to the Y position. The motor is now working as induction motor again.
32. Reduce the 3-phase supply to zero voltage.
33. Switch OFF all supplies
34. Right click mouse at any place on the graph window and select first "Set Marker", and then "Text". Label all the curves with their corresponding torque values.

Table 2: Wattmeter readings before and after synchronization

	Induction motor	**Synchronous motor**
P		
Q		
cosφ		
Speed		

<u>Report:</u>

1. Complete table 1 and table 2.
2. In view of the measurements recorded in table 2, state the major differences between the induction motors and synchronous motors.
3. Calculate the nominal torque of the synchronous motor
4. Include in your report the recorded V-curves plots at different loading torque conditions.
5. Click on right mouse at any place on the graph window and select first "Set Marker", and then "Text". Label all the curves with their corresponding torque values.

6. For each V-curve, identify the minimum excitation current, I_F , below which the synchronous motor pulls out of synchronism.
7. Identify the unity power factor, leading and lagging power factor regions of each V-curve. Specify whether the reactive power is generated or absorbed in each region.

EXPERIMENT # 4:	**EFFECT OF ROTOR RESISTANCE ON TORQUE SPEED CHARACTERISTICS OF INDUCTION MOTORS**

Objectives:

- To obtain the torque speed characteristics of 3-phase induction motors.
- To investigate the effect of varying the rotor resistance on the torque speed characteristics.

Apparatus:

- 1 kW three-phase multifunction machine.
- Three-phase AC supply.
- Magnetic brake
- Control unit
- Tachometer
- Multi Function Meter
- Couplings and coupling guards.
- Rotor starter.
- Isolation Amplifier, Profi-CASSY, Sensor-CASSY, and PC

Theory:

The three-phase squirrel-cage induction motor can, and many times does, have the same armature (stator) winding as the three-phase synchronous motor. As in the synchronous motor, applying three-phase currents to the armature creates a synchronously-rotating magnetic field.

The induction motor rotor is a completely short-circuited conductive cage. Figures 1 and 2 illustrate the rotor construction.

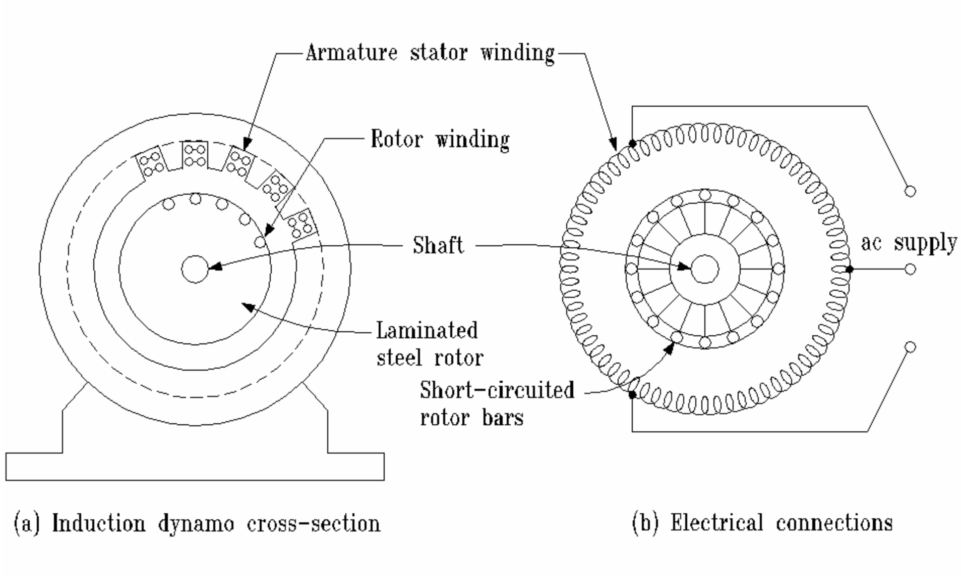

Figure 1: Induction machine construction.

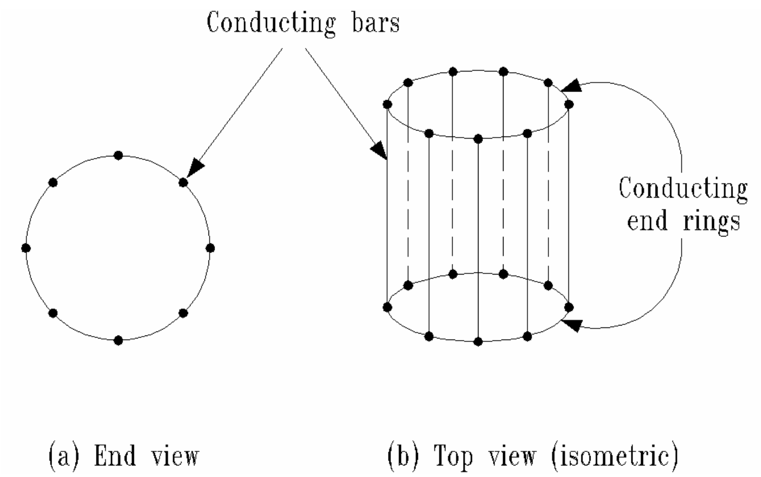

Figure 2: Squirrel-case rotor.

The rotor receives its excitation by induction from the armature field. Hence, the induction machine is a doubly-excited machine in the same sense as the synchronous and DC machines.

The basic principle of operation is described by Faraday's Law. If we assume that the machine rotor is at a standstill and the armature is excited, then the armature-produced rotating field is moving with respect to the rotor. In fact, the relative speed between the rotating field and the rotor is synchronous speed. For this condition, the rotating field induces a large voltage in the rotor bars. The large voltage causes a large current in the squirrel-case which, in turn, creates a magnetic field in the rotor. The rotor magnetic field interacts with the armature magnetic field, and a torque is produced. If the produced torque is larger than any load torque, the rotor begins to turn. As the rotor accelerates, the speed difference between the rotor and the armature field is reduced. This reduced speed difference (or slip) causes the induced rotor voltage to be reduced, the rotor current to be reduced, the rotor flux to be reduced, and the torque produced by the machine to be reduced. Eventually, the torque produced by the motor equals the torque demanded by the load, and the motor settles to an equilibrium rotor speed. This equilibrium rotor speed must be less than synchronous speed since there must be a slip to produce torque.
The frequency-dependent nature of the rotor impedances causes the torque versus speed characteristic of the induction motor to be quite non-linear.

Designers have learned to design rotors for specific torque characteristics. The National Electrical Manufacturers Association NEMA has classified and standard designs which satisfy a range of torque-speed characteristics. Figure 3 shows the NEMA designs and the rotor bar geometries that produce the responses.

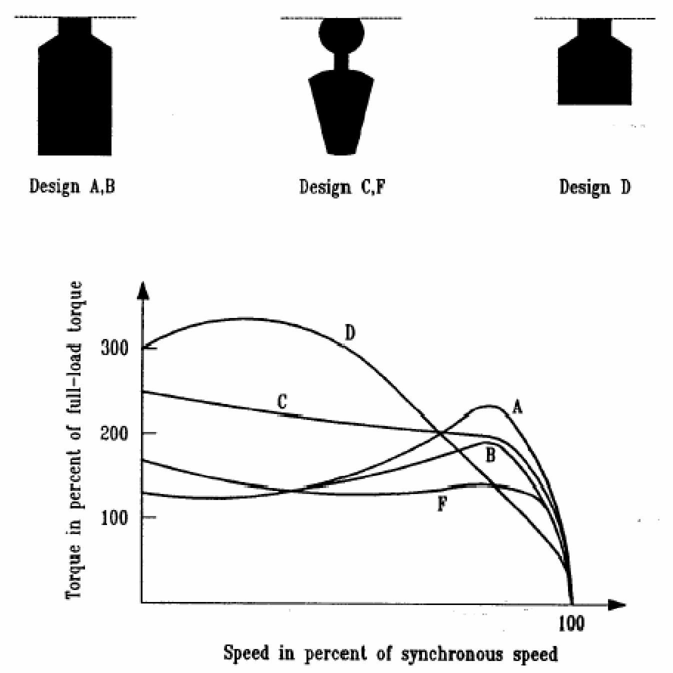

Figure 3: Effects of rotor bar geometry on torque characteristics in squirrel-case machines.

Procedure:

Note the rated values of current, voltage and speed of the synchronous machine as well as the DC motor and enter it into the Table 1.

Table 1: Machine ratings

AC Multifunction Machine	
Model No.	
Rated Voltage	
Rated Current	
Rated Power	
Rated Speed	
Power Factor	
Frequency	

