

DC MOTORS

EXPERIMENT 1 – SERIES MOTORS

The student will be able to measure motor resistances, to connect the series motor for either direction of rotation, and to determine the counterelectromotive force developed in the motor under varying load conditions.

EXPERIMENT 2 – SHUNT MOTORS

The student will be able to connect the motor as a shunt type, to determine how the armature and field currents control the operation, and to determine the CEMF developed under different operating conditions.

EXPERIMENT 3 – COMPOUND MOTORS

The student will be able to connect the motor as a compound type, to determine how changing the field and armature voltages affects the operation, and to determine the effects of loading the motor.

INTRODUCTION

One of the main needs of industry is mechanical rotation to operate rotating equipment. The rotation is supplied by the shaft of a *motor*, which changes electric energy to mechanical energy. So it is an energy converter. It can also be classed as an output transducer.

The shaft of a motor rotates because of the interaction of two magnetic *fields*. One field is stationary and can be caused by current flowing through a coil of wire or by a permanent magnet. The coil or permanent magnet is also referred to as the *field*. The other part of the motor rotates. It consists of many turns of wire wound around the shaft, and is called the *armature*. The shaft is mechanically supported on both ends so that the armature rotates within the stationary magnetic field.

MOTOR ACTION

To show motor action, consider a single piece of wire in a magnetic field, as shown in Figure 1. The parts labeled N and S represent the north and south pole pieces of a magnet, which produces a field around the wire. The field is indicated by the arrows from the north pole to the south pole. This figure, drawn in two dimensions, is shown in Figure 2.

If a battery is connected to the ends of the wire, current passes through it and produces a magnetic field around it. The field that exists due to this current flow is shown in Figure 3. This drawing shows the wire as a circle. The magnetic field around the wire is shown as larger circles with

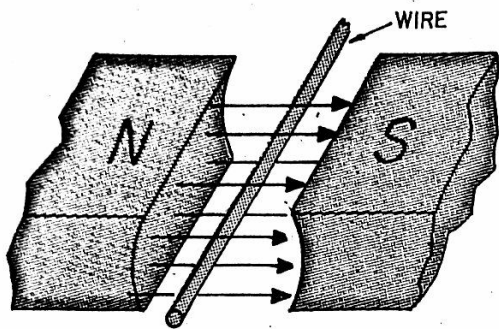


FIGURE 1, A Single Conductor in a Magnetic Field

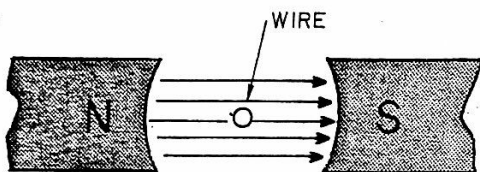


FIGURE 2, Two-Dimensional View of Conductor in a Magnetic Field

arrowheads above and below the wire. The direction of the field shown by the arrowheads is determined by the direction of current. Electron flow into the paper causes the magnetic field to be in the direction shown. If electron flow were out of the paper, the arrowheads would be reversed.

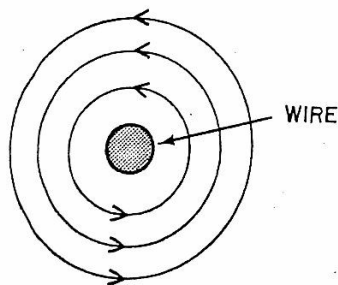


FIGURE 3, Magnetic Field Surrounding a Current-Carrying Wire

Figure 4 shows the result of placing a current-carrying wire in a magnetic field. The arrowheads show the direction of the field around the wire and between the pole pieces of the magnet. Notice that the arrowheads for both fields are in the same direction below the wire. But they are in opposite directions above the wire. This causes a stronger

magnetic field below the wire than above it. The stronger field exerts a force that pushes up the wire. Electric energy causing current in the wire has been changed to mechanical energy of motion, pushing the wire upward.

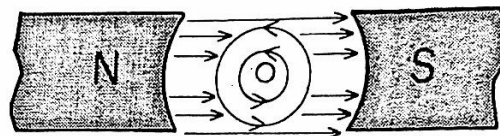


FIGURE 4, A Current-Carrying Conductor in a Magnetic Field

A loop of wire on a shaft placed in a magnetic field is shown in Figure 5. The connection to the battery is made through a split ring connected to the loop of wire. The ring moves with the loop. In contact with the ring, and connected to the battery, are the brushes. The ring slides against the brushes as the loop of wire rotates. As pictured, there is an electric circuit from the negative terminal of the battery to the right-hand brush and then to half of the split ring. From this ring, current travels in the direction indicated along the A part of the loop. It then travels back along the B part of the loop to the other half of the split ring. From here current goes to the left-hand brush and then to the positive terminal of the battery.

