

## Lab #8: Measuring Operating Characteristics of a Shunt-excited, Series-excited, and Compounded DC Motor

### 1. Purpose

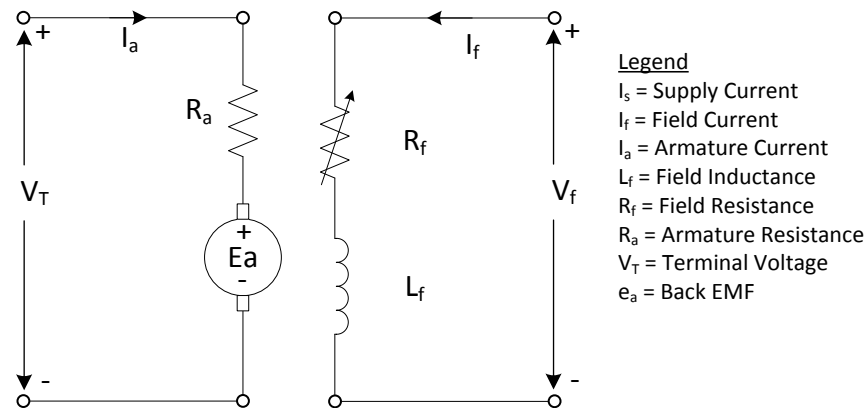
The purpose of this lab experiment is to acquaint students with the basic operating characteristics of DC motors. Three different DC motors will be analyzed under loading conditions to observe the torque-speed and torque-armature current relationships.

### 2. Theoretical Background

In most circumstances, a DC machine can be used as either a generator or a motor. In the following, a brief overview of the equivalent circuits of different types of DC motors and their characteristics is shown.

#### 2.1. Separately Excited DC Motor

The equivalent circuit of a DC separately-excited motor is shown in Figure 8.1.



**Figure 8.1: Equivalent circuit of a separately-excited DC motor**

As seen in Figure 8.1, the terminal armature voltage can be expressed as the sum of voltage drop across the armature resistance and the internally induced emf,  $E_a$ , as shown below:

$$V_T = R_a \times I_a + E_a \quad (8.1)$$

The back emf can be calculated by re-arranging the equation (8.1).

$$E_a = V_T - I_a \times R_a \quad (8.2)$$

Where the internally generated voltage in the armature or back emf,  $E_a$ , is defined by:

$$E_a = K_T \Phi \omega_m \quad (8.3)$$

Where:

$K_T$  = motor design constant

$\Phi$  = flux per pole

$\omega_m$  = angular velocity of the armature in mechanical radians per second

The mechanical torque developed by the separately-excited DC motor can be expressed by the following:

$$T_m = K_a \Phi I_a \quad (8.4)$$

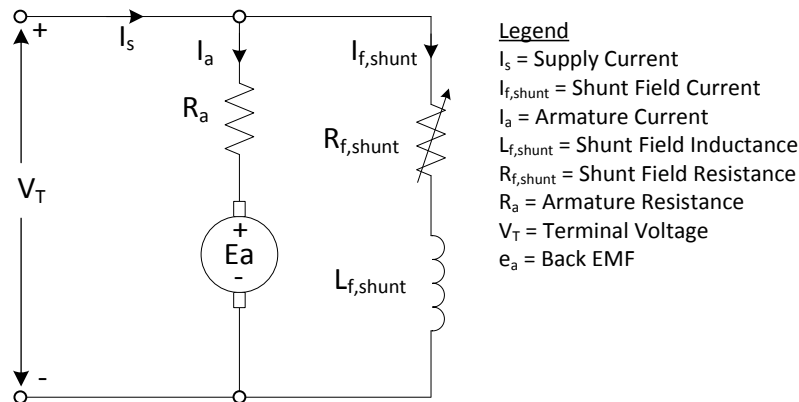
Where:

$I_a$  = armature current

Normally, DC machines are not separately excited. Instead, they may comprise of two different types of field windings (or their combination), shunt field winding and series field winding. The shunt field winding is in parallel with the armature and is made up of thinner wires and has many turns. The series field winding is in series with the armature and is made up of thicker wires with less number of turns. Therefore, the current through the series winding is equal to current through the armature. A compounded DC machine has both the series and the shunt windings.

### 2.1.1. Shunt-Excited DC motor

The equivalent circuit of a DC shunt motor is shown in Figure 8.2.



