EXPERIMENT DC Machine

DC Motors and Generators 1800RPM

OBJECTIVE

This experiment explores all the possible design connections of a DC machine. Also studied are the performance and control characteristics of these configurations. The method of testing to derive the equivalent circuit of a given design is demonstrated.

REFERENCES

1. "Electric Machinery", Fourth Edition, Fitzgerald, Kingsley, and Umans, McGraw-Hill Book Company, 1983, Chapters 2, 3 and 5.

2. "Electromechanical Energy Conversion", Brown and Hamilton, MacMillan Publishing Company, 1984, Chapters 2 and 5.

3. "Electric Machines, Steady-State Theory and Dynamic Performance," Sarma, M. S., Wm. C. Brown Publishers, 1985, Chapters 5 and 9.

BACKGROUND INFORMATION

DC machines are one of the three basic multiply-excited rotational electromechanical energy converters. Figure 1 shows an elementary doubly-excited magnetic system.
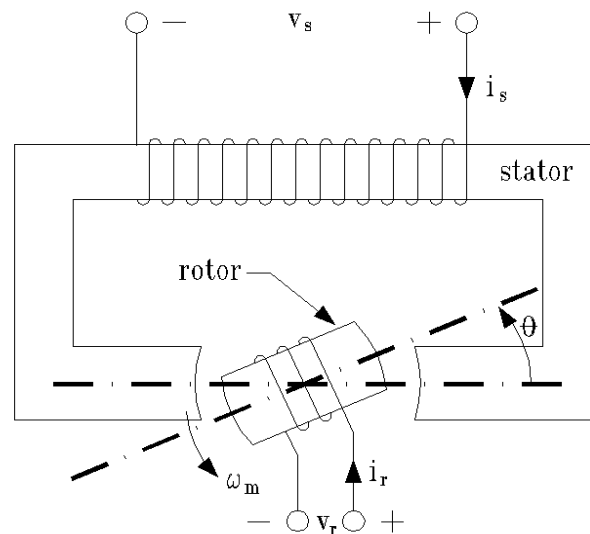

Figure 1: **Elementary doubly-excited magnetic system.**

The electromagnetic torque produced by a machine can be described by the following equation:

$$T_{dev} = \frac{1}{2} i_S^2 \frac{dL_{SS}}{d\theta} + i_S i_R \frac{dL_{sR}}{d\theta} + \frac{1}{2} i_R^2 \frac{dL_{RR}}{d\theta} \quad N-m \quad (4.1)$$

If the machine is to produce a continuous torque, one of the windings must provide for current switching. This current switching establishes a moving flux field which the machine rotor essentially "chases". The typical DC machine has a stator-mounted field winding which produces a flux that is stationary in space. The armature winding is located on the machine rotor, and the armature coils are terminated with copper bars that form segment of a commutator. The commutator is supplied armature current through a set of graphite brushes that ride on the commutator surface. As the rotor turns, successive commutator segments enter and leave the brush contact zone, thereby switching the current from one armature coil to the next. Figures 2 through 5 illustrate the general construction of DC machines and the commutator.
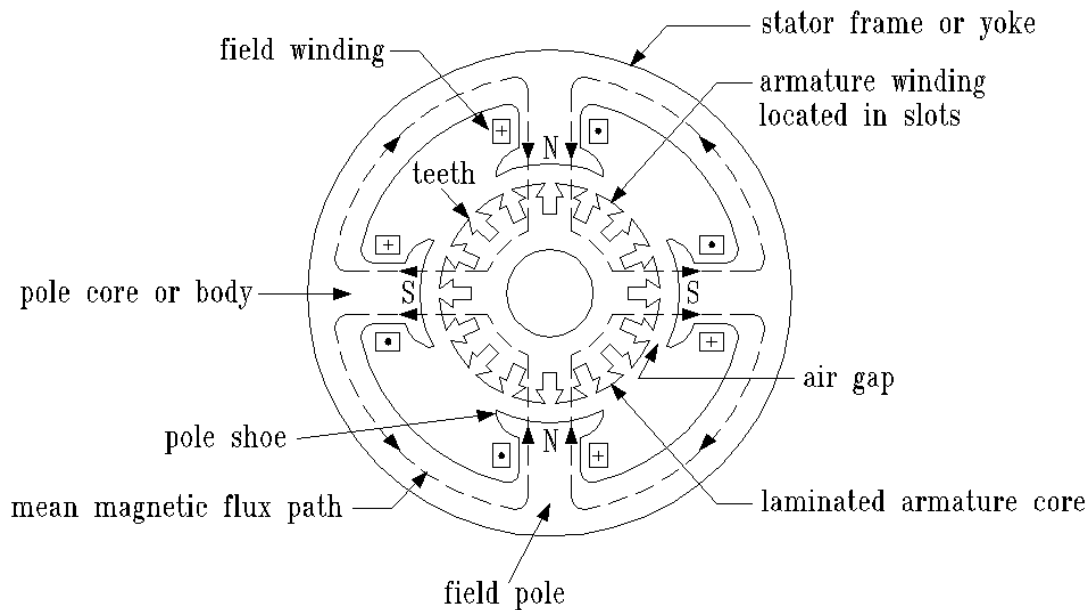

Figure 2: **Diagram of a DC machine.**

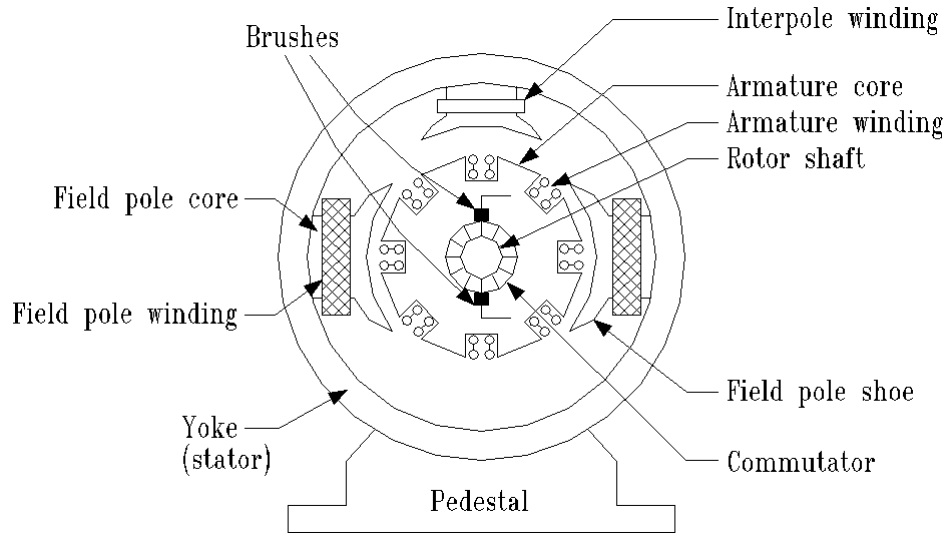**Figure 3**: **Cross-section of a DC machine showing the commutator.**