1. Connect the circuit as shown in the wiring diagram of Figure 4. **Make sure that switch "S" is at "OFF" position.**

2. Connect the motor thermal protection to the **“TEMP. ALARM”** in Control Unit.

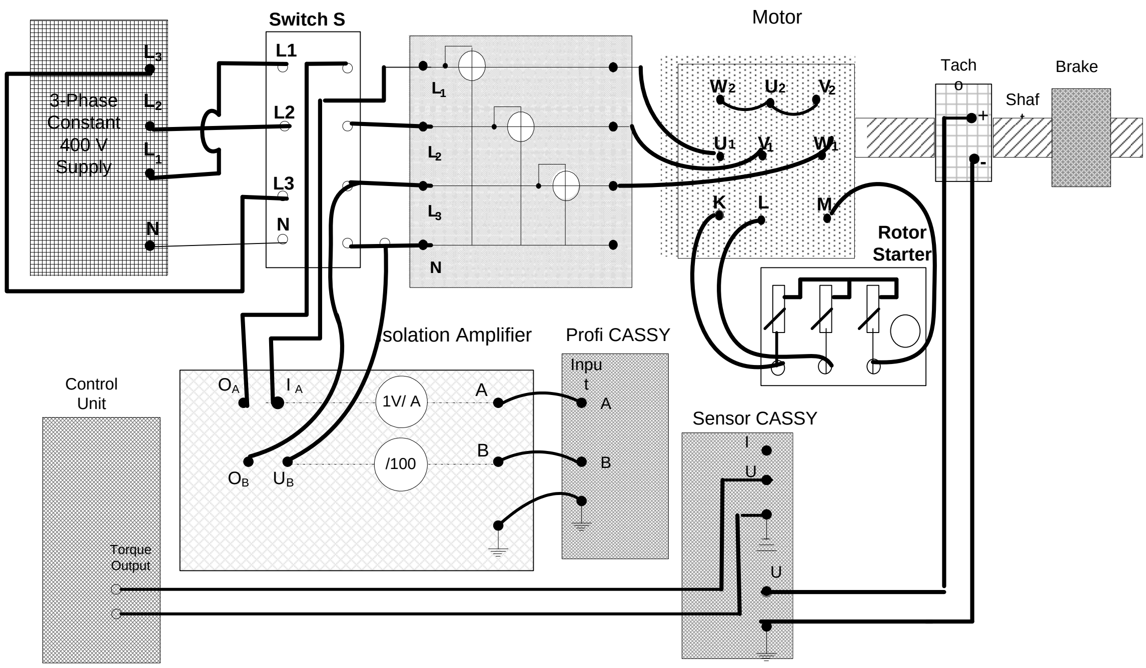

Figure 4: Wiring diagram

3. Set the "**Isolation Amplifier**" as follows: in case of current measurement, set the Switch to "1 V/A"; and in the case of voltage measurement, set the Switch to "/100".
4. From the PC, run the CASSY lab Software. Activate channels (UA1), (UB1), (UA2), and (UB2). Select “RMS” value option for UA1, UB1, and average value for UA2 and UB2.
5. Click on **Tool Box Button** and click on the “**Parameter/Formula/FFT**” option. Define the current as UA1 with a scale of 0 to 6 A, the voltage as UB1*100 with a scale of 0 to 230 V, the torque as UA2*3 with a scale of 0 to 10, and the speed as UB2*1000 with a scale of 0 to 2000 rpm.
6. Set the control unit as follows:
    - Set the torque scale to 30 which gives maximum torque of 30 Nm.
    - Select the **Ramp** control mode of the load, i.e., set the load to “Ramp 1” mode.
    - Set n_{min}% to 20. This will prevent the motor speed to drop below 20% of the synchronous speed.
    - Set M_{max}% to 60. This will limit the maximum torque to 60% of 30 Nm, i.e., 18 Nm.
7. Double click on the **Tool Box Button** and set the measuring parameters as follows: **Automatic** recording, and **"Append new meas. Series".**
8. From the "**Display Button**", select the x-axis as Speed and the y-axis as Torque and Current. Switch off all other channels.
9. **Ask your instructor to check your connections and CASSY Lab settings. Do not proceed to the next stage unless your connections and settings are completely examined by the instructor.**
10. Select position **"6"** on the rotor starter. This corresponds to zero external resistance on the rotor.
11. Switch **"ON"** the constant three-phase supply.
12. Change switch **"S"** to **"ON"** position.

13. On the control unit, press **"start"** to apply the load automatically and press "**F9"** on the computer keyboard at the same time to start recording.
14. Monitor the speed of the motor on the computer and change the "**S"** switch to the **"OFF"** position as the speed approaches to zero. **Don't wait until the motor stops.**
15. Repeat steps 10 to 14 for positions "3" (corresponds to 2.75 ohms) and "1" corresponds to 10 ohms) on the rotor starter.
16. Save the files obtained.
17. To get the characteristics manually, repeat steps 6 to 12 with the following modifications:
    - In **step 6-**, select the **Man/Ext** control mode of the load, i.e., set the load to "position 1" and **"OFF"** operating mode.
    - In **step 7-,** Double click on the **Tool Box Button** and set the measuring parameters as follows: **Manual** recording, and **"Append new meas. Series".**
    - In **step 13**, increase the **"brake potentiometer"** in steps as shown in Table 2.
18. For each torque value, record in Table 2 the torque and speed. Also, from the multifunction meter, record the current, input power, and power factor.
19. Repeat steps 6 to 18 for positions "3" and "1" on the rotor starter.

Report:

1. Complete Table 2 by calculation Pout, PF, and efficiency.
2. Draw on the same figure the N-T, N-PF, N-efficiency characteristics calculated in Table 2 for different rotor resistor values.
3. Comment on your results.
4. Using the files saved in **Automatic mode operation**, draw the output power, and efficiency for different values of external resistance.

5. Discuss the behavior of the T-N characteristics as the external rotor resistance varies.
6. Discuss the behavior of the I-N characteristics as the external rotor resistance varies.
7. Discuss the behavior of the efficiency- speed characteristics as the external rotor resistance varies.
8. Write a formal report that includes all measurements and calculations.
9. Write a solid conclusion out of your findings.

Table 2

	T (NM)	**1.0**	**2.0**	**3.0**	**4.0**	**5.0**	**6.0**
M E	**Speed (rpm)**						
A S	**Input current (A)**						
U R	**Input Power (W)**						
E D	**Power Factor**						
C A L	**Output Power (W)**						
C U L	**Power Factor**						
A T E D	**Efficiency**						

EXPERIMENT # 5: SINGLE PHASE INDUCTION MOTORS CHARACTERISTICS

Objectives:

- To familiarize with single phase induction motors (split phase and capacitor run) components.
- To demonstrate how to reverse the direction of rotation of single phase induction motors.
- To investigate different characteristics (torque, current, power and efficiency) of single phase induction motors.

Apparatus:

- 3- phase constant supply unit (used as single phase)
- On/Off switch
- Magnetic powder brake
- Control unit
- Coupling
- Coupling guard
- Shaft guard
- Tacho generator
- Capacitor Motor R
- Capacitive load 1

Theory:

Induction motors are probably the simplest and most rugged of all electric motors. They consist of two basic electrical assemblies: the wound stator and the rotor assembly. The rotor consists of laminated, cylindrical iron cores with slots for receiving the conductors. On early motors, the conductors were copper bars with ends welded to copper rings known as end rings. Viewed from the end, the rotor assembly resembles a squirrel cage, hence the name squirrel- cage motor is used to refer to induction motors. In modern induction motors, the most common type of rotor has cast-aluminum conductors and short-circuiting end rings. The rotor turns when the moving magnetic field induces a current in the shorted conductors. The speed at which the magnetic field rotates is the synchronous speed of the motor and is determined by the number of poles in the stator and the frequency of the power supply.

$$n_s = \frac{120f}{p} \tag{1}$$

n_s= synchronous speed

f = frequency

P = number of poles

Synchronous speed is the absolute upper limit of motor speed. At synchronous speed, there is no difference between rotor speed and rotating field speed, so no voltage is induced in the rotor bars, hence no torque is developed. Therefore, when running, the rotor must rotate slower than the magnetic field. The rotor speed is just slow enough to cause the proper amount of rotor current to flow, so that the resulting torque is sufficient to overcome windage and friction losses, and drive the load. This speed difference between the rotor and magnetic field, called slip, is normally referred to as a percentage of synchronous speed:

$$s = \frac{n_s - n}{n_s} \quad (2)$$

s = slip

n_s = synchronous speed

n = actual speed

Single-phase induction motors are commonly fractional-horsepower types, though integral sizes are generally available to 10 hp. The most common single phase motor types are shaded pole, split phase, capacitor start, and permanent split capacitor.

- *Shaded pole motors* have a continuous copper loop wound around a small portion of each pole, Figure 1. The loop causes the magnetic field through the ringed portion to lag behind the field in the un-ringed portion. This produces a slightly rotating field in each pole face sufficient to turn the rotor. As the rotor accelerates, its torque increases and rated speed is reached. Shaded pole motors have low starting torque and are available only in fractional and subfractional horsepower sizes. Slip is about 10%, or more at rated load.

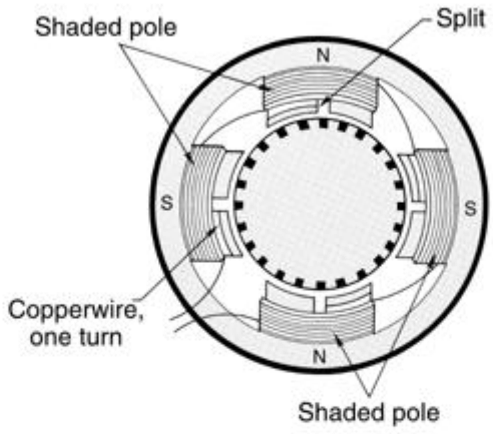

Figure 1: Rings in shaded-pole motor distort alternating field sufficiently to cause rotation.

- *Split phase motors*, Figure 2, use both a starting and running winding. The starting winding is displaced 90 electrical degrees from the running winding. The running winding has many turns of large diameter wire wound in the bottom of the stator slots to get high reactance. Therefore, the current in the starting winding leads the current in the running winding, causing a rotating field.

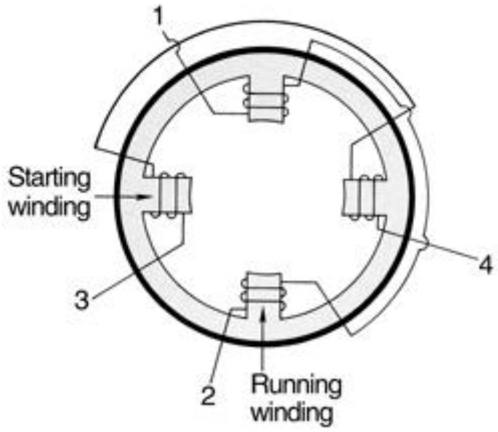

Figure 2: Split-phase windings in a two pole motor. Starting winding and running winding are 90 ° apart.

During startup, both windings are connected to the line, Figure 3.

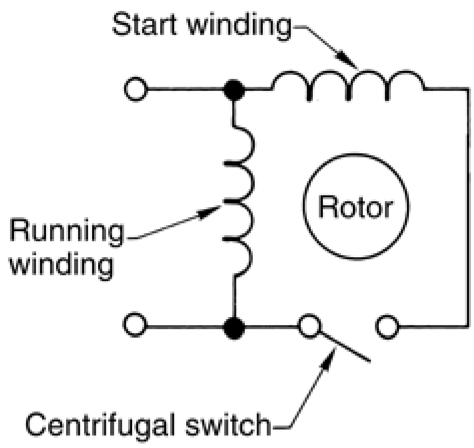

Figure 3: Split-phase start induction motor

Figure 4 demonstrates how a split phase induction motor starts. It is shown that if an auxiliary winding of much fewer turns of smaller wire is placed at 90° electrical to the main winding, it can start a single phase induction motor. With lower inductance and higher resistance, the current will experience less phase shift than the main winding. About 30° of phase difference may be obtained. This coil produces a moderate starting torque, which is disconnected by a centrifugal switch at 3/4 of synchronous speed. This simple (no capacitor) arrangement serves well for motors up to 1/3 horsepower (250 watts) driving easily started loads.