**Figure 8.2: Equivalent circuit of a shunt-excited DC motor**

As seen in Figure 8.2 the shunt-excited DC motor has one power source,  $V_T$ , supplying the current  $I_s$  to the armature windings, and the field current.

$$I_s = I_a + I_{f,shunt} \quad (8.5)$$

The current through the field can be found by

$$I_{f,shunt} = \frac{V_T}{R_{f,shunt}} \quad (8.6)$$

During the steady state operation of the DC motor the current through the armature nodal analysis:

$$I_a = \frac{V_T - E_a}{R_a} \quad (8.7)$$

Equation (8.1) can be re-written to express the relationship between speed and flux per pole as a function of the field current as shown below in (8.8) and (8.9):

$$V_T = R_a \times I_a + K_T \Phi \omega_m \quad (8.8)$$

$$\omega_m = \frac{V_T - R_a \times I_a}{K_T \times \Phi} \quad (8.9)$$

Where the flux per pole is defined in terms of the armature voltage, field resistance, and design constant, K:

$$\Phi = K \frac{V_T}{R_{f,shunt}} = V_T \times K_f \quad (8.10)$$

To relate the mechanical speed to the induced mechanical torque instead of current equation (8.4) can be expressed as:

$$I_a = \frac{T_m}{K_T \Phi} \quad (8.11)$$

Substituting equation (8.11) into (8.9), the speed torque operating characteristics of a shunt DC motor,  $\omega_m = f(T_m)$  can analytically be described by:

$$\omega_m = \frac{V_T}{K_T \Phi} - \frac{R_a}{(K_T \Phi)^2} T_m \quad (8.12)$$

Or in term of the armature voltage and torque by substituting (8.10) into (8.12):

$$\omega_m = \frac{1}{K_T \times K_f} - \frac{R_a}{(K_T \times K_f \times V_T)^2} T_m \quad (8.13)$$

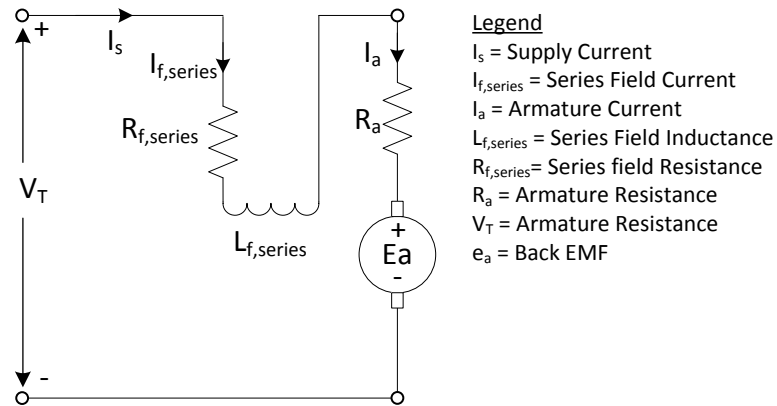
Where the no-load speed is:

$$\omega_{nl} = \frac{V_T}{K_a \Phi} \quad (8.14)$$

Note as the field resistance,  $R_{f,shunt}$ , is increased, the field current is decreased, therefore the flux per pole is decreased, increasing the mechanical speed of the DC motor. It can clearly be seen that if the field current is reduced to zero, the flux will decrease to a small residual value and weaken back emf of armature. This causes the current through armature to increase and the motor to increase to a dangerously high speed. The increase in current is enough to burn out the armature windings, while the increase in speed is high enough to damage the internal component of the motor. Therefore, a shunt-excited motor's field should never be opened during operation.

### 2.1.2. Series-Excited DC motor

The equivalent circuit of a DC shunt motor is shown in Figure 8.3.



**Figure 8.3: Equivalent circuit of as series-excited DC motor**

As seen above, the current through the series winding is equal to the circuit through the armature,  $I_a = I_{f,series}$ .