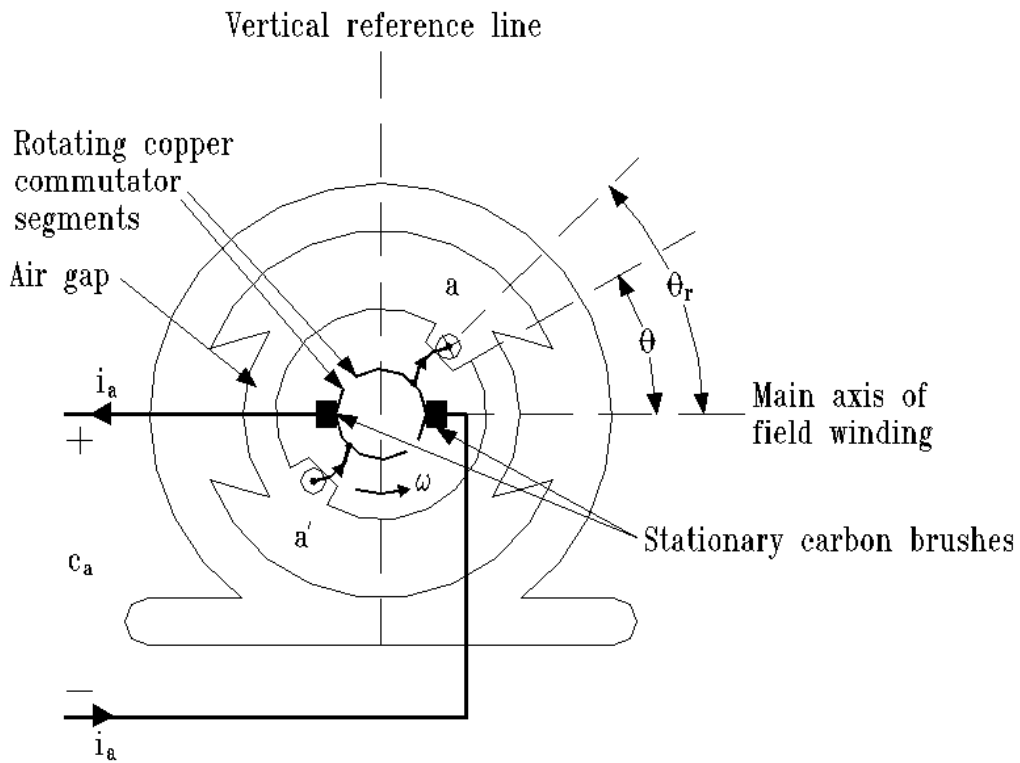**Figure 4**: **A single-coil elementary commutator system.**

From Figure 2, it is evident that keeping the fields 90 electrical degrees displaced causes each of the fields to "see" an essentially constant air gap. Therefore, Eq. 4.1 reduces to

$$T_{dev} = i_S i_R \frac{dL_{SR}}{d\theta} \quad \text{N} - \text{m} \qquad (4.2)$$

$$T_{dev} = i_S i_R \ \sin\theta \quad \text{N} - \text{m} \qquad (4.3)$$

It should now be evident that the 90 electrical degree displacement causes the machine to produce the maximum possible torque.

When both the field and armature circuits are excited, the rotor will begin to turn. As the rotor turns, the armature windings are moving through the flux created by the field windings. This action causes a voltage to be induced in the armature windings as described by Faraday's Law. The induced voltage acts to counteract the voltage that is producing the armature current and is, therefore, called the back EMF of the motor.

The magnitude of the back EMF is proportional to the number of turns in the armature winding and the time-rate-of-change of the field flux as seen by the armature winding. If steady-state operation is assumed, the time-rate-of-change of the flux is just the product of the rotor velocity and the flux magnitude. An additional simplification is made by recognizing that the magnitude of the field flux is essentially proportional to the field current. Thus, the back EMF can be described as

$$E \quad = \quad K\omega_m I_f \ \text{volts} \qquad (4.4)$$

Where: E   =   back EMF, volts

K   =   a constant representing armature winding geometry, H

ω_m =   rotor velocity, Rad/sec.

I_f =   field current, amperes

The armature circuit contains windings which have resistance. Therefore, the steady-state armature circuit is normally modeled as a voltage source in series with a resistance as shown in Figure 7. Since the model is for the steady-state, the inductances are not included.
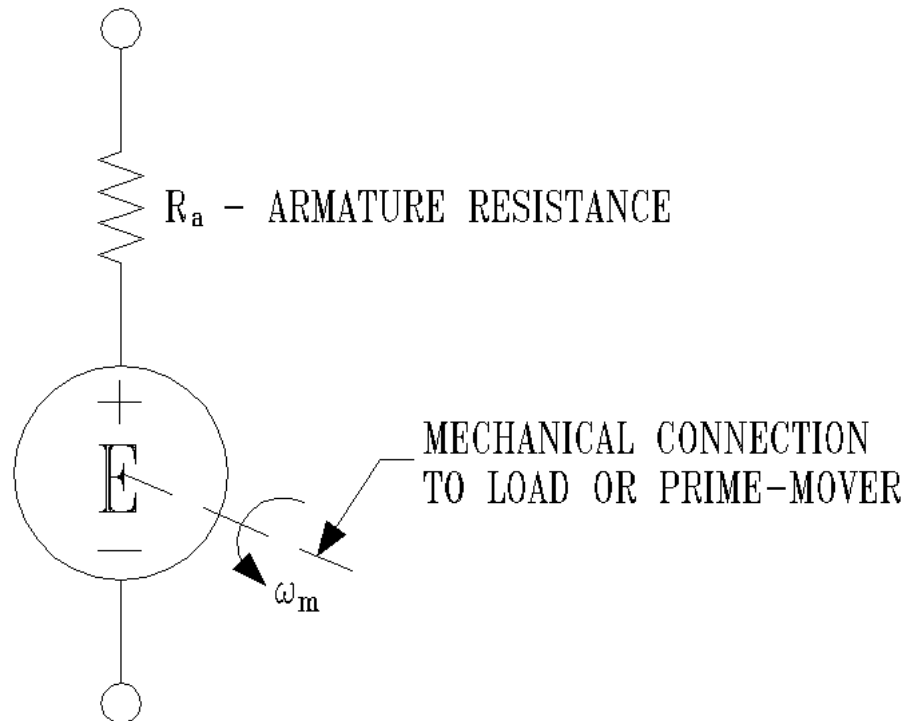