In two dimensions, the A and B parts of the loop appear as in Figure 6. The electron flow is into the paper for the A part of the loop. Its magnetic field is the same as that in Figure 4. The current is in the opposite direction, or out of the paper, in the B part of the loop. Its magnetic field is in the opposite direction. Within the magnetic field of the pole pieces, the A part of the loop feels an upward force. Just the reverse is true for the B part of the wire. The force acting on it is downward. The result is a twisting force, or *torque*, on the loop of wire and on the shaft to which it is connected. Electric energy in the battery has been converted to the mechanical energy of the rotating shaft.

After the loop has rotated a half-turn, the A and B parts are opposite from their positions shown in Figure 5. Loop A is then connected to the left brush and loop B to the right brush. The result is that the direction of current flow in the loop has been reversed. However, loop B is pushed upward by the torque, maintaining the same direction of rotation.

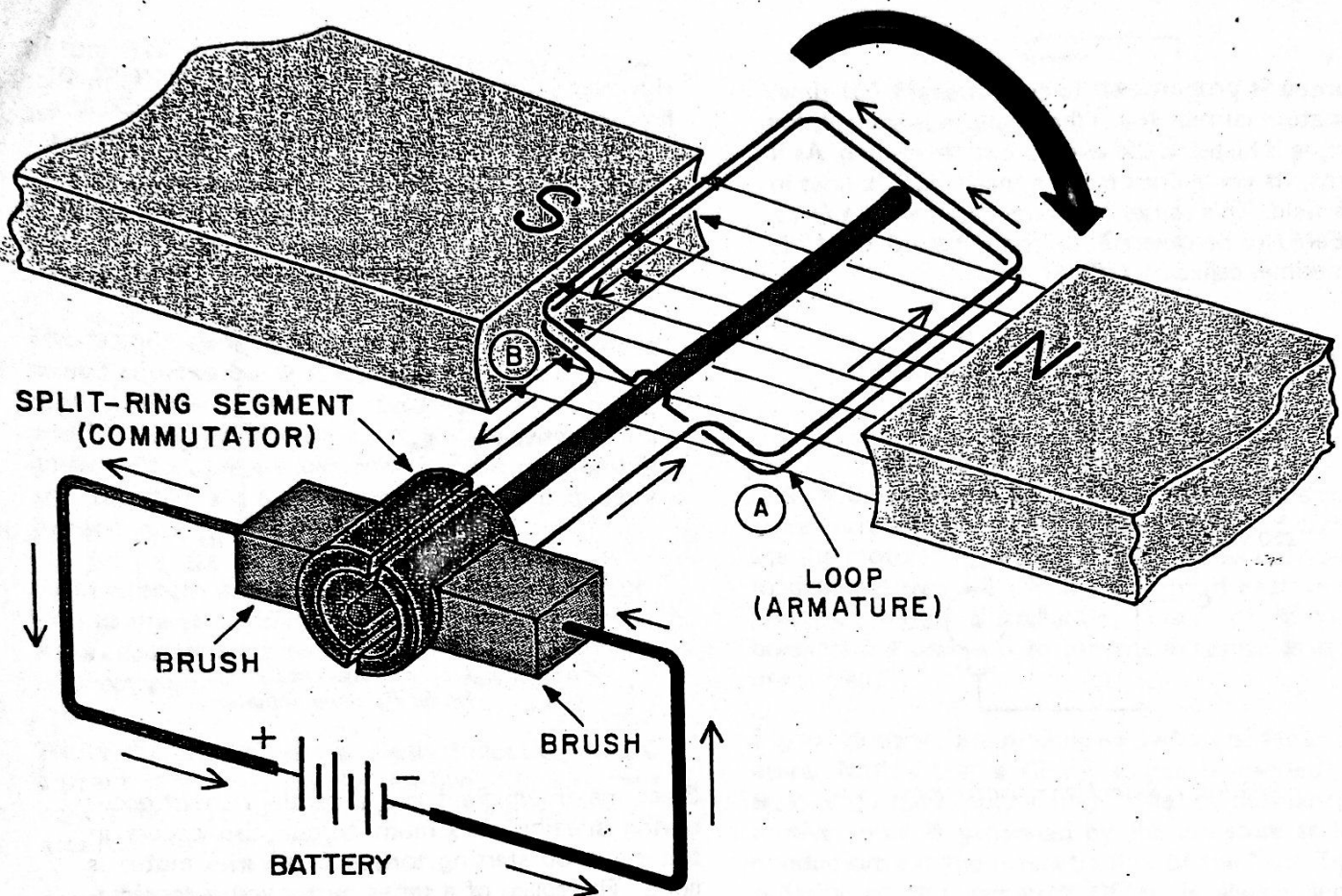


FIGURE 5, A Simple Motor Arrangement

The split-ring is called a *commutator*. Its purpose is to switch the current direction through the armature coil to make sure it keeps rotating in the same direction. In actual practice, many loops of wire are connected to a larger number of commutator segments. This provides greater torque and smoother operation. The many loops of wire wound on top of one another, the motor shaft, and the commutator make up the armature. So the two main parts of a motor are the armature and the field.