The terminal voltage of the series-excited DC motor can be expressed by:

$$V_T = (R_{f,series} + R_a) \times I_a + E_a = (R_{f,series} + R_a) \times I_a + K_T \Phi \omega_m \quad (8.15)$$

$$E_a = V_T - (R_{f,series} + R_a) \times I_a \quad (8.16)$$

In terms of the current

$$I_a = \frac{V_T - E_a}{(R_{f,series} + R_a)} = \frac{V_T - K_T \Phi \omega_m}{(R_{f,series} + R_a)} \quad (8.17)$$

The flux of the series-excited DC motor is proportional to its armature current:

$$\Phi = c \times I_a \quad (8.18)$$

Substituting equation (8.18) into equation (8.4), the torque can be expressed in terms of the design constants and the current through the armature:

$$T_m = K_T \times c \times I_a^2 \quad (8.19)$$

The torque-speed characteristics of the series-excited motor can be obtained by re-arranging (8.15) to solve for the mechanical speed:

$$\omega_m = \frac{V_T - (R_{f,series} + R_a) \times I_a}{\Phi \times K_T} \quad (8.20)$$

Re-arranging equation (8.18) to solve for the armature current

$$I_a = \frac{\Phi}{c} \quad (8.21)$$

Substituting equation (8.21) into equation (8.19):

$$T_m = K_T \times \frac{\Phi^2}{c} \quad (8.22)$$

Solving for the flux per pole:

$$\Phi = \sqrt{T_m} \times \sqrt{\frac{c}{K_T}} \quad (8.23)$$

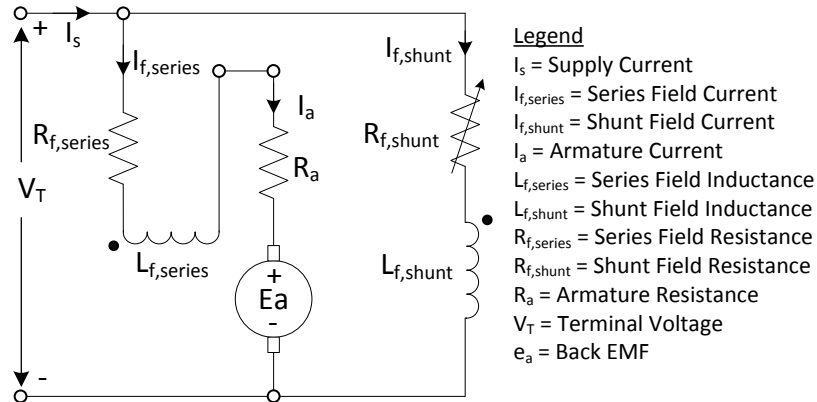
The resulting torque-speed torque relationship is found by substituting equations (8.19) and (8.23) into equation (8.20):

$$\omega_m = \frac{V_T}{\sqrt{c K_T} \times \sqrt{T_m}} + \frac{R_{f,series} + R_a}{c \times K_T} \quad (8.24)$$

If the load is removed from a series motor, its mechanical torque will reduce to zero, thus its field flux will decrease. Consequently, the motor will increase to dangerously high speeds or “runaway” causing damage to the internal components of the DC machine. Therefore, a series motor should never operate with no-load.

### 2.1.3. Cumulative compound DC motor (long-shunt DC motor)

The equivalent circuit of a cumulative compound (long-shunt) DC motor is shown in Figure 8.4.



**Figure 8.4: Equivalent circuit of a cumulative compound DC motor**

As seen in Figure 8.4, the cumulative compound (long-shunt) DC motor has both series and shunt field windings. The flow of current into the dots produces a positive magnetomotive force (mmf). Since the current is flowing into the dots of both field coils the net mmf is the sum of the mmf produced by both coils as shown below:

$$\Phi_{\text{total}} = \Phi_{\text{shunt}} + \Phi_{\text{series}} \quad (8.25)$$

If the dot on the series connection was flipped, showing current flowing out of the coil, the mmf would subtract.

As seen in Figure 8.4, the flux of the shunt winding remains constant proportional to the field resistance, while the flux of the series winding is proportional to its armature current. Therefore, the cumulative compound dc motor exhibits the operating characteristics of both the shunt- and series-excited DC motor. This includes a higher starting torque than the shunt motor but lower than series motor. Unlike the series-excited motor, the compounded dc motor does not “runaway” at low loads.