R_a – ARMATURE RESISTANCE

MECHANICAL CONNECTION TO LOAD OR PRIME-MOVER

ω_m

Figure 7: Model of armature circuit.

DC motors are described by the method used to excite the field. The four most common methods are: separately-excited, shunt-connected, series-connected, and compound. The separately-excited machine has no physical connection between the field and armature windings. Each circuit is excited from its own power supply. A shunt-connected machine has the field circuit connected in parallel with the armature circuit. Both circuits have the same total voltage drop across them. The series-connected machine has the field circuit in electrical series with the armature circuit. Both circuits share the same current. A compound machine contains two independent field circuits. One field circuit is connected in series with the armature circuit, and the other field circuit is connected to shunt either the armature circuit or the series combination of series field and armature circuits. The former is called a "short" shunt, and the latter is called a "long" shunt. Figure 8 shows the various connections.
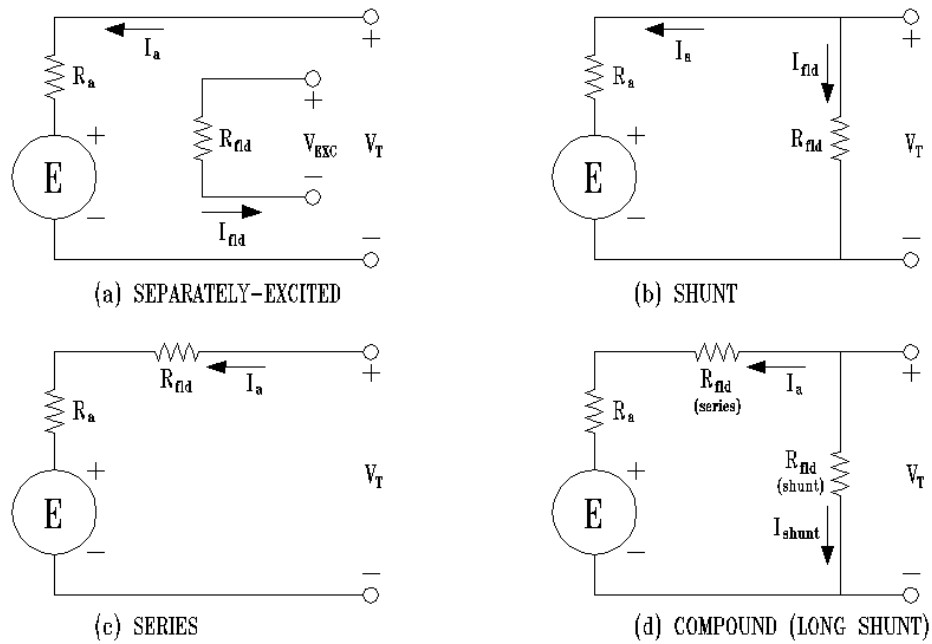
Figure 4-8: DC motor connections.

The symbols used in Figure 8 are:

V_T = motor terminal voltage

I_{fld} = field current

I_a = armature current

R_{fld} = field resistance

R_a = armature resistance

E = motor back EMF

V_{EXC} = excitation voltage

The torque produced by a DC motor is described as the ratio of output power to mechanical rotor speed. The output power is

$$P_{OUT} = EI_a \qquad (4.5)$$

hence, the output torque is

$$T = \frac{P_{OUT}}{\omega_m} = \frac{EI_a}{\omega_m} \qquad (4.6)$$

Combining Eq. 4.6 with Eq. 4.4 yields

$$T = \frac{K\omega_m I_f I_a}{\omega_m} = KI_f I_a \qquad (4.7)$$

Eq. 4.7 compares to Eq. 4.2 when we realize that the current I_f is analogous to the stator current i_S, current I_a is analogous to the rotor current i_R, and the constant K is analogous to the derivative of inductance with respect to position.

The different winding connections shown in Figure 8 produce different speed vs. torque characteristics. Figure 9 shows typical curves for three of the connections.
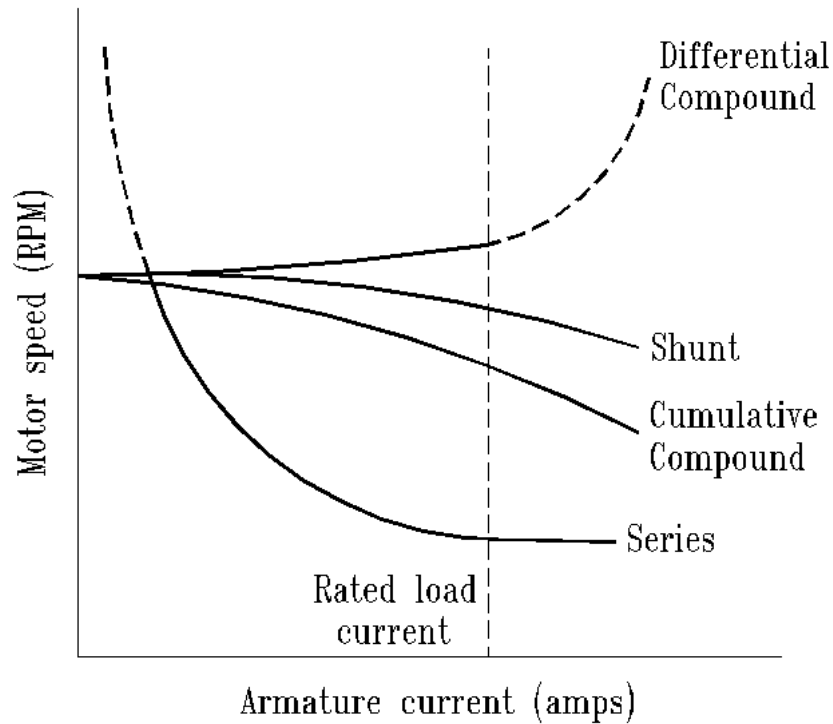
Figure 9: **Typical speed vs. load characteristics for DC motors.**