DC motors may be connected in either of two basic arrangements, either series or shunt. In a *series motor*, the armature and field are connected in series with each other. In a *shunt motor*, the armature and field are connected in shunt (parallel) with each other. A third arrangement for specially constructed DC motors is sometimes used. These are *compound motors*; they are discussed later.

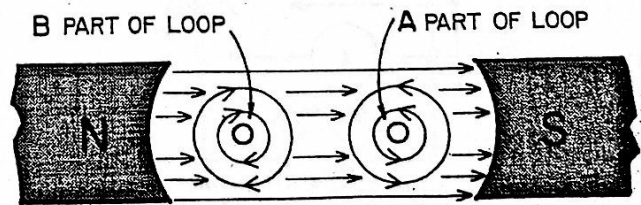


FIGURE 6, The Interaction of Magnetic Fields

SERIES MOTORS

Consider the series motor of Figure 7. Field resistance is 22 ohms and armature resistance is 0.5 ohm. Since these are in series, the total opposition to current flow is 22.5 ohms. The equivalent circuit, with the motor stalled, is shown in Figure 8. About 9.8 amperes flow through the field and armature. This is the *stall current*, the amount that flows when rated voltage is applied, but the armature is not turning. The current drawn by the motor when it is running is called *running current*.

Torque is proportional to *field strength* (Φ) times armature current (I_A). When voltage is applied, the torque is high and the armature starts turning. As it turns, its conductors cut the magnetic flux lines in the field. This causes a *counterelectromotive force (CEMF)* to be generated in the armature. CEMF is sometimes called *back EMF*.

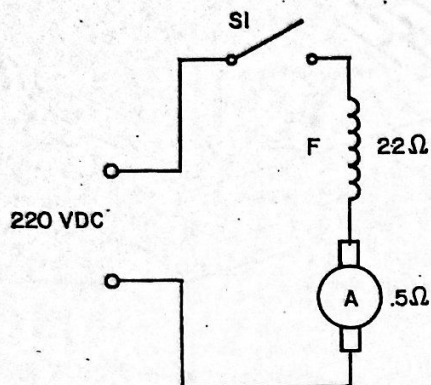


FIGURE 7, Series Motor Connections

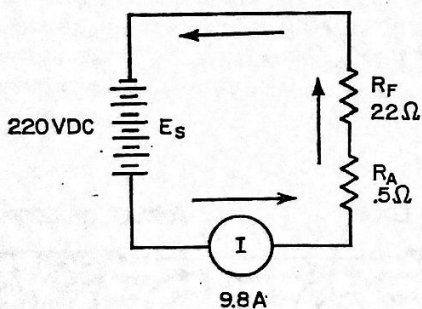


FIGURE 8, Motor Equivalent Circuit Under Stalled Conditions

Figure 9 shows the motor equivalent when the armature is turning. Notice that the armature CEMF polarity opposes current flow. As the armature speed increases, both field and armature current decrease due to the increase in CEMF. Armature speed and motor current then level off to constant values. No further change occurs unless some electrical or mechanical change is made. If a load is applied to the motor armature, speed decreases. This decrease in speed should cause CEMF to decrease, increasing motor current, and increasing torque.

However, this does not happen. An increase of field current causes an increase of CEMF. So the armature speed must be reduced in order to develop more torque to turn the load.

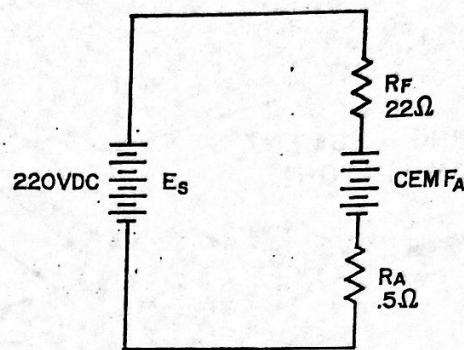


FIGURE 9, Motor Equivalent Circuit Under Running Conditions

Since maximum field and armature current occur during starting, maximum torque also occurs at this time. So starting torque of a series motor is good. The speed of a series motor varies considerably with load. So *speed regulation* is poor.

In an electric motor, electric energy is converted to mechanical energy, or torque. The unit of torque is the *pound-foot*, abbreviated lb-ft. Figure 10 illustrates the standard unit. A pulley with a radius of 1 foot has a 1 pound weight on a rope, and the rope is wrapped around the pulley. The rotating force developed is 1 lb-ft. If the radius of the pulley is increased to 2 ft, a 1 lb weight develops 2 lb-ft of torque. If the radius of the pulley remains at 1 ft and the weight is increased to 2 lbs, the torque developed would also be 2 lb-ft.