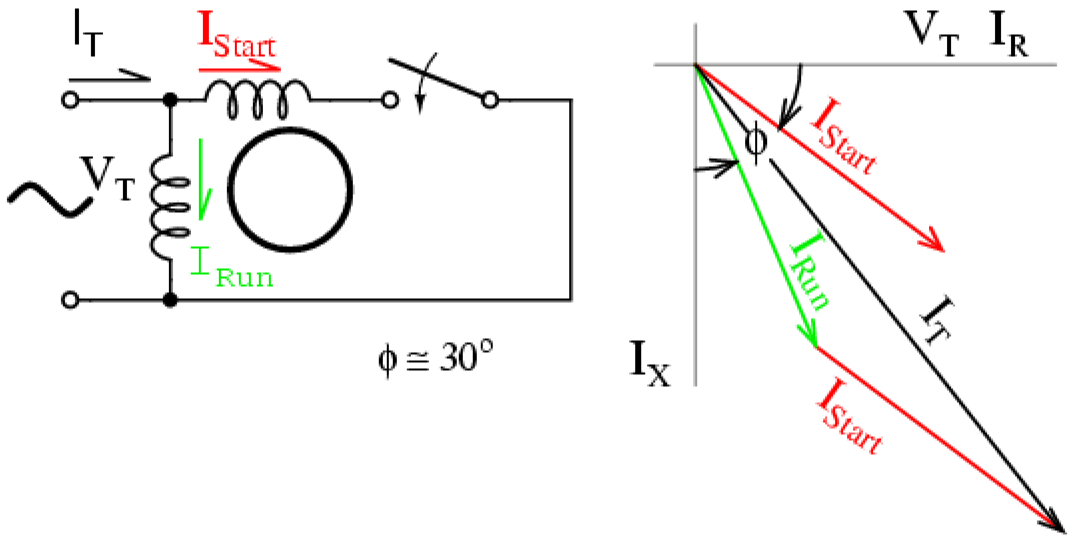

Figure 4: Schematic and phasor diagrams of main (run) and auxiliary (start) currents

- *Capacitor-start motors* are similar to split phase motors. The main difference is that a capacitor is placed in series with the auxiliary winding, Figure 5. This type of motor produces greater locked rotor and accelerating torque per ampere than does the split phase motor. Sizes range from fractional to 10 hp at 900 to 3600 rpm.

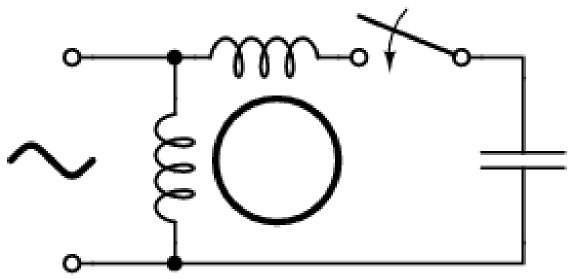

Figure 5: Capacitor start induction motor

- *Split-capacitor motors* (or capacitor run motors) also have an auxiliary winding with a capacitor, but they remain continuously energized and aid in producing a higher power factor than other capacitor designs, Figure 6. This makes them well suited to variable speed applications.

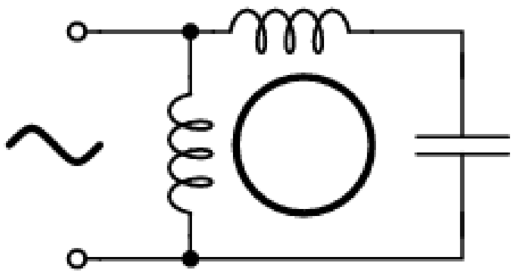

Figure 6: Capacitor run induction motor

<u>Procedure:</u>

Follow the following steps carefully:

1. Connect the **"split phase induction motor"** according to the circuit diagram shown in Figure 7.
2. Connect the motor thermal protection to the **"TEMP. ALARM"** in Control Unit.

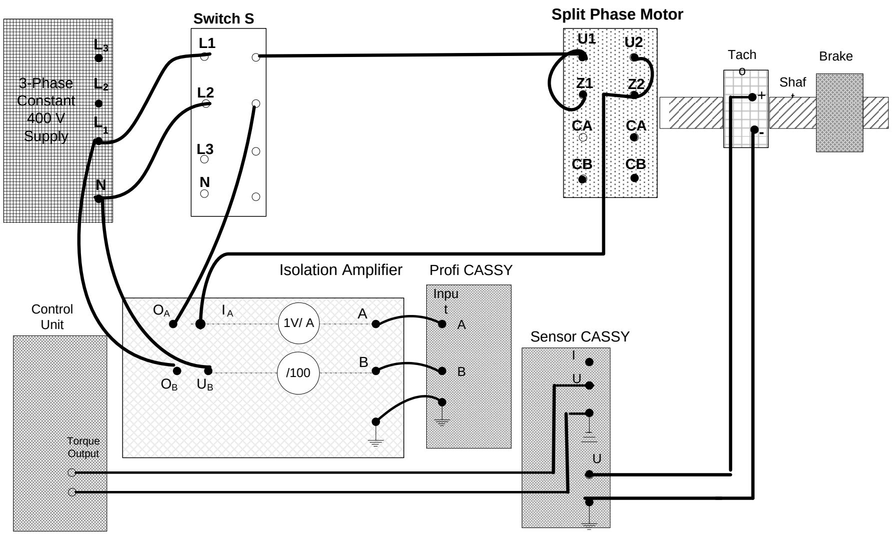

Figure 7: Wiring diagram of split phase induction motor

3. **Ask your instructor to check your circuit.**

4. Put switch **S** at the **"ON"** position and **<u>notice that the motor does not run</u>**.

5. Give the motor a move by your hand. Check if it runs!! **What can you conclude?**

6. Put switch S at the **"OFF"** position.

7. Modify the circuit diagram of Figure 7 by adding a capacitor of 16 μF between U1 and Z1 as shown in the circuit diagram shown of Figure 8.

8. **Ask your instructor to check your circuit.**

9. Put switch S at the "ON" position. Record the direction of rotation**.**

10. To reverse the direction of rotation, exchange Z1 and Z2.

11. Put switch S at the **"OFF"** position.

12. Set the "**Isolation Amplifier**" as follows: in case of current measurement, set the Switch to "1 V/A"; and in the case of voltage measurement, set the Switch to "/100".

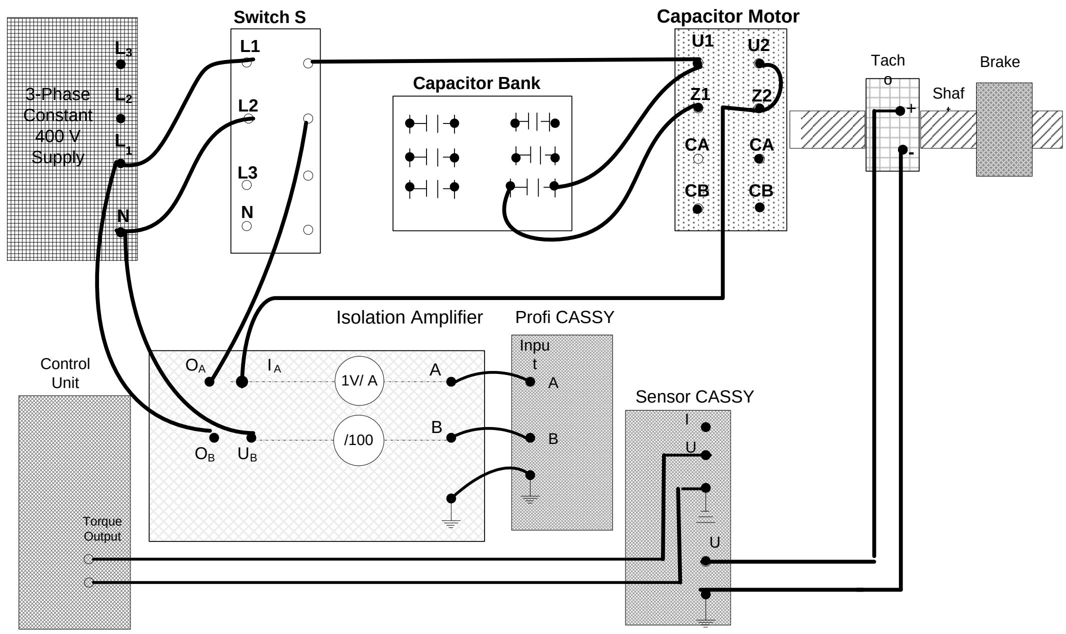

Figure 8: Wiring diagram of capacitor induction motor

13. From the PC, run the CASSY lab Software. Activate channels (UA1), (UB1), (UA2), and (UB2). Select “RMS” value option for UA1, UB1, and average value for UA2 and UB2.
14. Click on **Tool Box Button** and click on the “**Parameter/Formula/FFT**” option. Define the current as UA1 with a scale of 0 to 6 A, the voltage as UB1*100 with a scale of 0 to 230 V, the torque as UA2 with a scale of 0 to 10, and the speed as UB2*1000 with a scale of 0 to 3000 rpm.
15. Set the control unit as follows:
    - Set the torque scale to 10 which gives maximum torque of 10 Nm.
    - Select the **Ramp** control mode of the load, i.e., set the load to “Ramp 1” mode.
    - Set n_{min}% to 10. This will prevent the motor speed to drop below 10% of the synchronous speed.
    - Set M_{max}% to 100. This will limit the maximum torque to 100% of 10 Nm.