The fourth connection, separately-excited, can be made to respond like any of the other three by proper control of the excitation voltage. For the cumulative compound machine shown in the figure, both the series and shunt field produce flux in the same orientation. The differential compound machine is connected so the series and shunt fields are in magnetic opposition. Eq. 4.6 shows that the armature current is a good measure of the torque load on the motor.

A question that often arises is how the torque forces produced by the motor are neutralized, or equally opposed. The basic concept, from Newtonian mechanics, is that for every force there is an equal and opposite force that brings the entire system into equilibrium. A primary force (torque) is created by the magnetic field interaction in the air gap of the motor and transmitted to the load. The balancing force is caused by the motor stator (frame) interacting with its mountings, perhaps the floor of a room. Thus, the system is neutralized by an object of great mass.

The DC motor creates torque from electrical excitation of two magnetic circuits, the field and the armature. If the process is partially reversed by electrically exciting the stator mounted field and providing torque from an external prime-mover, the machine becomes a generator. As the prime-mover spins the armature circuit through the magnetic field, a voltage is created in the armature circuit. The generated voltage is described by Eq. 4.4. A schematic diagram of a separately excited DC generator looks identical to Figure 8 (a), but the armature current I_a is reversed.

As with the DC motor, the shaft torque of the DC generator is countered by a force created at the stator mounting point. If the stator mounting is through a measurement device such as a strain gauge, the force that counteracts the shaft torque can be measured. A DC generator mounted in this fashion is called a dynamometer. A dynamometer equipped with a speed measuring device (tachometer) can be used to determine the power output of any type of rotating prime-mover.

To this point, we have assumed that the DC machine is a linear device; such is not the case. The influence of magnetic saturation can be seen by observing the no-load terminal voltage of the separately excited DC generator at different excitation levels. At high levels of excitation (large I_f), the field magnetic circuit becomes saturated and the voltage generated per ampere of exciting current tends to decrease. Figure 10 shows a typical curve.
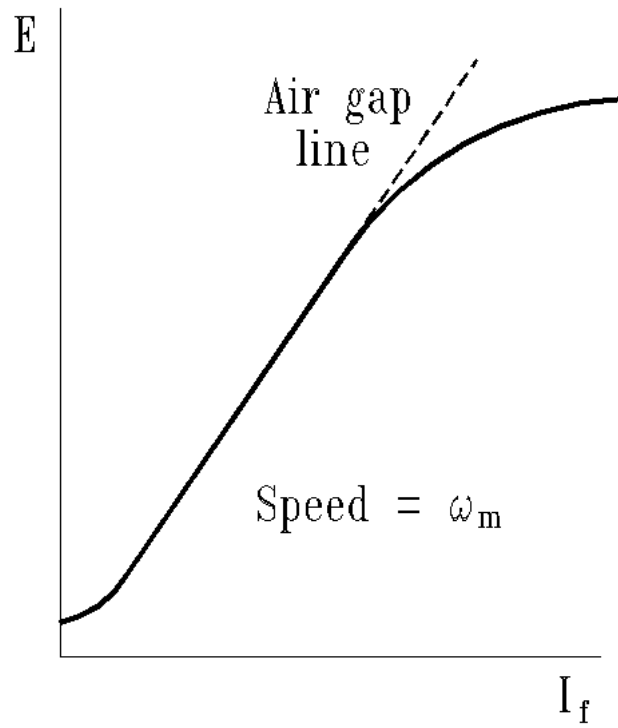
Figure 10: **No-load terminal voltage versus field current for a separately-excited generator at rated speed.**

THE TEST SET-UP

The DC machine to be tested and the dynamometer have already been placed on the bench and mechanically coupled. On the right-hand end of the dynamometer is a clamp which locks the rotor and stator. This lock is used when measuring the locked-rotor torque of the test machine. Observe how the lock is installed so it may be properly replaced when the time arrives.

The force required to counteract the shaft torque is measured by the strain gauge that connects the overhanging arm to the dynamometer stator. The strain gauge is connected through a cable (follow it) to a gray box on top of the bench. This box contains A/D converter, digital display, and assorted drivers. The display indicates torque in Newton-meters. Be sure to set the torque meter to zero before each measurement.

The dynamometer acts as a generator when it is being used to load a motor. The dynamometer armature is loaded by the resistor bank. All switches should be in the center "off" position for no-load tests. To load the dynamometer, move all the switches to "up" position.

Speed measurements are made with a tachometer. On the bench is a portable digital tachometer. It's the little blue box that has RPM on the front. Attached to the box is a cable with an optical head at the remote end. This head contains a light source and an optical receiver. On the large pulley connected to the dynamometer you'll find a piece of reflective tape. When the light source is aimed at the pulley, a small amount of light is reflected back each time the tape crosses the beam. The reflected light causes an electrical pulse from the receiver. The blue box times the pulses, converts them to RPM, and displays the speed.