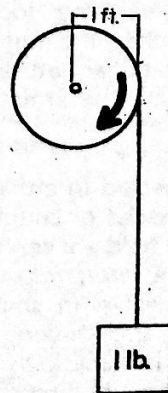


FIGURE 10, Equivalent of a Pound-Foot of Torque

Motors are usually rated in *horsepower*. One horsepower is the equivalent of 550 foot-pounds per second of power. The electrical equivalent is 746 watts. Small motors are rated in terms of fractions of a horsepower. Large motors may be rated in hundreds or thousands of horsepower. Motor speed is usually expressed in *revolutions per minute (RPM)*.

The torque developed at the shaft of an electric motor equals $I_A \times \Phi \times K_T$. I_A is the armature current in amperes, Φ is the field strength in gauss, and K_T is the torque constant. K_T is constant for a given motor. So we can simplify this relationship and say that, for a given motor, torque is directly proportional to $I_A \times \Phi$.

Field strength is equal to $I_F \times K_F$. I_F is the field current in amperes and K_F is the field constant. Since K_F is constant for a given motor, field strength (Φ) is directly proportional to field current (I_F).

While the motor field is highly inductive, to DC current it appears purely resistive. Field current equals field voltage divided by field resistance, according to Ohm's Law.

SHUNT MOTORS

In applications where speed regulation is a prime factor, and starting torque is not too important, a shunt motor is generally used. Figure 11 is an example; the armature and field are in parallel. The purposes of R_1 and R_2 are explained later.

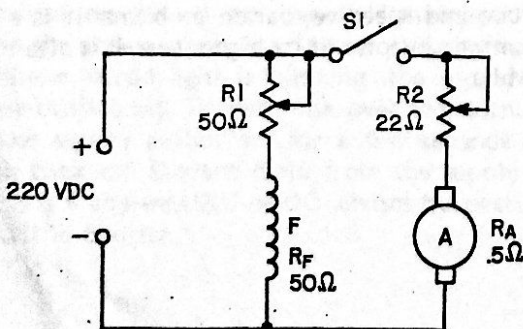


FIGURE 11, Shunt Motor Connections

The armature resistance of a shunt DC motor is generally very low compared to field resistance. For example, the armature resistance of a 220 V shunt DC motor is less than one ohm. Figure 12 shows the stalled equivalent of the armature.

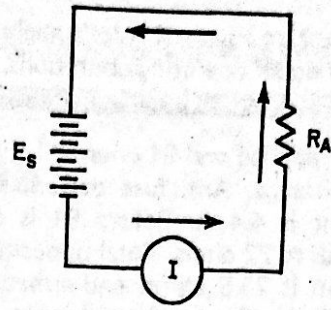


FIGURE 12, Equivalent Armature Circuit Under Stalled Conditions

If $R_A = 0.5$ ohm and $E_s = 220$ V, the stalled armature current = 440 A. This, of course, would damage the motor. The armature windings would have to dissipate over 96 kW in the form of heat. In a practical motor installation, fuses or circuit breakers are provided to prevent excessive armature current.

Figure 13 shows the running equivalent of the armature. Notice that a CEMF source is inserted in series with the supply voltage. This counterelectromotive force is generated by the armature as its conductors cut the magnetic flux of the field. The polarity of this armature CEMF is always such that it opposes armature current flow.

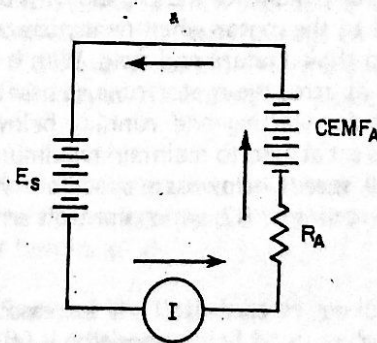


FIGURE 13, Equivalent Armature Circuit Under Running Conditions

Let us assume that in Figure 13 the armature current, I_A , is 10 A. Ohm's Law tells us that the voltage drop across the armature resistance is 0.5 ohm \times 10 A = 5 V. Kirchhoff's Law tells us that if $E_s = 220$ V, the armature CEMF = $220 - 5 = 215$ V. It is quite evident that armature current is controlled primarily by armature CEMF. Armature CEMF = $E_s - (I_A \times R_A)$. It is an induced voltage. So it is proportional to the rate of cutting of the field flux by the armature conductors. So it is proportional to the armature RPM and the field strength (Φ).

Referring back to Figure 11, let's analyze the motor behavior under operating conditions.

With 220 V applied and S1 open, R1 should be set to zero resistance. Armature current is zero and field current is 4.4 A. Before S1 is closed, R2 should be set to 22 ohms. Total opposition to armature current is 22.5 ohms, and armature current is about 9.8 A. The resulting torque causes the armature to start turning. As the armature RPM increases, armature CEMF increases, causing armature current to decrease. The armature speed levels off and armature current levels off. Its value is quite a bit less than the starting current of 9.8 A.