- o Double click on the **Tool Box Button** and set the measuring parameters as follows: **Automatic** recording, and **"Append new meas. Series".**

16. From the "**Display Button**", select the x-axis as Speed and the y-axis as Torque, Current, and Voltage. Switch off all other channels.
17. **Ask your instructor to check your connections and CASSY Lab settings. Do not proceed to the next stage unless your connections and settings are completely examined by the instructor.**
18. Switch **"ON"** the constant three-phase supply.
19. Change switch **"S"** to **"ON"** position.
20. On the control unit, press **"start"** to apply the load automatically and press "**F9"** on the computer keyboard at the same time to start recording.
21. Monitor the speed of the motor on the computer and change the "**S"** switch to the **"OFF"** position as the speed approaches to zero. **<u>Don't wait until the motor stops.</u>**
22. Save the recorded data in a file.
23. Repeat steps 18 to 22 for capacitor values of 20 and 24 μF.
24. Save the files obtained.

<u>Report:</u>

1. From the saved files, calculate the input power, output power, and efficiency.
2. Compare between the starting of split phase and capacitor induction motors.
3. Comment on the performance of capacitor motors as you change the capacitance value.
4. Write a formal report that includes all measurements, calculations and conclusions.

THIS PAGE IS INTENTIONALLY LEFT BLANK

EXPERIMENT # 6:	PERFORMANCE OF UNIVERSAL MOTORS

Objectives:

- To familiarize with universal motors.
- To operate universal motor as single phase induction motor and as DC series motor.
- To investigate the performance (torque, current, power and efficiency) of universal motors when operated from AC voltage source (as single phase induction motor) and DC voltage sources (as DC series motor).

Apparatus:

- 3- phase constant supply unit (used as single phase)
- Variable 40-250 V/ 0-10A DC power Supply
- On/Off switch
- Magnetic powder brake
- Control unit
- Coupling
- Coupling guard
- Shaft guard
- Tacho generator
- Universal Motor

Theory:

The name "universal" is derived from the motor's compatibility with both AC and DC power. Among the applications using these motors are vacuum cleaners, food mixers, portable drills, portable power saws, and sewing machines. These motors seldom exceed one horsepower.

In most cases, universal motors reach little more than a few hundred rpm under heavy loads. If the motor is run with no load, speed may approach up to 15,000 rpm. This can result in serious heat damage to the motor's components.

Universal series motors differ in design from true induction motors. They have series wound rotor circuitry similar to that of DC motors. The rotor of a universal series motor is made of a laminated iron core with coils around it. The ends of the wire coils connect directly to the commutator.

Electric current in the motor flows through a complete circuit formed by the stator winding and rotor winding, Figure 1. Brushes ride on the commutator and conduct current through the rotor from one stator coil to the other. The rotor current interacts with the magnetic field of the stator causing the rotor to turn. As long as an electrical current is present in the rotor coils, the motor continues to run

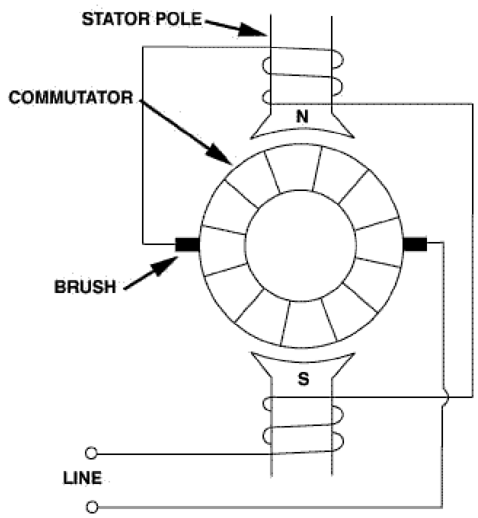

Figure 1: Schematic diagram of Universal motor

Applications of Universal motors include:

- Pumps
- Blowers
- Centrifuges
- Spa Bath Pumps
- Floor Cleaners and Vacuums
- Paint Sprayers
- Hand Dryers
- Air Compressors
- Lawn and Garden Products
- Power Tools
- High Volume Industrial Products
- Starter Motors
- String Trimmers

Procedure:

Note the rated values of current, voltage and speed of the synchronous machine as well as the DC motor and enter it into the Table 1.

Table 1: Machine ratings

Universal Motor	
Model No.	
Rated Voltage	
Rated Current	
Rated Power	
Rated Speed	
Power Factor	
Frequency	

(A) *UNIVERSAL MOTOR OPERATED FROM* **"AC"** *VOLTAGE SOURCE* **(As single phase induction motor)**

1. Connect the **"Universal motor"** according to the circuit diagram shown in Figure 2.
2. Connect the motor thermal protection to the **"TEMP. ALARM"** in Control Unit.

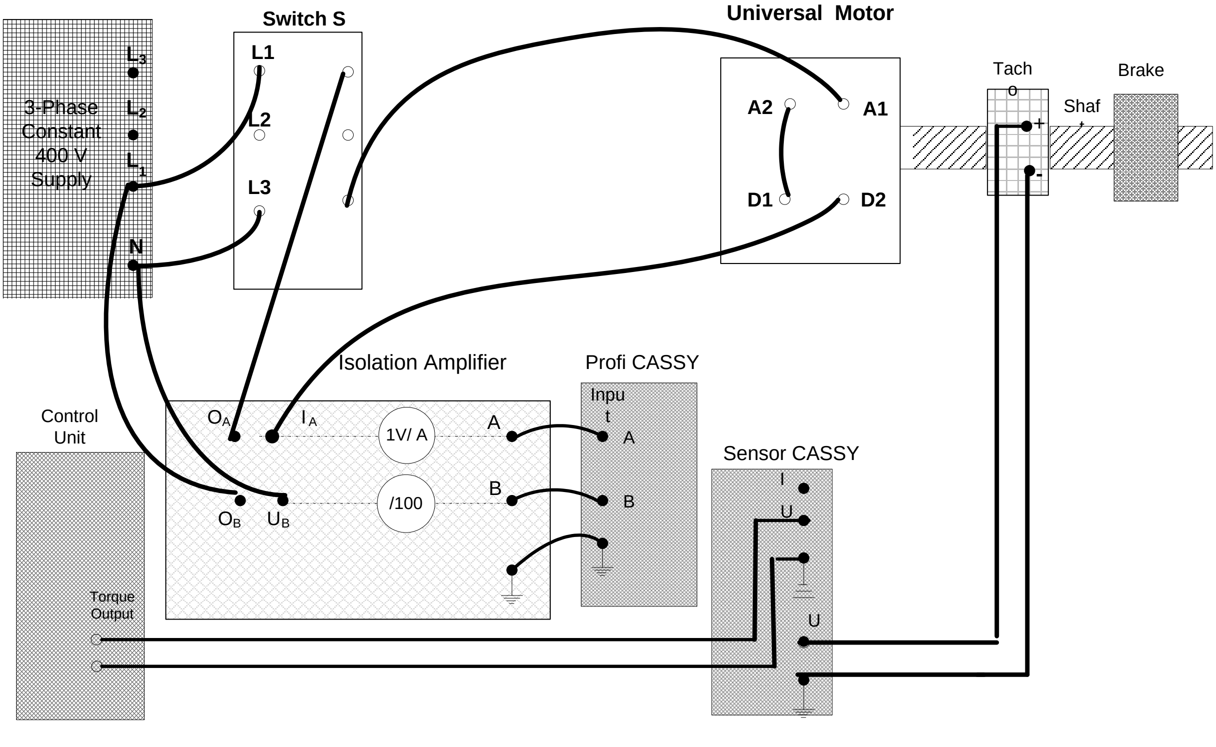

Figure 2: Wiring diagram of **AC** operated Universal motor

3. Put switch S at the **"OFF"** position.
4. Set the "**Isolation Amplifier**" as follows: in case of current measurement, set the Switch to "1 V/A"; and in the case of voltage measurement, set the Switch to "/100".
5. From the PC, run the CASSY lab Software. Activate channels (UA1), (UB1), (UA2), and (UB2). Select "RMS" value option for UA1, UB1, and average value for UA2 and UB2.

6. Click on **Tool Box Button** and click on the "**Parameter/Formula/FFT**" option. Define the current as UA1 with a scale of 0 to 8 A, the voltage as UB1*100 with a scale of 0 to 230 V, the torque as UA2 with a scale of 0 to 7, and the speed as UB2*1000 with a scale of 0 to 5000 rpm.
7. Set the control unit as follows:
    - Set the torque scale to 10 which gives maximum torque of 10 Nm.
    - Set the speed scale to 6000 RPM.
    - Select the **Man/Ext** control mode of the load, i.e., set the load to **"Mode 1".**
    - Set n_{min}% to 10. This will prevent the motor speed to drop below 10% of the synchronous speed.
    - Set M_{max}% to 100. This will limit the maximum torque to 100% of 10 Nm.
    - Set the torque value at zero position.
    - Double click on the **Tool Box Button** and set the measuring parameters as follows: **Manual** recording.
8. From the "**Display Button**", select the x-axis as Torque and the y-axis as Speed, input current, and voltage. Switch off all other channels.
9. **Ask your instructor to check your connections and CASSY Lab settings. Do not proceed to the next stage unless your connections and settings are completely examined by the instructor.**
10. Switch **"ON"** the constant three-phase supply (used as single phase supply).
11. Change switch **"S"** to **"ON"** position.
12. Press "**F9"** on the computer keyboard to start recording.
13. Increase the torque in steps of 0.3 NM on the control unit **(Monitor the input current which should not exceed 6.5 A)**. After each increase, wait for 2 seconds and press "**F9"** on the computer keyboard to record.
14. As the input current is about 6.5 A**, reduce the applied torque to zero.**

15. Change switch **"S"** to the **"OFF"** position.

16. Switch off the constant three-phase supply (used as single phase supply).

17. Save the recorded data with a proper file name and keep it open.

(B) *UNIVERSAL MOTOR OPERATED FROM* **"DC"** *VOLTAGE SOURCE*
(As DC series motor)

1. Connect the **"Universal motor"** according to the circuit diagram shown in Figure 3. **Notice that the only difference from Figure 2 is that L1 is replaced by + DC and N is replaced by –DC.**