## 2.2. Inrush Current

During the steady state operation of DC motor the current through armature is given by equation (8.7). However, during the start-up of a DC motor from stand still the back emf of armature is zero. The current during start-up, commonly referred to as inrush current, becomes:

$$I_{a \text{ inrush}} = \frac{V_a}{R_a} \quad (8.26)$$

If the DC motor is started directly from the line, the current through the armature reaches high value, then decrease to its steady state value when the back emf builds up in the armature. For this lab, assuming that the armature resistance is 0.05 pu of its base voltage of 120 V and its rated current is 2.4 A, the inrush current can be found by:

$$I_{a \text{ inrush}} = \frac{120 \text{ V}}{6\Omega} = 20\text{A} \quad (8.27)$$

The magnitude of the current is large enough to overheat and damage the armature windings of the DC machine or the DC driving source.

## 2.3. Efficiency

The efficiency of the DC motor is given by the power output over the power input as shown in the equation below:

$$\eta_T = \frac{P_{out}}{P_{in}} \times 100 = \frac{P_{in} - \sum P_{Losses}}{P_{in}} \times 100 (\%) \quad (8.28)$$

Or in terms of the electrical power input and mechanical power output:

$$\eta_T = \frac{P_{out_{mechanical}}}{P_{in_{electrical}}} \times 100 = \frac{\omega \times T_m}{V_s \times I_s} \times 100 (\%) \quad (8.29)$$

The losses in the shunt field can be calculated from the sum of the following components:

$$P_{shunt_{loss}} = \frac{V_f^2}{R_f} \quad (8.30)$$

The total copper loss is the sum of losses in the primary and secondary sides as shown in equation (8.31):

$$P_{series_{loss}} = I_a^2 \times R_{series} \quad (8.31)$$

The losses in the armature can be calculated from:

$$P_{armature_{Loss}} = I_a^2 \times R_{armature} \quad (8.32)$$

The losses in the brushes can be calculated from the voltage drop across the brushes and the current through the armature:

$$P_{brush} = V_{brush} \times I_a \quad (8.33)$$

Since the rotational losses at the full-load and no-load is equivalent to the input power to the armature:

$$P_{rotational_{Loss}} = V_T \times I_{a_{no\ load}} \quad (8.34)$$

## 2.4. Speed Regulation

The speed regulation of a DC motor is defined by:

$$Speed\ Reg = \frac{\omega_{nl} - \omega_{fl}}{\omega_{fl}} \quad (8.35)$$

Where:

$\omega_{nl}$  = no-load angular speed in rad/s

$\omega_{fl}$  = full-load angular speed in rad/s

The speed regulation is a measure of the steepness of the slope of the torque-speed characteristic.

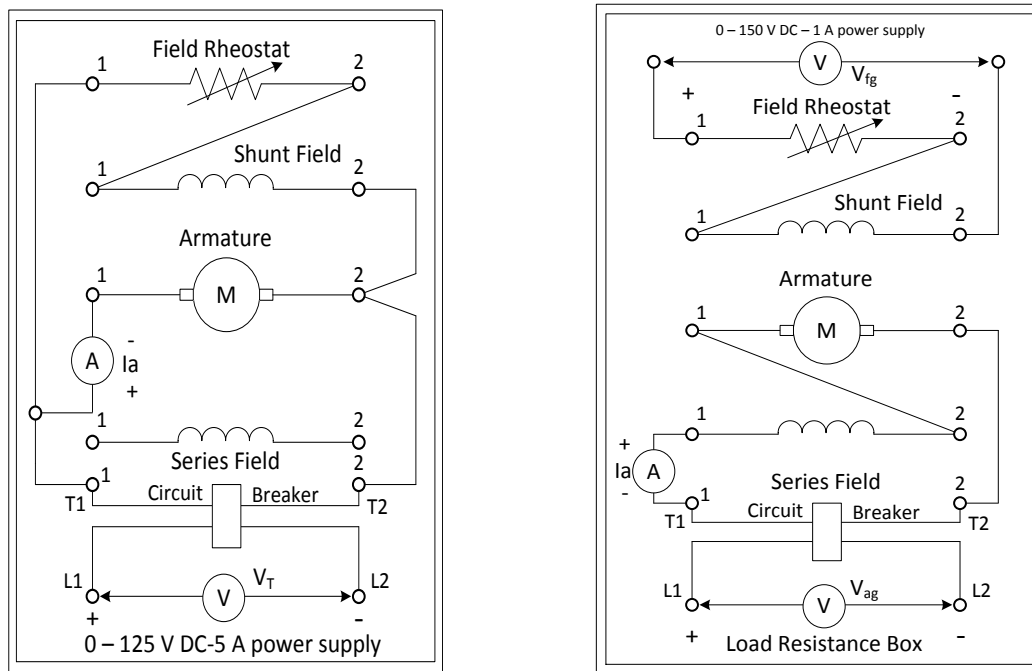
## 3. Procedure, Measurements, and Calculations