If R2 is reduced to 11 ohms, armature current, torque, and armature speed all increase. This increase in armature speed causes armature CEMF to increase. Again the armature current and RPM level off to steady values. If R2 is reduced to zero, a momentary increase in armature current, and a resulting increase of RPM, again cause CEMF to increase. This increase in CEMF causes armature current to decrease and level off at a steady value. Speed is now stabilized. The motor should run at a constant speed until some other change is made.

Base speed for a shunt-wound DC motor is defined as the RPM of the motor when nameplate voltage is applied to the armature and field. With both R1 and R2 set at zero, the motor runs at base speed. Notice that for starting and running below base speed, R1 is set at zero to maintain maximum field strength. All speeds below base speed are determined by the setting of R2, which controls armature current.

With R2 still set at zero, if R1 is increased from zero to 10 ohms, total field opposition is 60 ohms. Field current decreases from 4.4 A to 3.6 A. The resulting decrease in field strength causes armature CEMF to decrease and armature current to increase. This increase in armature current causes the RPM to increase above base speed. A further increase in the resistance of R1 causes a further decrease in field strength. This causes a further decrease in CEMF, and a further increase in RPM. Notice that to operate the shunt-wound motor above base speed, R2 was held at zero. This kept nameplate voltage on the armature, and R1 was varied to adjust the RPM above base speed. If the resistance of R1 is again reduced to zero, the armature RPM decreases and returns to base speed.

With the motor running at base speed, if a load is applied to the motor shaft, the RPM tends to decrease. This decrease in RPM causes a decrease in armature CEMF. A resulting increase in armature current automatically increases torque to turn the load. Due to this effect, the shunt motor compensates for changes in load, and maintains relatively constant RPM. So its speed regulation is good. The shunt motor must be started under reduced armature voltage conditions. So starting torque is poor.

COMPOUND MOTORS

Combining the high starting torque of series motors with the good speed regulation of shunt motors results in a good general purpose motor. The compound motor of Figure 14 is such a device. It is designed for uses requiring relatively high starting torque and relatively good speed regulation. Notice that it employs both a series and a shunt field.

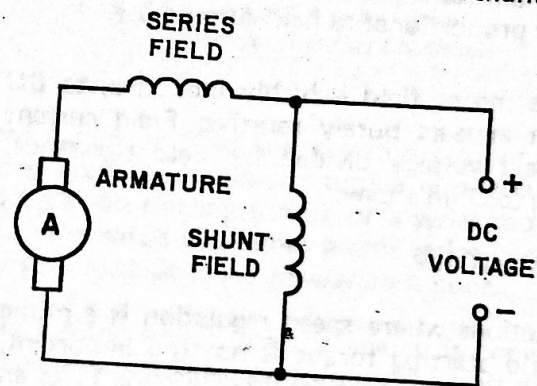


FIGURE 14, Compound Motor Connections

This is by no means a perfect solution to the starting torque and speed regulation problems. It is a compromise. In spite of its higher cost, it is often worthwhile.

EXPERIMENT 1 SERIES MOTORS

EXPERIMENT OBJECTIVES

- A. To measure the resistances of the two field coils, also the armature resistance.
- B. To connect the motor as a series type and determine what is necessary to reverse its direction of rotation.
- C. To measure the current drawn by the motor and calculate the CEMF generated in the motor for unloaded and loaded conditions.

MATERIAL REQUIRED

- Motor-Generator Assembly
- Variable DC Power Supply (0-25 V)
- FET Multimeter
- Resistor Module

DISCUSSION

The Motor-Generator Assembly consists of a metal base with a built-in power supply. A DC motor and a DC generator are quick-mounted on top.

The built-in power supply delivers 24 volts AC or about 34 volts DC, with no load, selectable with the AC/DC switch. The On-Off switch is also a circuit breaker. A pilot light and overload light are provided on the control panel. If the pilot light is lit, the power supply is on and working normally. If the overload light is blinking, the supply has been overloaded. To reset the overload, turn the power supply switch off for a few seconds and then back on. Current drain from the supply exceeding 4 amperes, AC or DC, causes the overload circuit to operate.

Provisions are made for measuring current from the power supply. Use a high-impedance voltmeter connected between the current jacks on the front panel of the Motor-Generator Assembly. Each volt measured indicates 1 ampere of power supply current.

Twelve terminal jacks are provided to make connections to the various parts of the DC motor and generator terminals.

Figure 15 shows the Motor-Generator Assembly control panel. The power supply controls and the motor and generator terminals are clearly identified.