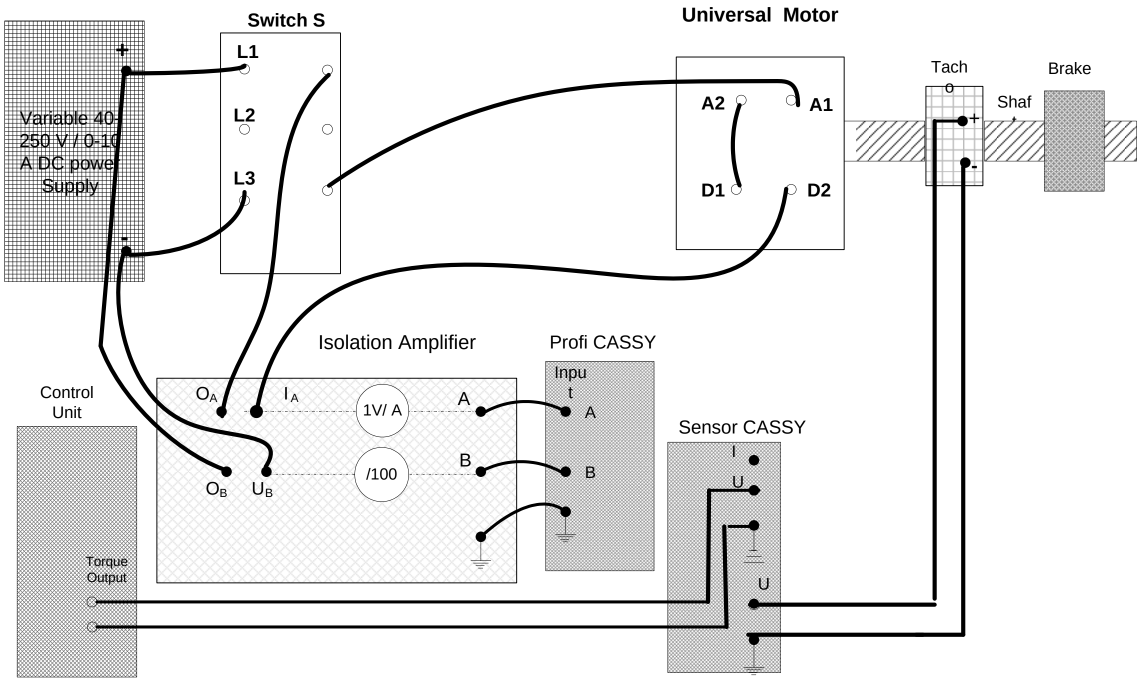

Figure 3: Wiring diagram of **DC** operated Universal motor

2. Go to CASSY lab and change the selection of UA1 and UB1 to **"Average"** value.

3. Remove all previous measurements.

4. Make sure that the variable 40-250 V/ 0-10 A DC supply is at zero value. Also make sure that the DC supply current range is at 10 A.
5. **Ask your instructor to check your connections and CASSY Lab settings. Do not proceed to the next stage unless your connections and settings are completely examined by the instructor.**
6. Switch **"ON"** the variable 40-250 V/ 0-10 A DC supply.
7. Change switch **"S"** to **"ON"** position.
8. Increase the variable 40-250 V/ 0-10 A DC supply to **110 V.**
9. Press "**F9"** on the computer keyboard to start recording.
10. Increase the torque in steps of 0.3 NM on the control unit **(Monitor the input current which should not exceed 6.5 A)**. After each increase, wait for 2 seconds and press "**F9"** on the computer keyboard to record.
11. As the input current is about 6.5 A**, reduce the applied torque to zero.**
12. Increase the variable 40-250 V/ 0-10 A DC supply to **220V.**
13. Double click on the **Tool Box Button** and set the measuring parameters as follows: **Manual recording** and "**Append new meas. Series**".
14. Repeat steps 10-13.
15. As the input current is about 6.5 A**, reduce the applied torque to zero.**
16. Decrease the variable 40-250 V/ 0-10 A DC supply to **0V.**
17. Change switch **"S"** to the **"OFF"** position.
18. Switch off the variable 40-250 V/ 0-10 A DC supply.
19. Save the recorded data again.

Report:

1. For Universal motor operated from AC power supply:

- From the saved files, calculate and plot the input power, output power, and efficiency.

2. **For Universal motor operated from DC power supply**:

- From the saved files, calculate and plot on the same figure the input power, output power, and efficiency for the cases where the input voltage is 110 V and 220 V.
- Discuss the effect of reducing the motor's applied voltage on the motor performance.
- Compare between the performance of Universal motor when operated from 220 V DC and AC voltages.

3. **Write a formal report that includes all measurements, figures, calculations and conclusions.**

EXPERIMENT # 7: PARAMETER IDENTIFICATION OF A SEPARATELY EXCITED DC MOTOR

Objectives:

- To identify the electrical and mechanical parameters of a separately excited DC motor with a mechanical load system.
- To develop the block diagram for a separately excited DC motor.
- To derive the transfer function of the system between the motor speed (output) and input voltage (input).

Apparatus:

- DC Motor.
- Magnetic Powder Brake
- Control unit
- Variable DC Power Supply 40 – 250V / 10A.
- Variable DC Field Supply 0 – 250V / 2.5A.
- Variable DC supply, 0 – 24 V / 0 – 20 A
- Tachogenerator.
- Isolation Amplifier, Profi-Cassy, and Sensor-Cassy.
- Professional Digital Multimeter.

Theory:

The ultimate aim of this experiment is to investigate how the motor speed responds to changes in the voltage applied to the armature terminals of a separately excited DC motor. The analysis involves electrical transients in the

armature circuit and the dynamics of the mechanical load driven by the motor. A schematic diagram of the system under consideration is shown in Fig. 1.

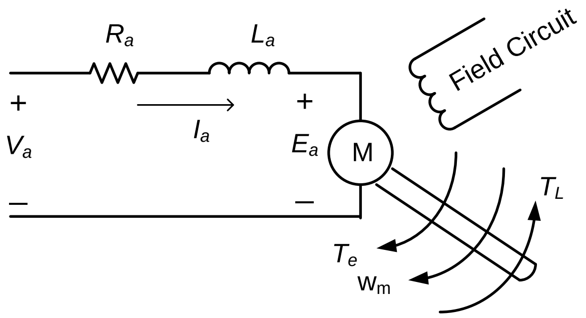

Fig. 1: Schematic diagram of the separately excited DC motor

At a constant field current, the generated emf E_a and the electromagnetic torque T_e are given by:

$$E_a = K_m \omega_m \tag{1}$$

$$T_e = K_m I_a \tag{2}$$

where : -

K_m is the motor constant,

I_a is the armature current, and

ω_m is the motor speed.

The differential equation for the motor armature current and the motor speed are given by:

$$L_a \frac{dI_a}{dt} + R_a I_a = V_a - E_a \tag{3}$$

$$J \frac{d\omega_m}{dt} + B\omega_m = T_e - T_L \tag{4}$$

where : -

R_a is the armature resistance,

L_a is the armature inductance,

V_a is the voltage applied to the armature , i.e., input voltage,

J is the moment of inertia of the load and the rotor of the motor,

B is the equivalent viscous friction constant of the load and the motor,

T_L is the mechanical load torque.

Substituting from (1) and (2) into (3) and (4) respectively, (3) and (4) can be rewritten as:

$$L_a \frac{dI_a}{dt} + R_a I_a = V_a - K_m \omega_m \qquad (5)$$

$$J \frac{d\omega_m}{dt} + B\omega_m = K_m I_a - T_L \qquad (6)$$

The armature circuit time constant is defined as:

$$\tau_a = \frac{L_a}{R_a} \qquad (7)$$

The mechanical time constant is defined as:

$$\tau_m = \frac{J}{B} \qquad (8)$$

Laplace transforms of (5) and (6) with (7) and (8) lead to the following:

$$I_a(s) = \frac{V_a(s) - K_m \Omega_m(s)}{R_a(1+\tau_a s)} \qquad (9)$$

$$\Omega_m(s) = \frac{K_m I_a(s) - T_L(s)}{B(1+\tau_m s)}$$

(10)

The corresponding block diagram representing these equations is given in Fig. 2 in terms of the state variables $I_a(s)$ and $\Omega_m(s)$ with $V_a(s)$ and $T_L(s)$ as inputs. From the block diagram, the transfer function relating $\Omega_m(s)$ and $V_a(s)$ with $T_L(s) = 0$:

$$\frac{\Omega_m(s)}{V_a(s)} = \frac{K_m}{R_a(1+\tau_a s)B(1+\tau_m s) + K_m{}^2}$$

(11)

Therefore, to derive the transfer function of motor speed responds with the voltage applied to the armature terminals of a separately excited DC motor, R_a, τ_a, B, τ_m, and K_m are to be determined.

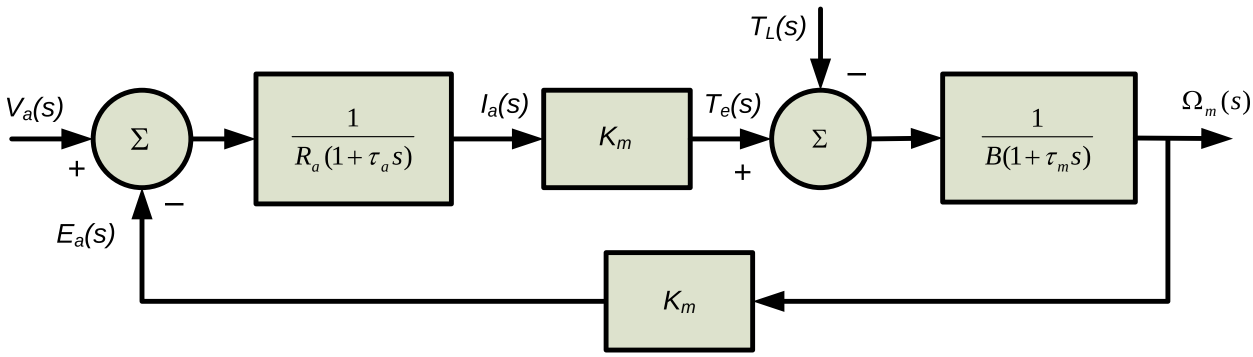

Fig. 2: Block diagram of the separately excited DC motor

Procedure:

A: Preliminary Measurements

1. First read and enter the rating plate data of the DC Generator in Table 1.

2. Then use the Multimeter to measure the machine resistances and fill Table 2.

Table 1: Motor Nameplate Data

Nominal Voltage (V)	
Nominal Current (A)	
Nominal Field Current (A)	
Nominal Speed (RPM)	
Nominal Power (W)	

Table 2: Armature Winding Resistances

$R_{A1,A2}$ (Ω)	$R_{B1,B2}$ (Ω)	$R_{C1,C2}$ (Ω)

B: Armature Resistance (R_a)

3. Connect the armature winding as shown in Fig. 3 and use the Multimeter to measure the resistance between the armature terminals A2 and C1.