### 3.1. Measuring the operating characteristics of DC motor

The DC machine used for this lab is compound wound machine where the field and armature circuit can be connected in several different ways. The nameplate rating for the DC machine is: H.P. = 0.3 kW,  $V_T = 125$  V,  $I_a = 2.4$ ,  $n_{nominal} = 1800$  R.P.M.,

### 3.1.1. Observing the relationships between torque, internal voltage, and speed

3.1.1.1. Construct the circuit shown in Figure 8.5.



**Figure 8.5: Electrical connection for the shunt-excited DC motor and separately-excited DC generator**

3.1.1.2. Look at the back of your station and note the workstation number

3.1.1.3. Bring three-phase AC power from “SUPPLIES” and “120/208V-3 $\phi$  4W 60~” to your corresponding work station number on “DISTRIBUTION #1” by making the necessary connections between the two.

3.1.1.4. Verify that every group has brought three-phase to the corresponding distribution station.

3.1.1.5. Close the main circuit breaker above “120/208V-3 $\phi$  4W 60~”

3.1.1.6. Close the corresponding breaker on “DISTRIBUTION #1” to bring three-phase power to your workstation.

3.1.1.7. Set the field resistance of the DC motor to its “min” position and the DC generator to its “max” position.

3.1.1.8. If everything is wired correctly, close the main AC Circuit Breaker, located at the left side of the workstation.

3.1.1.9. Close the circuit breaker for 0-150 (V) DC-1 (A) power supply, labeled “PRI.5 SEC. 2”

3.1.1.10. Adjust the power supply knob until the DC separately-excited generator field voltage becomes  $V_{fg} = 110$  (V).

3.1.1.11. Close the circuit breaker of the 0-125 (V) DC-5(A) power supply, labeled “PRI.10 SEC. 8”, and adjust the voltage of the shunt-excited DC motor to  $V_T = 0$  (V).

3.1.1.12. Close the circuit breaker of the shunt-excited DC motor.

3.1.1.13. Using the 0-125 (V) DC-5 (A) rheostat, slowly increase the armature voltage,  $V_T$ , to 125 (V).

Note: Observe the ammeter measuring the current through the armature. As you increase the voltage the current will decrease as the back emf builds up in the motor.

3.1.1.14. Record the values of the armature and field current, terminal voltage, and mechanical speed in Table 8.1. Use the strobosch to measure the mechanical speed of the DC motor. Flash the strobosch on the rotor or shaft of the motor and adjust the dial until there appears to be one stationary block on the rotor. The number on the dial is the mechanical speed of the motor in rpm.

3.1.1.15. Adjust the rheostat until it is in between the minimum and maximum position. Record the results in Table 8.1.

3.1.1.16. Repeat the last step this time when the field is set to its maximum position.

**Table 8.1: Measured values of the mechanical speed, armature and field current, and the voltages of a shunt-excited DC motor.**

|           | Measured  |           |             | Computed  |
|-----------|-----------|-----------|-------------|-----------|
| $I_f$ (A) | $V_T$ (V) | $I_a$ (A) | $N_m$ (rpm) | $E_a$ (V) |
| max       |           |           |             |           |
| mid       |           |           |             |           |
| min       |           |           |             |           |

3.1.1.17. Calculate the back emf for each case and record the results in Table 8.1.

3.1.1.18. Comment on the results.

### 3.1.2. Observing the operating characteristics of a shunt DC motor

3.1.2.1. Make sure the motor's field resistance is set to its "max" position.

3.1.2.2. Use a strobetach to measure the mechanical speed,  $n_m$ , of the shunt-excited DC motor. Select the high range of the strobetach labeled "HIGH TACH". Flash the light directly on the shaft or on the perpendicular to it. Adjust the dial until you see one stationary block on the shaft of the DC motor.

3.1.2.3. Measure the armature current,  $I_a$ , the mechanical speed,  $n_m$ , and the torque,  $T_m$ , of the DC shunt-excited motor, when the DC separately-excited generator is not loaded.