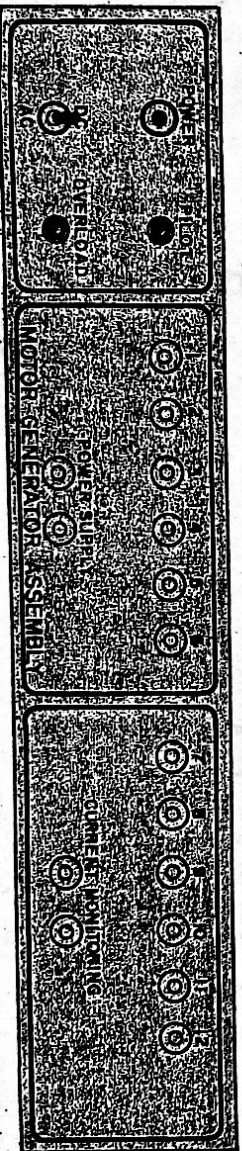
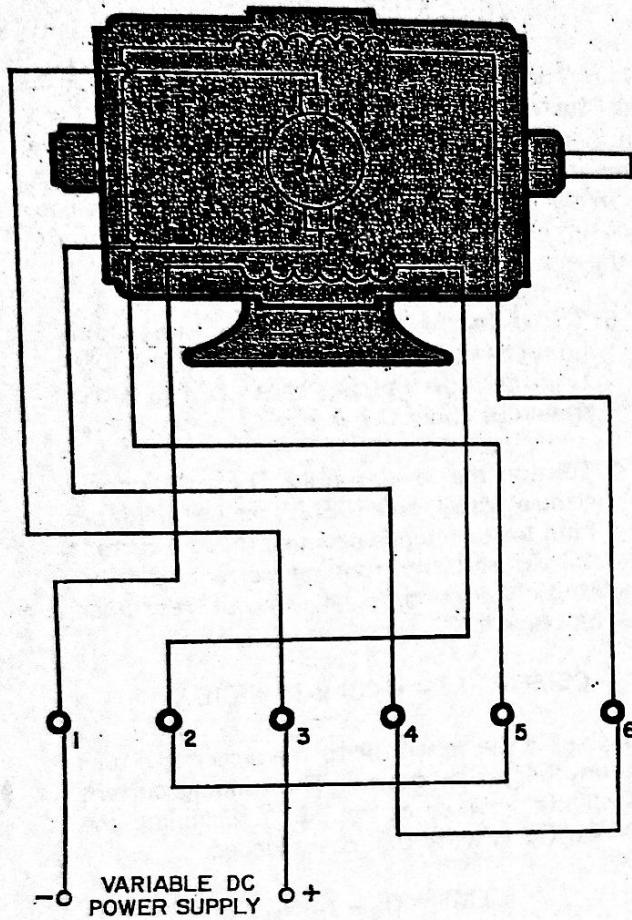
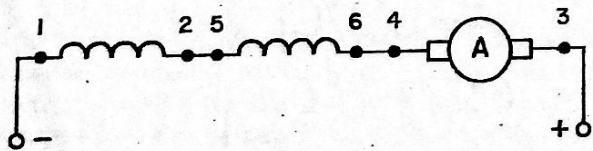


FIGURE 15. Motor-Generator Assembly Control Panel

MOTOR



A



B

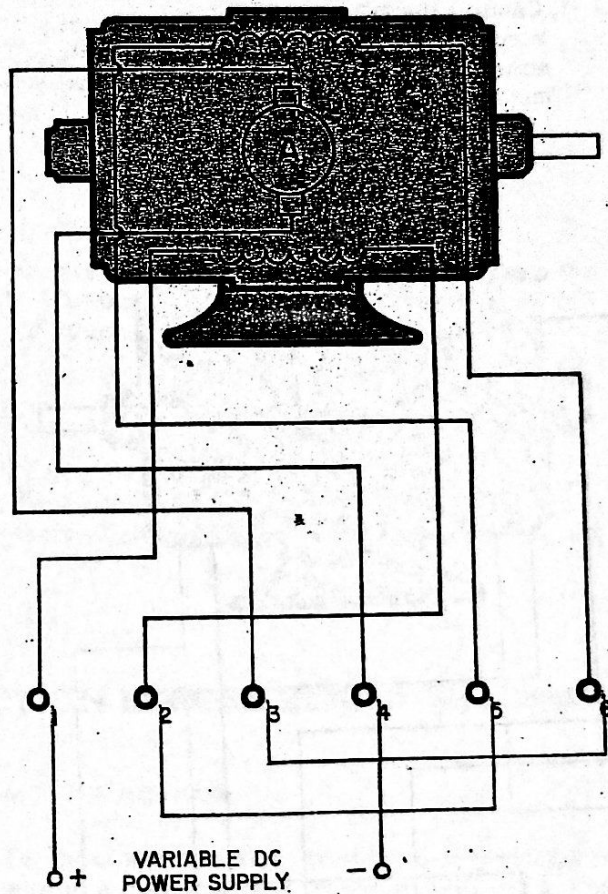
FIGURE 18, Series Motor Connections with Reversed Polarity

- 4. Turn on the power supply. Make sure that the voltage control is turned up enough, so the motor turns. We have reversed the current through both the field and armature. Has the direction of rotation of the motor shaft reversed? _____. It should still

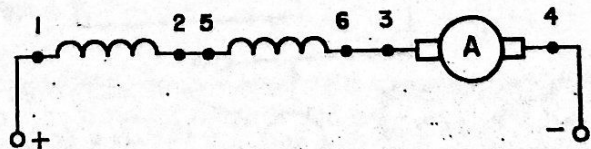
be turning clockwise. Turn off the power supply.