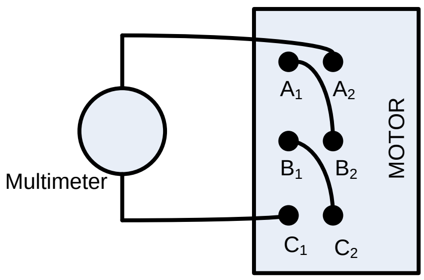

Fig. 3: Wiring diagram for R_a measurement

C: Armature Time Constant (τ_a)

4. Connect the circuit as shown in Fig. 4.

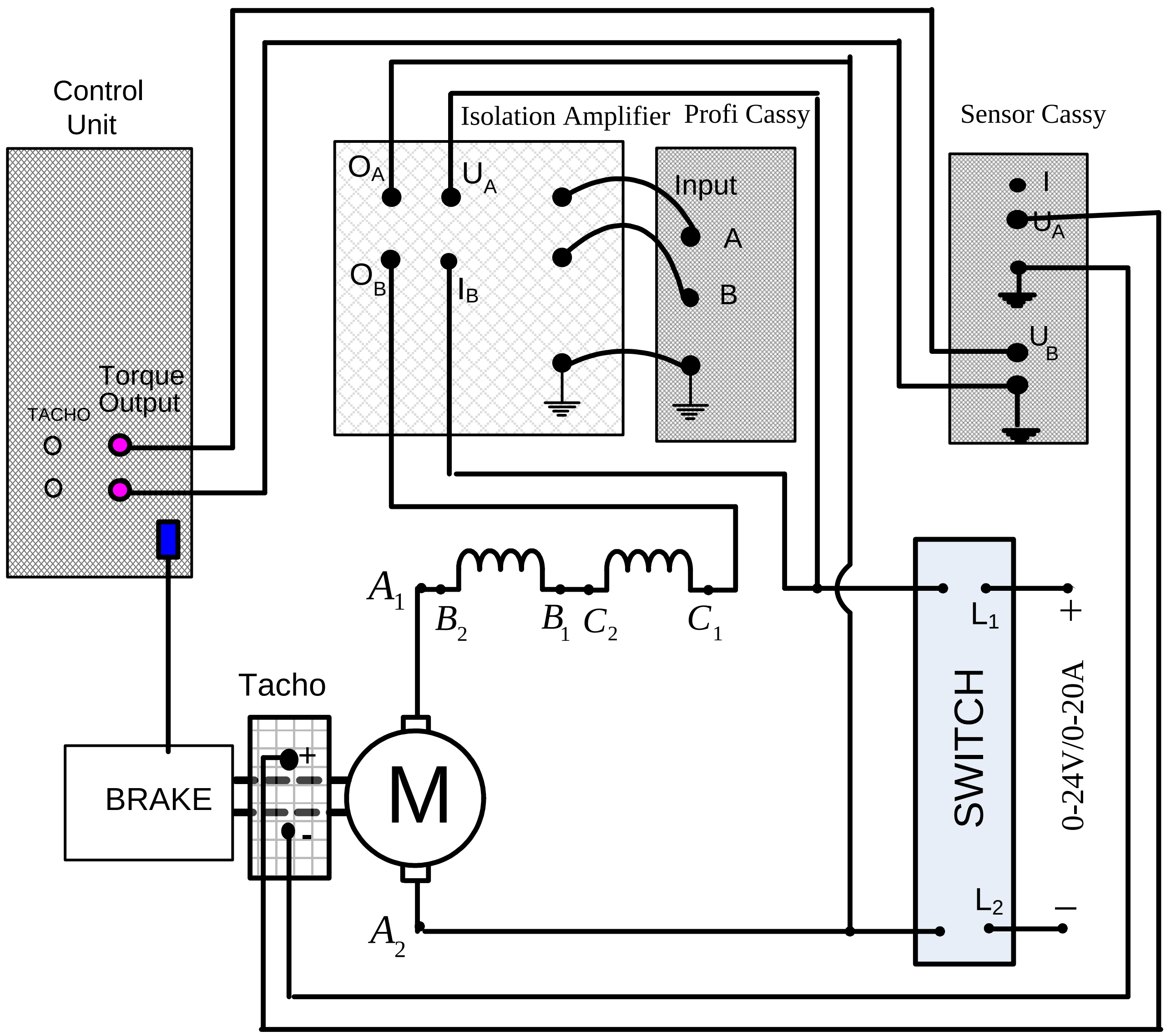

Fig. 4: Wiring diagram for armature time constant measurement

5. For the Control Unit setting, do the following:
   a) Set the torque scale to 10 which gives maximum torque of 10 N.m.
   b) Select the manual control mode of the load, i.e., set the load to "MAN/EXT" mode at position 1.
   c) Set n_{min}% to 10. This will prevent the motor speed to drop below 10% of the rpm of the speed scale.
   d) Set M_{max} % to 60. This will limit the maximum torque to 60% of 10 Nm, i.e., 6 N.m.

e) Connect the motor thermal protection to the "TEMP. ALARM" in Control Unit.

6. In the Isolation amplifier, adjust the scale of channel *A* as “/100” and the scale of channel *B* as “1 V/A”. Note that channel *A* represents the input voltage while channel *B* represents the armature current.
7. From the PC, run the CASSY Lab software.
8. Activate Cassy lab channels for applied voltage as UA_1, armature current as UB_1, rotor speed as UA_2, and the load torque as UB2. Select the **Averaged Values** option for all channels.
9. From “Parameter/Formula/FFT” option, use new quantity to define the applied Voltage V_a as (UA_1*100), armature current I_a as (UB_1), rotor speed N_m as (UA_2*1000), and load torque T_L as (UB_2).
10. Double click on the “Setting” icon to activate the Measuring Parameters. Select the “Automatic Recording” option. Set the “Measurement Interval” at 1 ms with a “number” of 2000. This gives a measuring time of 2 s.
11. Go to Cassy lab **display** option and select the time as x-axis and the armature current I_a as y-axis.
12. **Ask your instructor to check your connections and CASSY Lab settings. Do not proceed to the next stage unless your connections and settings are completely examined by the instructor.**
13. Make sure that the switch is OFF and the DC supply voltage control knob is at zero position.
14. Gradually increase the DC supply voltage till reaching 20 V.
15. Start recording by pressing F9 then move the switch to ON position immediately. Don’t wait more than the measuring time.
16. Move the switch to OFF and reduce the supply voltage to zero. Then switch OFF the DC supply.
17. Save your Cassy file with a proper name and keep it open.

18. Report the value of the armature resistance to your instructor.

D: Motor Constant (K_m)

19. Remove all the recorded measurements from the Cassy file.
20. Connect the circuit as shown in Fig. 5. Note that the 0 – 24V/0 – 20 A DC supply is replaced by 40 – 250V/10A one. In addition the motor field $E_1 – E_2$ is connected to 0 – 250V/2.5A supply.
21. Make sure that the both DC supplies are OFF and their voltage control knobs are at zero position.
22. From "Parameter/Formula/FFT" option, use new quantity to define the generated emf E_a as (V_a - $R_a * I_a$) and motor angular speed ω_m as (N_m/9.55). Replace R_a by its value measured earlier.
23. Double click on the "Setting" icon to activate the Measuring Parameters. Select the "Manual Recording" option.
24. Go to Cassy lab **display** option and select angular speed ω_m as x-axis and the generated emf E_a as y-axis.
25. Gradually apply the DC field supply voltage till reaching the rated field current (0.24 A).