Record the results in Table 8.2

**Table 8.2: Measured and computed values of the shunt-excited DC motor**

| $V_T = 125$ (V) | No-load | 1 | 12 | 123 | 1234 | 12345 |
|-----------------|---------|---|----|-----|------|-------|
| $N_m$ (rpm)     |         |   |    |     |      |       |
| $I_a$ (A)       |         |   |    |     |      |       |
| $T_m$ (Nm)      |         |   |    |     |      |       |
| $P_{in}$ (W)    |         |   |    |     |      |       |
| $P_{out}$ (W)   |         |   |    |     |      |       |
| Efficiency (%)  |         |   |    |     |      |       |

3.1.2.4. Close the generator circuit breaker. Close the switch on the resistance load box labeled "1".

3.1.2.5. Using the generator's field rheostat adjust the generator's armature voltage to  $V_{ag} = 110$  (V).

3.1.2.6. If necessary, re-adjust the motor's armature voltage to  $V_T = 125$  (V).

3.1.2.7. Repeat steps 3.1.2.3. – 3.1.2.6. for each case in Table 8.2.

3.1.2.8. Once all the measurements are recorded, adjust the shunt-excited motor's field resistance to its minimum position and the separately-excited generator's field to its maximum position. Open each load on the load resistance box then open the separately excited generator's circuit breaker.

3.1.2.9. Adjust the armature voltage to zero volts then open the motor's circuit breaker. Then adjust the excitation voltage of the generator to zero then open the circuit breaker. Next open the circuit breaker labeled "Main AC".

3.1.2.10. Plot the speed-torque characteristics of a shunt-excited DC motor, i.e.  $n_m = f(T_m)$ .

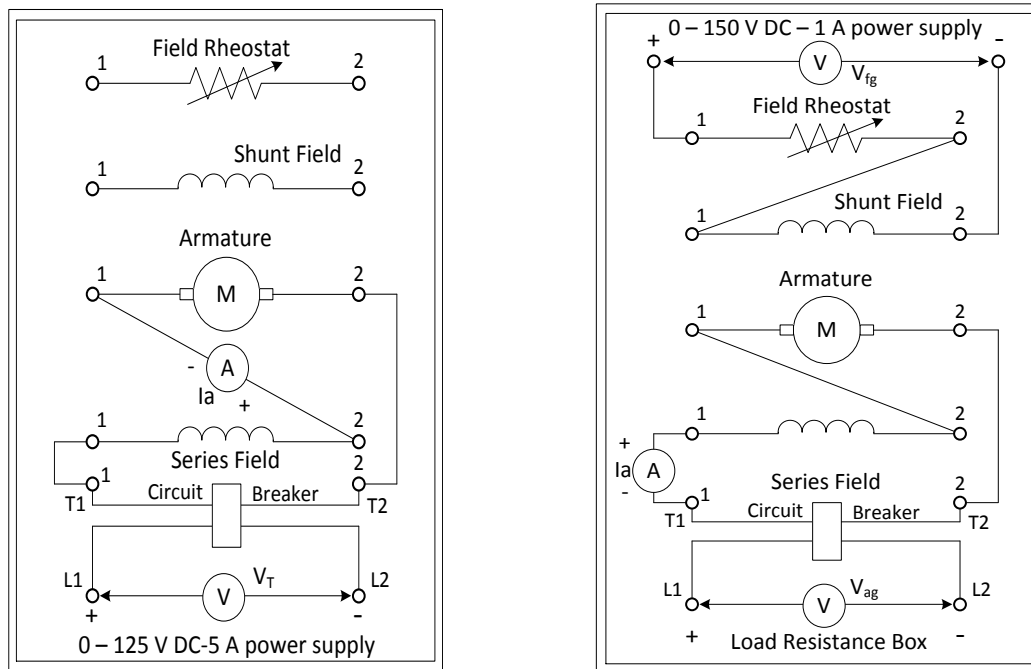
3.1.2.11. Plot the torque-armature current characteristics of a shunt-excited DC motor, i.e.  $T_m = f(I_a)$ .