CAUTION – **Do not look into the light source. It is very intense and will hurt your Eyes!!!!**

The efficiency of the coupling system is, in very good approximation, 96 percent. Figure 12 illustrates the faceplates of the Dynamometer and figure 11 shows the connections of the DC motor, there are two shunt fields wired internally in series. **Rfld = internal Rfld1 in series Rfld2.**

DC Supply
Vt
Terminal
voltage

DC

Motor
Current

F1
Yellow

Rfld1

F2

F3

Rfld2

F4
Blue

Ifld
Field
Current

A1
Red

Ra

DC

E
Back EMF

A2
Black
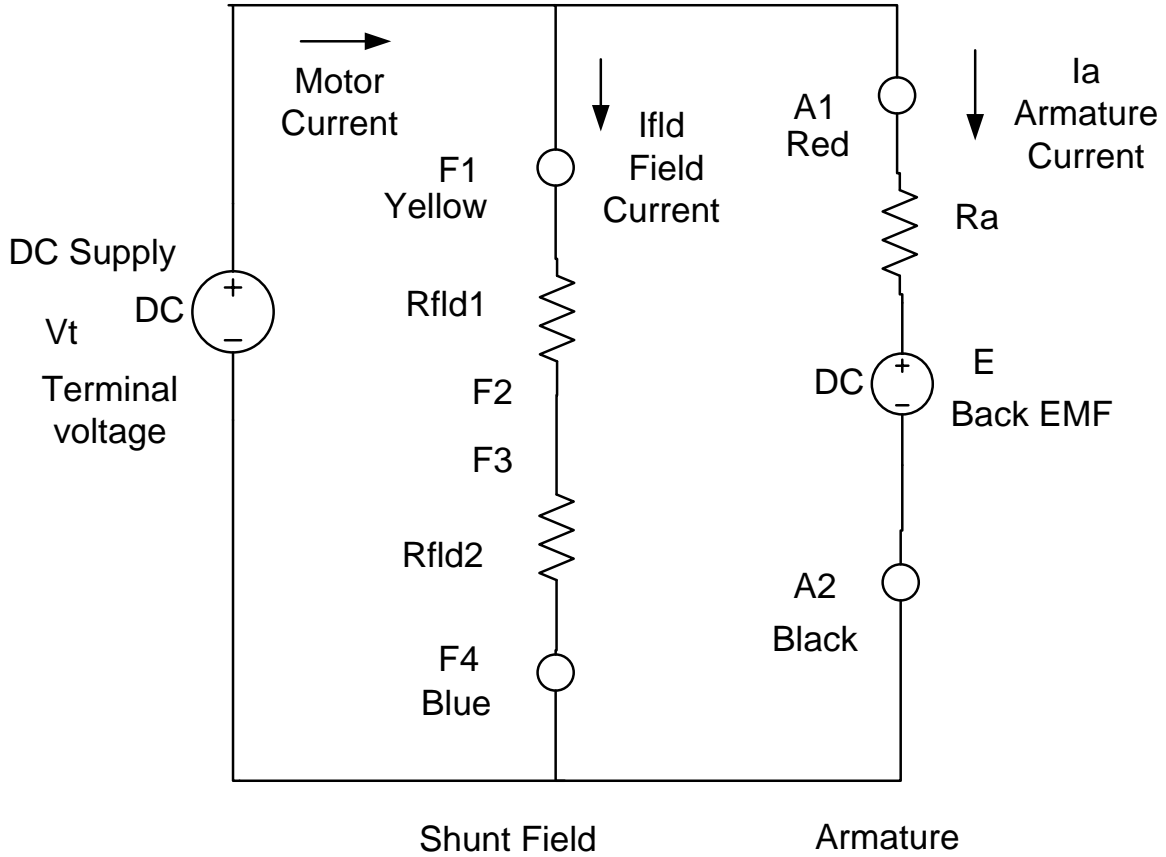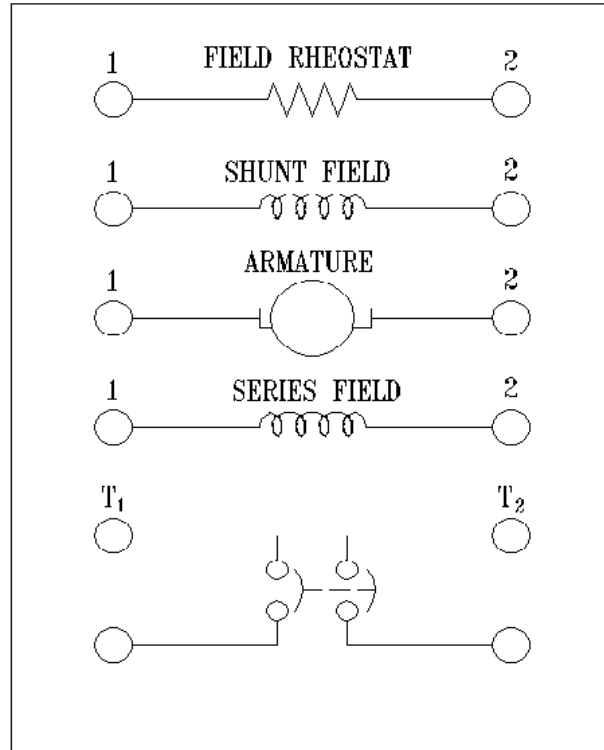
Ia
Armature
Current

Shunt Field

Armature

Figure 11 **DC shunt motor connections**

Note: To reverse the direction of the motor you must reverse the ether the Field or the Armature connection but not both.

DYNAMOMETER

1 = RED
2 = BLACK

Figure 12 Dynamometer face plate

SUGGESTED PROCEDURE

Be sure to make all connections as shown in the figures. Variations might cause erroneous data. Before proceeding, make sure you have read the Test-Setup-Section.