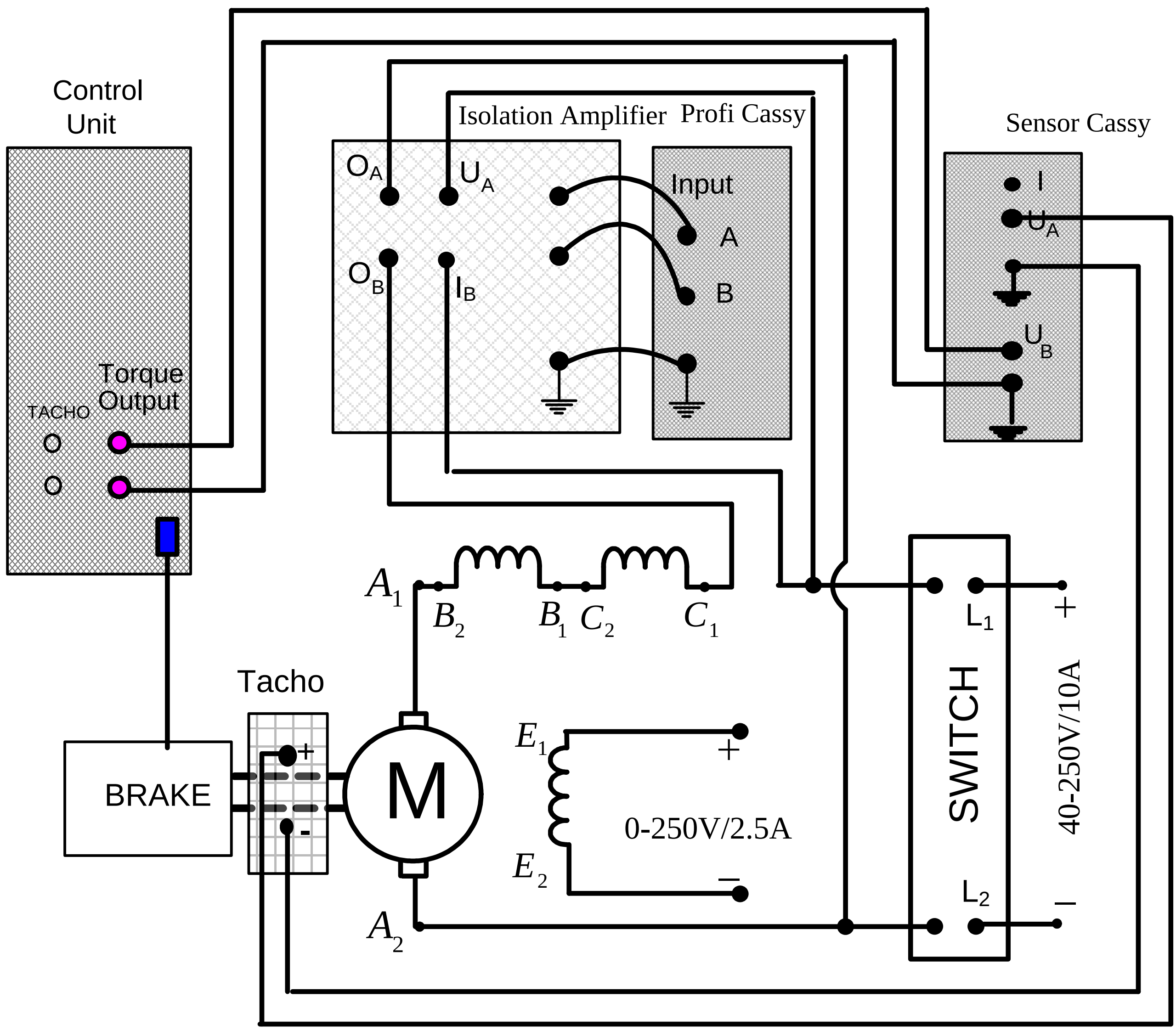

Fig. 5: Wiring diagram of separately excited DC motor

26. Move the switch to ON position and gradually apply the DC Motor power supply voltage to start the motor till reaching a speed of 1000 rpm. Press F9 to record the readings.
27. Gradually increase the supply voltage to reach a speed of 2000 rpm in 5-10 steps. Press F9 to record the reading after each adjustment.
28. Reduce the supply voltage to zero and move the switch to OFF position.
29. Save your Cassy file with a proper name and keep it open.

30. Calculate the motor constant K_m as the slope of the recorded measurement. You can also evaluate K_m by fitting the results with a straight line passing through the origin.
31. Report the value of the motor constant K_m to your instructor.

E: Viscous Friction Constant (B)

32. Remove all the recorded measurements from the Cassy file.
33. From "Parameter/Formula/FFT" option, use new quantity to define the electromagnetic torque T_e as ($K_m * I_a$) and the torque difference ΔT as (T_e – T_L). Replace K_m by its value measured earlier.
34. Double click on the "Setting" icon to activate the Measuring Parameters. Select the "Manual Recording" option.
35. Go to Cassy lab **display** option and select the motor angular speed ω_m as x-axis and the torque difference ΔT as y-axis.
36. Move the switch to ON position and gradually apply the DC Motor power supply voltage to start the motor till reaching a speed of 1000 rpm. Press F9 to record the readings.
37. Gradually increase the supply voltage to reach a speed of 2000 rpm in 5-10 steps. Press F9 to record the reading after each adjustment. Wait for 3 seconds before recording the measurements. Why?
38. Reduce the supply voltage to zero and move the switch to OFF position.
39. Save your Cassy file with a proper name and keep it open.

F: Mechanical Time Constant (τ_m)

40. Remove all the recorded measurements from the Cassy file.
41. Double click on the "Setting" icon to activate the Measuring Parameters. Select the "Automatic Recording" option. Set the "Measurement Interval" at 1 ms with a "number" of 2000. This gives a measuring time of 2 s.

42. Go to Cassy lab **display** option and select the time as x-axis and the motor angular speed ω_m as y-axis.
43. Move the switch to ON position and gradually apply the DC Motor power supply voltage to start the motor till reaching a speed of approximately 2000 rpm.
44. Start recording by pressing F9 then move the switch to OFF position immediately. Don't wait more than the measuring time.
45. Save your Cassy file with a proper name.
46. Reduce the supply voltage to zero.

Report:

1. Display the recorded data of Table 1 and Table 2.
2. Calculate the time constant from the current response stored. You may need to adjust the time scale for accurate calculation.
3. Calculate the viscous friction constant B as the slope of the recorded measurement by fitting the results with a straight line passing through the origin.
4. Calculate the time constant from the speed response stored. You may need to adjust the time scale for accurate calculation.
5. Display the stored plots of the armature time constant, motor constant, viscous friction constant, and mechanical time constant. Include on the plots all fittings and calculations carried out using CASSY.
6. Complete the following Table:

Table R1: Identified motor parameters

R_a (Ω)	L_a (mH)	K_m (Nm/A)	B(Kg. m^2/s)	J (Kg. m^2)	τ_a (s)	τ_m (s)

7. Using the measured and calculated parameters, write the transfer function of the motor as given in equation (11).
8. What would be the steady state angular speed for 200 V input voltage?

IMPORTANT NOTE

The next experiment is based on the transfer function derived in this experiment. It is required to design a PI controller to improve the motor response in terms of overshoot and settling time. Therefore, the student is asked to search for a well-known method for PI controller design and use MATLAB to carry out the next experiment on his own. You can consult your instructor if you have any question.

EXPERIMENT # 8: PI SPEED CONTROLLER DESIGN FOR A SEPARATELY EXCITED DC MOTOR

Objectives:

- To design a proportional-integral speed controller of a separately excited DC motor.
- To examine the effectiveness of the designed controller by investigating the closed loop system performance under a disturbance.

Apparatus:

- PC
- MATLAB software.

Theory:

In this experiment, the basic speed-controller design concepts are analyzed. Considering proportional and integral control actions, the key transfer functions are derived, and design goals formulated. PI (proportional integral) control is one of the earlier control strategies. Its early implementation was in pneumatic devices, followed by vacuum and solid state analog electronics, before arriving at today’s digital implementation of microprocessors. It has a simple control structure which was understood by plant operators and which they found relatively easy to tune. Since many control systems using PI control have proved satisfactory, it still has a wide range of applications in industrial control. According to a survey for process control systems conducted in 1989, more than 90% of the control loops were of this type.

A typical structure of a PI control system is shown in Fig. 1, where it can be seen that in a PI controller, the speed deviation signal $y(t)$ is used to generate the proportional and integral actions, with the resulting signals weighted and summed to form the control signal $u(t)$ applied to the plant model. A mathematical description of the PI controller is

$$u(t) = K_P \times y(t) + K_I \int_0^t y(\tau)d\tau \tag{1}$$

or;

$$\frac{U(s)}{Y(s)} = K_P + \frac{K_I}{s} \tag{2}$$

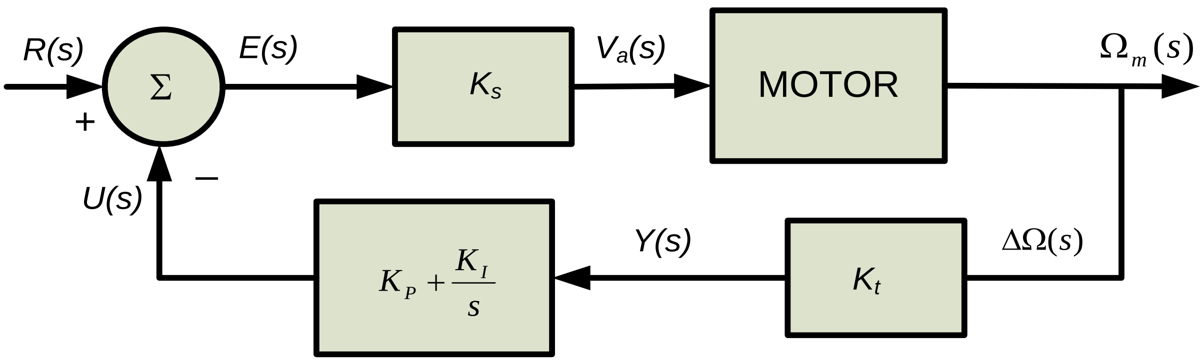

Fig. 1: PI speed control system

where

$u(t)$ is the output signal of the controller,

$e(t)$ is the error signal,

$r(t)$ is the reference input signal,

$y(t)$ is the feedback signal,

$\Delta\omega(t)$ is the speed deviation, $\Delta\omega = \omega - \omega_{ref}$

K_P is the proportional gain,

K_I is the integral gain

K_s is the source gain, set it as K_s = 25 (V/V)

K_t is the tachometer gain, set it as K_t = 1/104.7 (V.s/rad)

The motor block in Fig. 1 is replaced by its transfer function relating $\Omega_m(s)$ and $V_a(s)$ with $T_L(s) = 0$ as derived in the previous experiment as:

$$\frac{\Omega_m(s)}{V_a(s)} = \frac{K_m}{R_a(1+\tau_a s)B(1+\tau_m s)+K_m{}^2} \tag{3}$$

Therefore, the closed loop transfer function can be derived. The controller gains K_P and K_I can be tuned to achieve the desired closed loop system performance.

Procedure:

1. Prepare the numerator and denominator of the open loop motor transfer function as derived in the previous experiment.
2. Carry out the step response of the open loop motor transfer function.
3. Derive the closed loop transfer function for the system block diagram shown in Fig. 1.
4. Search and apply a well-known and systematic approach to tune the PI controller gains K_P and K_I in order to improve the closed loop system response.
5. Simulate the closed loop system with a sequence of step changes in the speed reference.

Report:

1. Display the step response for the open loop transfer function.
2. Calculate the steady state value of the motor speed with a step change in V_a and compare it with that of the response displayed.

3. Describe in steps the method used to design the controller. Include all figures used to tune the controller.
4. Report the values of the PI controller gains K_P and K_I.
5. Display the step response for the closed loop system with a step change in the reference.
6. Include in your report the MATLAB programs developed to design the controller.

IMPORTANT NOTE

The next experiment is to implement the designed controller and to examine its effectiveness. Therefore, it is worth to pay attention and design the controller carefully. The success of your design will be examined experimentally in the next lab.

EXPERIMENT # 9:	**PI CONTROLLER IMPLEMENTATION OF A SEPARATELY EXCITED DC MOTOR**

Objectives:

- To implement the theoretically designed PI speed controller of a separately excited DC motor.
- To examine experimentally the effectiveness of the designed PI speed controller for a step change of the reference speed and load torque.
- To highlight the main differences in the system response between the theoretical design and the experimental implementation of the speed controller.