- 5. Return the power supply polarity to that of Figure 17A. Reverse the connections at Jacks 3 and 4 as shown in Figure 19A. The schematic is shown in Figure 19B. In this change we have reversed the current through only the armature.

MOTOR



A



B

FIGURE 19, Series Motor Connections with Armature Reversed

PROCEDURE

Before we attempt to run the motor, we should determine some of the electrical characteristics of the motor. See that the generator is uncoupled from the motor.

A.

- 1. Use an ohmmeter to measure the resistance between the motor terminals indicated in the chart of Figure 16. Enter the resistance readings in the chart.

	FIELD 1-2	ARMATURE 3-4	FIELD 5-6
R =	13.0A	66.7A	13.7A

13.0A 66.7A 13.7A

The left and right field coils should be identical. So the resistance between Jacks 1 and 2 should be about the same as that between Jacks 5 and 6. This should be about 15 ohms.

- 2. The armature resistance measured between Jacks 3 and 4 varies somewhat with shaft rotation. Rotate the shaft manually to observe this effect. Enter the lowest reading in the chart. This should be about 4 ohms.

B.

11.5A

- 1. Connect the motor as shown in Figure 17A. For this experiment, we will use one of the variable DC supplies located in the Industrial Console. The power supply should be turned off and the output voltage control set at minimum. The schematic of this motor circuit is shown in Figure 17B.
- 2. When the patch cords are all in place, turn on the power supply. Gradually turn the output voltage control clockwise until the motor begins to turn. Is the direction of rotation clockwise or counterclockwise?
_____ . Direction is determined by looking at the shaft end of the motor.

MOTOR

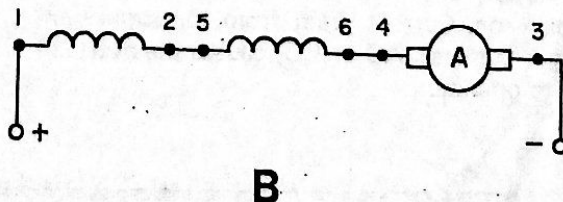
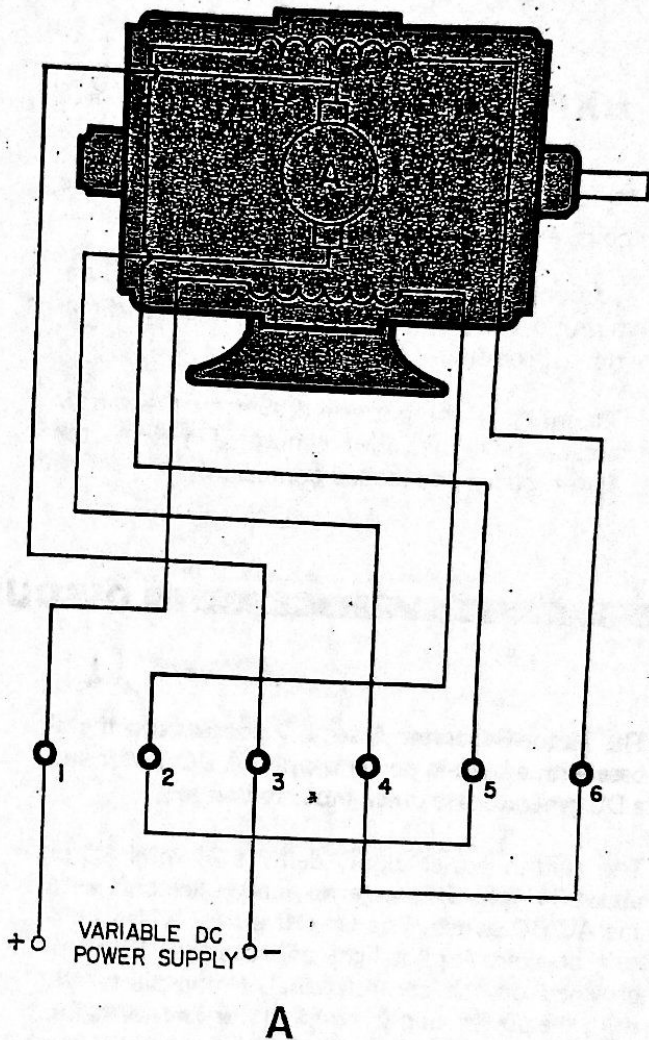