Open the Metering instruments in the software LVDAC-EMS. Change the current range for I1 to 40A on the right-hand menu, and set up 2 displays to measure E1 and I1. Change the operating modes for the voltage meter E1 and the current meter I1 accordingly.
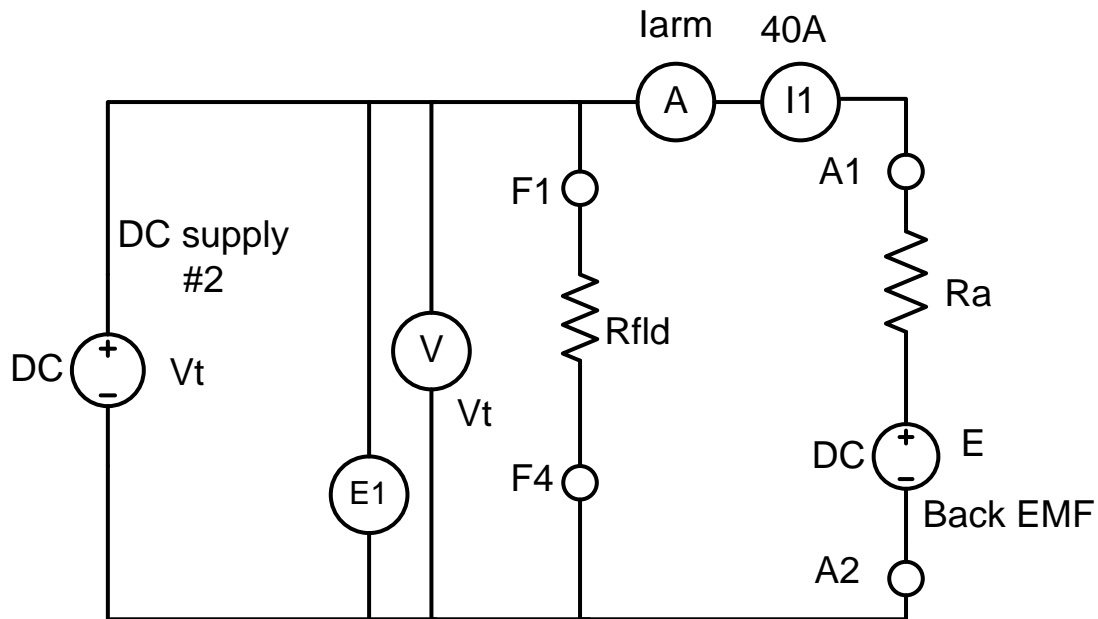

Figure 13 Shunt Configuration DC Motor

Part 1a: Connect the dc motor in the **shunt configuration (figure 13).** Make sure that the torque meter is set to 0 Newton-meters before energizing the DC motor and that it only reads positive torques as the motor starts running. **Note: To reverse the direction of the motor, you must reverse either the Field or the Armature connection but not both**. With the dynamometer **locked**, adjust the motor terminal voltage (Vt) power supply (#2) until the motor armature current is 3.4 amperes: **Caution the terminal voltage will be less than 15Vdc**. This is the rated armature current for the machine. Record the torque, armature current and terminal voltage in table 1.

The terminal voltage and armature current values obtained during the locked-rotor test are used to determine the **armature resistance** of the machine.

Table 1: Locked Rotor armature resistance Vt<15Vdc (**figure 13)**

Iarm	Vt (Varm)	Torque
3.4A		

Ra = Varm/Iarm = _____

Make sure power is turned off before removing the lock.

Part 1b: Remove the dynamometer lock. Maintain the shunt configuration DC motor connections and wire the dynamometer circuit below **(figure 14).** Adjust the motor (**Figure 13**) power supply (#2) until the terminal voltage (Vt) is 90Vdc, no load dynamometer (dynamometer field voltage = 0Vdc). Record in **table 2** the armature current (Iarm), motor speed (RPM), torque reading (windage and friction of the dynamometer).

Table 2: No load (figure 13)

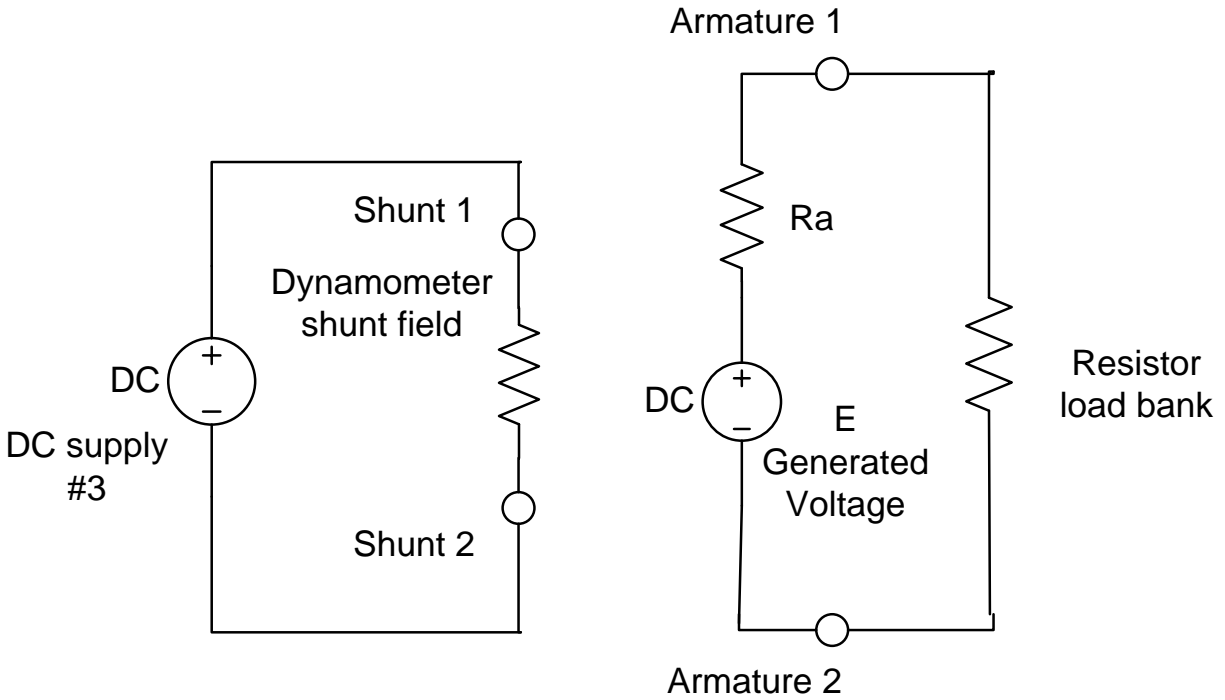| Vt (Varm)	Iarm	Torque	RPM
90Vdc			

Figure 14 Dynamometer

Part 1c: Place all the dynamometer load switches in the **up** position, adjust the motor terminal voltage to 90Vdc and then increase the dynamometer field voltage until the motor armature current is 3.4A. This is the **rated load point** for the motor. Record in table 3 the motor terminal voltage (90V), motor armature current, torque, and speed.

Table 3: Rated Load Point Shunt Motor circuit in (**figure 13).**

Vt (Varm)	Iarm	Torque	RPM
90Vdc			

Part 1d: You are now going to record a few points for the speed vs. torque curve. Place all the dynamometer load switches in the **up** position. The motor terminal voltage must be adjusted so it remains constant during this test. Set the **Rated Load Point** of the motor from **part 1c.** Then adjust the dynamometer until the motor is 20% overloaded; 4.0 amperes armature current. Record in **table 4** the torque and speed. Now, check a few points below and above the rated load. (Ranging from 4.0 to 2.5 in 0.3 A increments).