Apparatus:

- DC Motor.
- Magnetic Powder Brake
- Control unit
- Variable DC Power Supply 40 – 250V / 0 – 10A.
- Variable DC Field Supply 0 – 250V / 2.5A.
- Tachogenerator.
- Isolation Amplifier, Profi-Cassy, and Sensor-Cassy.

Theory:

A typical implementation of a PI control system is shown in Fig. 1, where it can be seen that in a PI controller, the speed deviation signal $\Delta\omega(t)$ is used to generate the proportional and integral actions, with the resulting signals weighted and summed to form the control signal $u(t)$ applied to the plant model.

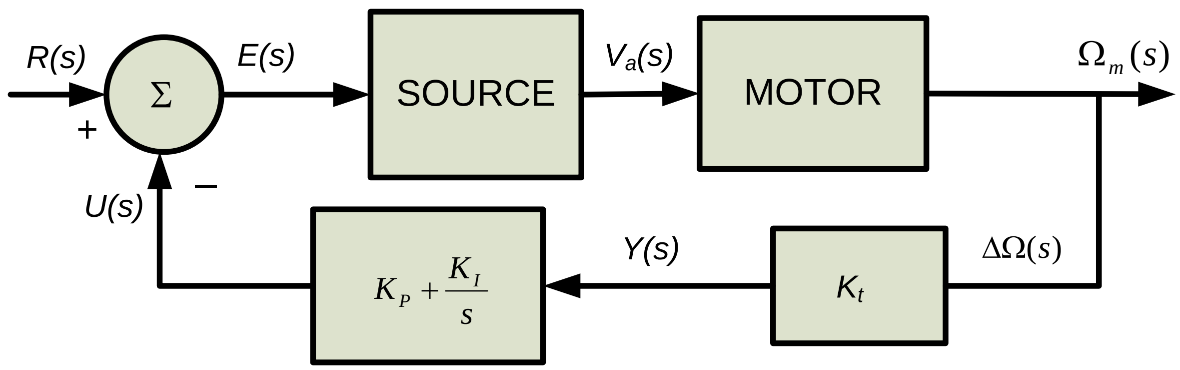

Fig. 1: Block diagram of the DC motor with a PI speed controller

In Fig. 1, the different signals can be defined as follows.

$u(t)$ is the output signal of the controller,

$e(t)$ is the error signal,

$r(t)$ is the reference input signal,

$y(t)$ is the feedback signal,

$\Delta\omega(t)$ is the speed deviation, $\Delta\omega = \omega - \omega_{ref}$

K_P is the proportional gain,

K_I is the integral gain,

K_t is the tachometer gain, $K_t = 1/104.7$ (V.s/rad)

Procedure:

1. Connect the circuit as shown in Fig. 2.

2. On the Control Unit setting, do the following:

a) Set the torque scale to 10 which gives maximum torque of 10 N.m.

b) Select the manual control mode of the load, i.e., set the load to “MAN/EXT” mode at position 1.

c) Set n_{min}% to 10. This will prevent the motor speed to drop below 10% of the rpm of the speed scale.

d) Set M_{max} % to 60. This will limit the maximum torque to 60% of 10 Nm, i.e., 6 N.m.

e) Connect the motor thermal protection to the "TEMP. ALARM" in Control Unit.

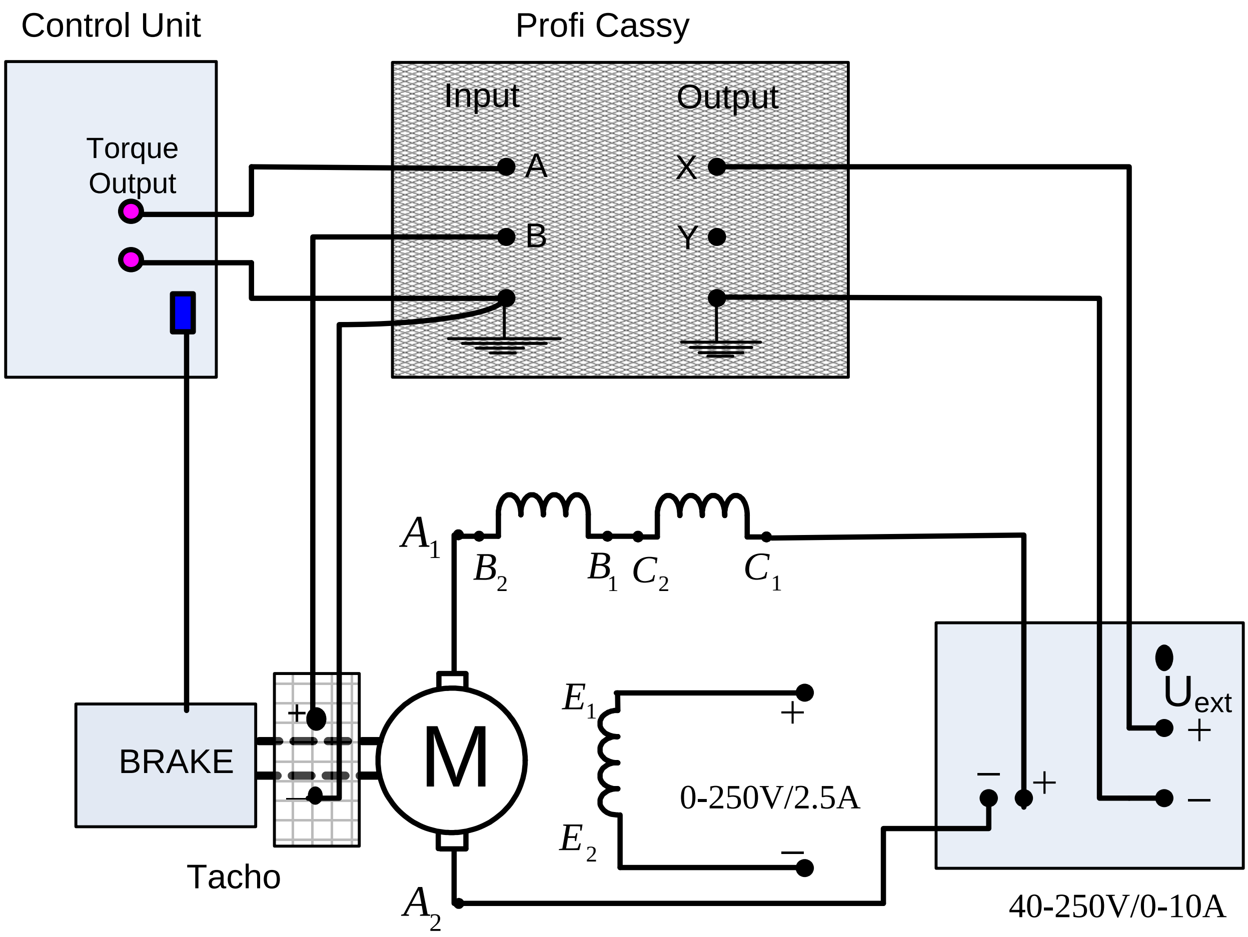

Fig. 2: Wiring diagram for implementation of a PI speed controller of separately excited DC motor

3. From the PC, run the CASSY Lab software.

4. Activate Cassy lab channels for load torque as UA_1 and motor speed as UB_1. Select the **Averaged Values** option for all channels.

5. From "Parameter/Formula/FFT" option, use new quantity to define the following quantities: -

a. load torque T_L as "Formula" (UA1) with a range of 0-5 Nm

b. motor speed ω as "Formula" (UB1*104.7) with a range of 0-250 rad/s.

c. reference voltage r as "Parameter" and set it at (4) with a range of 0-5 V.

d. desired speed ω_{ref} as "Parameter" (150) with a range of 0-250 rad/s.

e. speed deviation $d\omega$ as "Formula" (ω -ω_{ref}) with a range of 0-250 rad/s.

f. input control signal y as "Formula" ($d\omega$/104.7) with a range of 0-5V.

g. proportional gain of the controller K_P as "Parameter" (enter the value obtained by theoretical design). Adjust the range accordingly with a margin of ± 50% of the obtained value. You may need to tune this parameter.

h. integral gain of the controller K_I as "Parameter" (enter the value obtained by theoretical design). Adjust the range accordingly with a margin of ± 50% of the obtained value. You may need to tune this parameter.

i. integral part of the controller *int* as "integral over time" from (y).

j. output control signal u as "Formula" (K_P*y+K_I*int).

k. error signal e as "Formula" (r-u).

6. Go back to "CASSY" and activate the output channel X. Select "DC" option as "Signal Form" and select the signal e as "Parameters".

7. Double click on the "Setting" icon to activate the Measuring Parameters. Select the "Automatic Recording" option. Set the "Measurement Interval" of 500 ms.

8. Go to Cassy lab **display** option and select the time as x-axis and the motor speed ω, the reference speed ω_{ref}, and load torque T_L as y-axis.

9. **Ask your instructor to check your connections and CASSY Lab settings. Do not proceed to the next stage unless your connections and settings are completely examined by the instructor.**
10. Make sure that the field supply voltage control knob is at zero position.
11. Switch ON the field supply and gradually increase the voltage till the field current reaches its rated value of 0.24 A. You can observe the current on the supply meter.
12. Press "U_{ext}" button on the power supply to get an output voltage of the source proportional to the input voltage signal generated by Profi Cassy. The voltage knob in this case is deactivated.
13. Start recording by pressing F9. Wait for 1 minute until the speed catches the reference value. You may need to make fine tuning of the controller gains to improve the response.
14. Change the reference voltage to 3 and observe the response.
15. Change the reference speed to 100 and observe the response.
16. Increase the torque from the control unit to 1 Nm and observe the response.
17. Change the controller gains and observe the response.
18. Press F9 to stop recording.
19. Reduce the field supply voltage to zero.
20. Switch OFF all sources.
21. Save your Cassy file with a proper name.

<u>Report:</u>

1. Display the recorded data showing all the responses with the different disturbances.
2. Highlight the differences, if any, between the simulated and experimental results.
3. Write a formal report with your comments and conclusions.