3.1.2.12. Calculate the input and output power of DC motor and its efficiency.

3.1.2.13. Compute the speed regulation of a shunt-excited DC motor using “12345” as the full load.

### 3.1.3. Observing the operating characteristics of Series DC motor

3.1.3.1. Construct the circuit shown in figure in Figure 8.6.



**Figure 8.6: Electrical connection for the series-excited DC motor and separately-excited DC generator**

3.1.3.2. If everything is wired correctly, close the main AC Circuit Breaker, located at the left side of the workstation

3.1.3.3. Close the circuit breaker for 0-150 (V) DC-1 (A) power supply, labeled “PRI.5 SEC. 2”

3.1.3.4. Adjust the power supply knob until the DC separately-excited generator field voltage becomes  $V_{fg} = 110$  (V).

3.1.3.5. To prevent the “runway” of the series-excited DC motor close the generator circuit breaker. Close the switch on the resistance load box labeled “1”.

3.1.3.6. Make sure the generator's field resistance is set to its "max" position

3.1.3.7. Close the circuit breaker of the 0-125 (V) DC-5(A) power supply, labeled "PRI.10 SEC. 8", and adjust the voltage of the shunt-excited DC motor to  $V_T = 0$  (V).

3.1.3.8. Close the circuit breaker of the series-excited DC motor.

3.1.3.9. Using the 0-125 (V) DC-5 (A) rheostat, slowly increase the armature voltage,  $V_T$ , to 90 (V).

3.1.3.10. Using the generator's field rheostat adjust the generator's armature voltage to  $V_{ag} = 120$  V.

3.1.3.11. Measure the armature current,  $I_a$ , the mechanical speed,  $n_m$ , and the torque,  $T_m$ , of the DC series-excited motor. Record the results in Table 8.3.

**Table 8.3: Measured values of the mechanical speed, armature and field current, and the voltages.**

| $V_T = 90$ (V) | 1 | 12 | 123 | 1234 | 12345 |
|----------------|---|----|-----|------|-------|
| $n_m$ (rpm)    |   |    |     |      |       |
| $I_a$ (A)      |   |    |     |      |       |
| $T_m$ (Nm)     |   |    |     |      |       |

3.1.3.12. Close the switch on the resistance load box labeled "2".

3.1.3.13. If necessary re-adjust the armature voltage of the motor to  $V_T = 90$  (V).

3.1.3.14. Re-adjust the armature of the generator to  $V_{ag} = 120$  V.

3.1.3.15. Repeat steps 3.13.10.-3.1.3.14. for each case in Table 8.3.

3.1.3.16. Once all the measurements are recorded, adjust the the separately-excited generator's field resistance to its maximum position.

3.1.3.17. Adjust the armature voltage to zero volts then open the motor's circuit breaker. Then adjust the excitation voltage of the generator to zero then open the generator's circuit breaker. Next open the circuit breaker labeled "Main AC"

3.1.3.18. Open each load on the load resistance box.

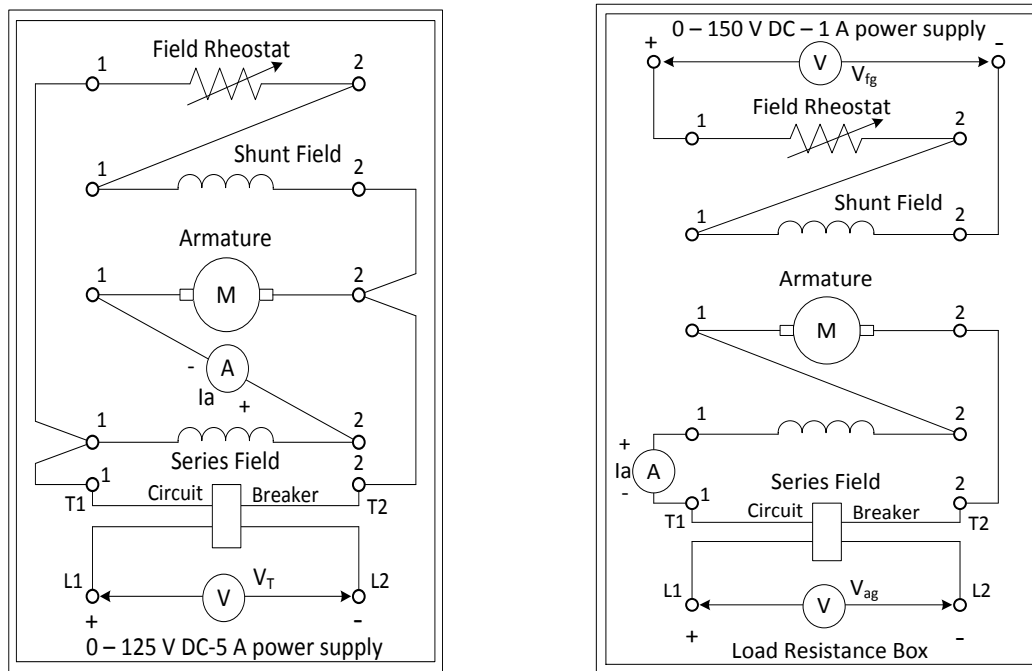
3.1.3.19. Plot the speed-torque characteristics of a shunt-excited DC motor, i.e.  $n_m = f(T_m)$