Table 4: **Speed vs. torque** shunt configuration of (**Figure 13**).

Vt const	Iarm	Torque	RPM
90Vdc	3.4A		
90Vdc	4.0A		
90Vdc	3.7A		
90Vdc	3.4A		
90Vdc	3.1A		
90Vdc	2.8A		
90Vdc	2.5A		

Part 2a: Connect the **separately-excited configuration** shown in **Figure 15**. Keeping the previously used Metering instruments in the software LVDAC-EMS, change the current range for I2 to 40A on the right-hand menu, and set up 2 additional displays to measure E2 and I2. Change the operating modes for the voltage meter E2 and the current meter I2 accordingly.

Adjust the motor **field** supply (#3) to 90 volts and record in **table 5** the field voltage and field current. These two values are needed to determine the **shunt field resistance** seen in the equivalent circuit of the shunt DC configuration. **Vt = 0V**
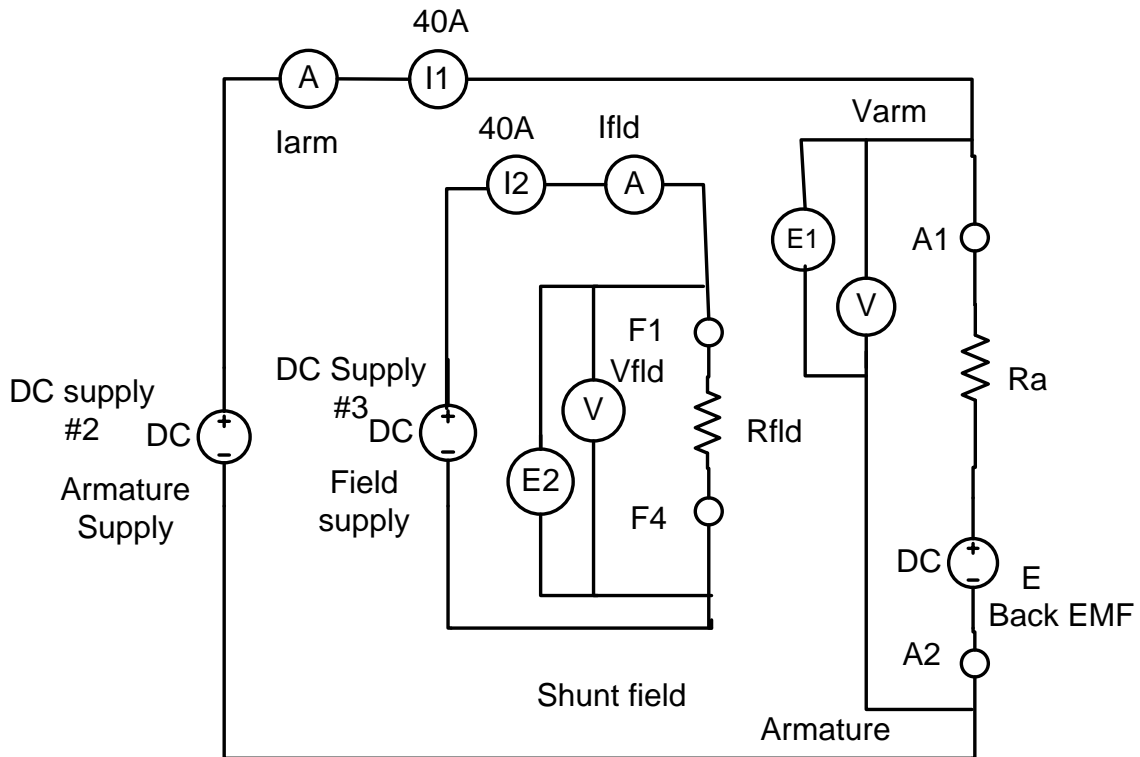

Figure 15 Separately excited Motor configuration

Table 5: Shunt Field Resistance circuit of figure 15.

Vt or Varm	Vfld	Ifld	RPM Dyno
0V	90V		0 RPM

Rshunt = Vfld/Ifld = _____

Part 2b: In the circuit of **figure 15**, adjust the **motor field** supply (#3) until the field current is **0.3 amperes**. Make sure that the torque meter is set to 0 Newton-meters before energizing the DC motor and that it only reads positive torques as the motor starts running. Adjust the motor terminal voltage (DC supply #2) to obtain rated speed (2000RPM) Investigate the effect of the motor field current with a constant motor **armature voltage (Vt)** on the motor performance at no load by filling-up the **table 6** below. Note: torque will be small.

Table 6: Constant (Vt) VS Varying Field Current

No Load, Separately excited Circuit of **(figure 15).**

Vt ≈ 90Vdc

	Vt	Ifld	Torque	RPM Dyno	Iarm
Const Vt Var Ifld		0.30A		2000 rpm	
		0.275A			
		0.25A			

Part 2c.   **Lock** the dynamometer and investigate the effect of the motor field current with a constant motor armature voltage on the starting torque. Recalibrate the torque meter to 0 Newton-meters if need be. The motor armature voltage will be small **less than 15Vdc**. Adjust the armature voltage (#2) to obtain an armature current of 3.4A. Maintain the armature voltage constant. Do not exceed **amperes armature current of 4.0A**. Fill-up the table 7 below.

Table 7: Field Current VS Starting Torque

Locked Rotor Circuit of (figure 15). Vt <15Vdc

	Vt	Ifld	Torque	Iarm
Const Vt Var Ifld		0.30A		3.4A
		0.25A		
		0.20A		

Part 2d. Make **sure power is turned off before removing the lock.**

Unlock the dynamometer. Recalibrate the torque meter to 0 Newton-meters if need be. In the circuit, adjust the motor field supply (#3) until the field current is **0.3 amperes.** Adjust the motor armature voltage **Vt** (#2) to **90Vdc.** Investigate the effect of the motor terminal voltage with a **constant** motor **field** current on the motor performance by filling-up the **table 8** below.

Table 8: Constant motor **field** current VS **Varying** the **terminal voltage**
No Load Circuit of (figure 15.)