FIGURE 17, Series Motor Connections

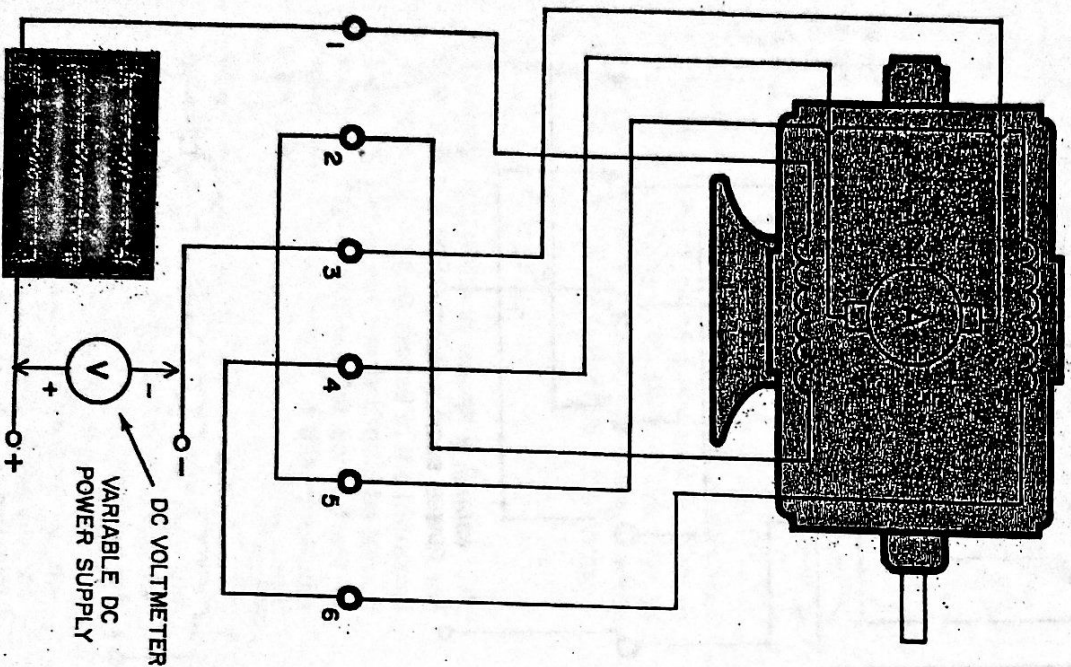
- 3. Turn off the power supply and reverse the polarity at Jacks 1 and 3, as shown in Figure 18A. The schematic is shown in Figure 18B.

- 6. Turn on the power supply. Does the motor shaft rotate clockwise or counterclockwise?
Yes - counterclockwise.
- 7. Turn off the power supply.

It is evident that reversing the current through the series motor does not reverse the direction of rotation. Reversing the current through the armature with respect to the field does change the direction.

- 1. Connect the DC voltmeter across the power supply as shown in Figure 20. Turn up the power supply voltage control until the voltmeter indicates 24 VDC.

MOTOR



- 2. Connect the FET Multimeter across the 1 ohm current measuring resistor. The current is 0.50 A. This should be about 0.46 A.

Refer back to Part A of this experiment. The resistance chart of Figure 16 shows that each field coil has a resistance of 15 ohms. The armature has a resistance of 4 ohms. Since these resistances are all in series, as in Figure 19B, the total resistance is 34 ohms. With 24 VDC applied, the stall current of the motor is 0.7 A.

- 3. To verify this, turn off the power supply, hold the motor shaft so it cannot turn, and turn the power supply back on. The current should be about 0.7 A.

- 4. Turn off the power supply. The total counter-electromotive force (CEMF) can be calculated. Find the difference between the stall current, 0.7 A, and the running current, 0.46 A. Multiply this times the motor resistance, 34 ohms.

$$\text{CEMF} = (0.7 - 0.46) \times 34 = 8.16 \text{ V}$$

- 5. Couple the generator to the motor and turn on the power supply. The running current should now be about 0.6 A. Calculate the new CEMF with the motor loaded.

$$\text{CEMF} = (I_s - I_r)R_m$$

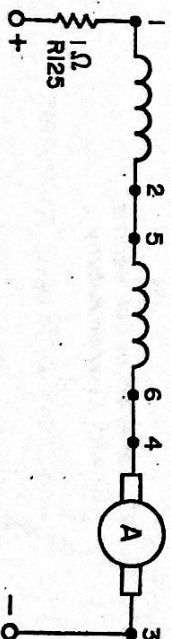
Where I_s is the stall current

I_r is the running current

R_m is the motor resistance

$$\text{CEMF} = 6.74 \text{ V}$$

$$(0.72 - 0.52 \text{ A}) 33.4$$



1 Ω
R125

FIGURE 20, Voltmeter Connections to Motor Terminals