3.1.3.20. Plot the torque-armature current characteristics of a shunt-excited DC motor, i.e.  $T_m = f(I_a)$

3.1.3.21. Compute the speed regulation of a shunt-excited DC motor using "12345" as the full load.

### 3.1.4. Observing the operating characteristics of cumulative compound DC motor

3.1.4.1. Construct the circuit shown in Figure 8.7.



**Figure 8.7: Electrical connection for the compound DC motor and separately-excited DC generator**

3.1.4.2. Set the field resistance of the DC motor to its “min” position and the DC generator to its “max” position.

3.1.4.3. If everything is wired correctly, close the main AC Circuit Breaker, located at the left side of the workstation

3.1.4.4. Close the circuit breaker for 0-150 (V) DC-1 (A) power supply, labeled “PRI.5 SEC. 2”

3.1.4.5. Adjust the power supply knob until the DC separately-excited generator field voltage becomes  $V_{fg} = 110$  (V).

3.1.4.6. Close the circuit breaker of the 0-125 (V) DC-5(A) power supply, labeled “PRI.10 SEC. 8”, and adjust the voltage of the shunt-excited DC motor to  $V_T = 0$  (V).

3.1.4.7. Close the circuit breaker of the shunt-excited DC motor.

3.1.4.8. Using the 0-125 (V) DC-5 (A) rheostat, slowly increase the armature voltage,  $V_T$ , to 125 (V).

3.1.4.9. Adjust the field resistance of compound dc motor to its “max” position.

3.1.4.10. Measure the armature current,  $I_a$ , the mechanical speed,  $n_m$ , and the torque,  $T_m$ , of the DC shunt-excited motor, when the DC separately-excited generator is not loaded. Record the results in Table 8.4.

**Table 8.4: Measured values of the mechanical speed, armature and field current, and the voltages.**

| $V_T = 125$ (V) | No-Load | 1 | 12 | 123 | 1234 | 12345 |
|-----------------|---------|---|----|-----|------|-------|
| $n_m$ (rpm)     |         |   |    |     |      |       |
| $I_a$ (A)       |         |   |    |     |      |       |
| $T_m$ (Nm)      |         |   |    |     |      |       |

3.1.4.11. Close the generator circuit breaker. Close the switch on the resistance load box labeled “1”.

3.1.4.12. Using the generator’s field rheostat adjust the generator’s armature voltage to  $V_{ag} = 110$  (V).

3.1.4.13. If necessary, re-adjust the motor’s armature voltage to  $V_T = 125$  (V).

3.1.4.14. Repeat steps 3.1.4.10 – 3.1.4.13 for each case in Table 8.4.

3.1.4.15. Once all the measurements are recorded, adjust the shunt-excited motor’s field resistance to its minimum position and the separately-excited generator’s field to its maximum position. Open each load on the load resistance box then open the separately excited generator’s circuit breaker.

3.1.4.16. Adjust the armature voltage to zero volts then open the motor’s circuit breaker. Then adjust the excitation voltage of the generator to zero then open the generator’s circuit breaker. Next open the circuit breaker labeled “Main AC”.

3.1.4.17. Plot the speed-torque characteristics of a shunt-excited DC motor, i.e.  $n_m = f(T_m)$

3.1.4.18. Plot the torque-armature current characteristics of a shunt-excited DC motor, i.e.  $T_m = f(I_a)$

3.1.4.19. Compute the speed regulation of a compound DC motor using “12345” as the full load.

3.1.4.20. Discuss the relationships between the three types of motors covered in the lab. Compare the operating characteristics of each motor.