	Vt	Ifld	Torque	RPM Dyno	Iarm
Const Ifld **Var Vt**	*90 V*	**0.30A**			
	80 V	**0.30A**			
	70 V	**0.30A**			

Part 2e: Lock the dynamometer and investigate the effect of the motor armature voltage with a constant motor field current on the starting torque. Recalibrate the torque meter to 0 Newton-meters if need be. Do not exceed 3.5 amperes armature current. Fill-up the table 9 below. Use Vt*0.67 for row 2, use Vt*0.33 for row 3.

Table 9: Armature Voltage VS Starting Torque

Locked Rotor circuit of (figure 15). Vt < 20Vdc

	Vt	Ifld	*Torque*	Iarm
Const Ifld **Var Vt**		**0.30A**		**3.4A**
		0.30A		
		0.30A		

 Part 3a. **Make sure power is turned off before removing the lock.**

Unlock the dynamometer and connect the **separately-excited generator configuration** shown in Figure 16. Set the dynamometer field rheostat to the mid-point and make sure that the torque meter is set to 0 Newton-meters before energizing the dynamometer and that it only reads positive torques as the motor starts running. Adjust the dynamometer supply so the dynamometer runs at 2000 RPM and maintain this speed. With no load on the generator, increase the generator field supply in 20-volt steps until it reaches 120 volts. Record the generator field current, the generator terminal voltage and the torque, also calculate K at each step in table 10. The terminal voltage and field current data points will yield the curve shown in **Figure 10** plot this table for your report.

Figure 16 circuit diagrams: Shunt field motor, Armature motor, Dynamometer wired as a motor
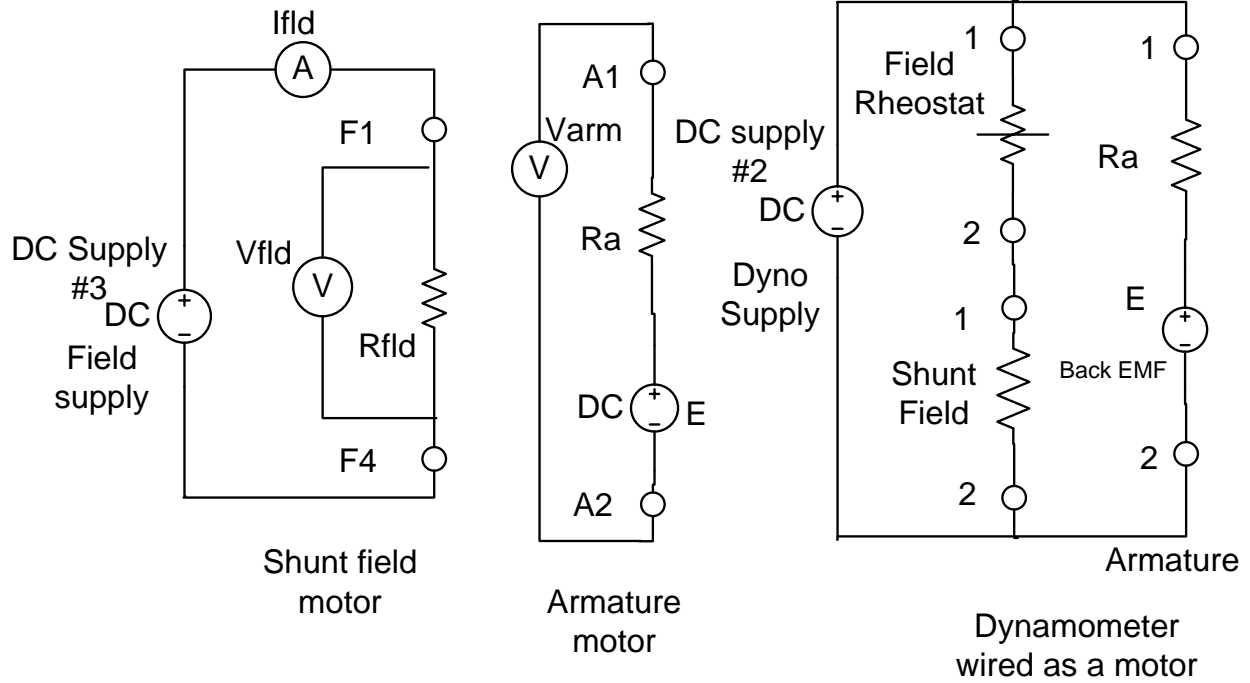
Figure 16 Separately excited generator configuration

Table 10: Field Current Vs Generated Voltage at rated speed

No Load Magnetization Curve circuit (figure16)

Vfld	Ifld	Vt	Torque	RPM	K
20				2000 rpm	
40				2000 rpm	
60				2000 rpm	
80				2000 rpm	
100				2000 rpm	
120				2000 rpm	

$$K = E/(\omega_m \text{ Ifld}) = \underline{\hspace{3cm}}$$

Part 3b: Adjust the dynamometer speed (DC supply #2) to 2000 RPM with no load on the generator. Set the generator field voltage to 90V (DC supply #3).

By adjusting the dynamometer voltage, investigate the effect of speed changes on the generator output voltage by recording data in **table 11** below. Plot this **table 11** for your review. After completing this section, reinstall the lock on the dynamometer and clean up the bench for the next lab class.

Table 11: Speed VS Generated Voltage

No Load circuit (figure 16)

Vfld	Ifld	Vt	RPM Dyno
90V			*2000*
90V			1800
90V			1600
90V			1400
90V			1200
90V			1000

Review **Things to keep in mind as you complete the experiment.**

1. Use the data from the locked-rotor tests in Parts 1a find the armature resistance of the machine. From the field test in Part 2a find the shunt field resistance. From the no-load test in Part 3a table 10 to find **average** value of k for the machine.

    Ra=_____ Rshunt=_____ k=_____

    Explain the procedure used to find the values in terms of the model of each machine setup.

2. Draw speed vs. torque curves for the shunt motor. Relate these performance curves to the general theory of multiply-excited rotating energy converters. Should magnetic saturation be considered for the performance and why?

3. Explain the generator performance observed in Part 3 in terms of general energy conversion theory. Is magnetic saturation a factor in the performance, how does it affect the performance? Plot table 5 and table 6 and explain the plots.