5.DC Machines

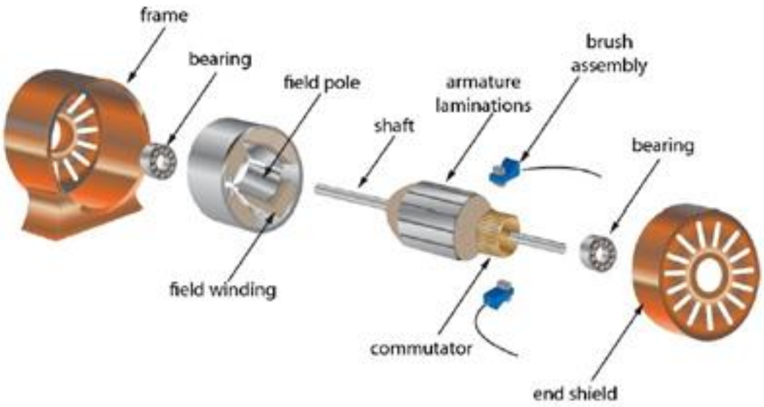
Introduction

The operating principles of d.c. motors and d.c. generators are similar. The difference lies in the flow of energy in the machine. Motors convert electrical energy into mechanical energy, whilst generators convert mechanical energy into electrical energy. Both d.c. motors and d.c. generators have field poles to create the main magnetic field, and a rotating armature. Conductors on the armature carry current to generate an e.m.f. in a generator, or develop torque in a motor.

This topic will help you develop your understanding of d.c. machine construction, testing, care and maintenance.

Components of a d.c. Machine

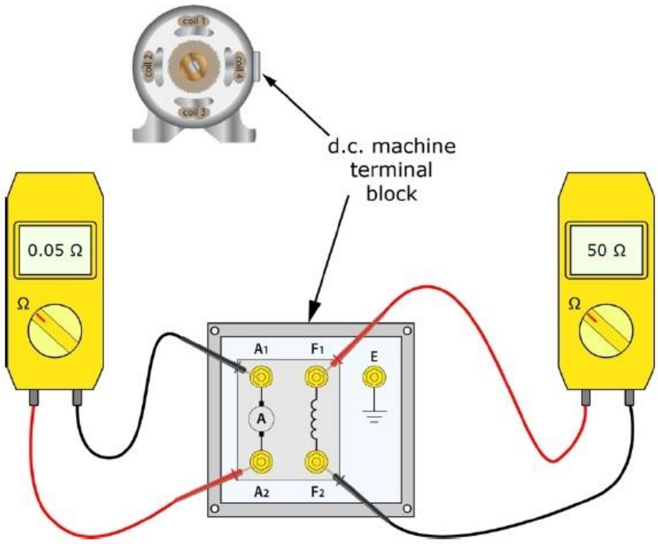
The components of d.c. machines are common to both d.c. motors and d.c. generators. These components enable the machine to convert energy from one form to another form.



The functions of d.c. machine components are listed in the following table.

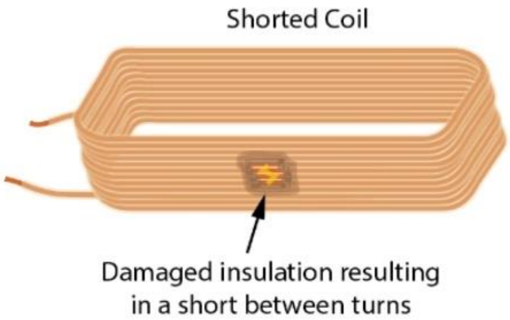
Functions of a d.c. Machine Components	
Frame	• Supports all components of the d.c. machine • Made from ferromagnetic material which provides the magnetic circuit for the main magnetic field created by the field poles
Bearing	• Supports the armature shaft • Provides a low friction bearing surface for the armature to rotate
Field pole	• Provides the main magnetic field for the machine
Field winding	• Creates the magnetomotive force for the magnetic flux in the field poles
Armature	• Provides support for the armature conductors/windings • Armature rotates within the magnetic field • Laminated to reduce eddy current losses

The armature resistance is a very low value of 0.05 Ω.



Voltage Drop Test – Shorted Coil

A voltage drop test is used to check for short circuited coils in the field windings. A 'shorted coil' occurs when the insulation fails at a particular point causing a short between several turns. This can be the result of thermal stress/hot spots, mechanical damage, or ingress of a contaminant such as dust, dirt or moisture.



When operating correctly, each coil should have the same resistance and same voltage drop when energised. A short circuit in one coil will reduce both its resistance and inductance, thereby allowing more current to flow, and changing the voltage drops across each coil.

This diagram shows a voltage drop test being carried out on the four coils of a d.c. machine with no faults. The field supply voltage is 200 V d.c. and the voltage drop across each individual coil is 50 V d.c.

Introduction

Direct current generators play an important role in many industries that require d.c. for their operating processes. Driven by a prime mover, the operating characteristics of d.c. generators are dependent on the field excitation methods used.

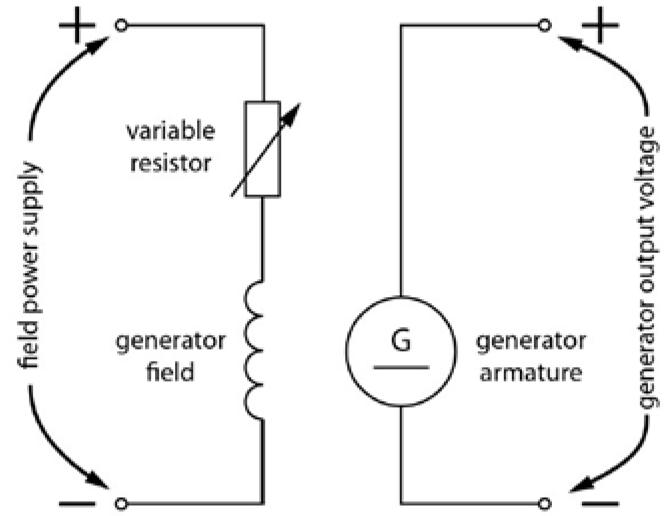
This topic will help you develop your understanding of the different types of d.c. generators, the methods of field excitation, and basic operating principles of generators, open circuit and load characteristics, and the importance of residual magnetism in some types of generators.

Types of d.c. Generators

Direct current generators are classified according to the method of 'field excitation'. Field excitation refers to the method of creating the main magnetic field in the generator.

d.c. Generator Circuit Diagram

Australian Standard symbols are used when drawing a d.c. generator circuit diagram. This diagram represents a typical circuit diagram of a d.c. generator. The generator is 'separately excited' because an external d.c. power supply is connected to the generator field. The variable resistor enables the generator output voltage to be adjustable. The output voltage is generated in the armature windings and available at the terminals.

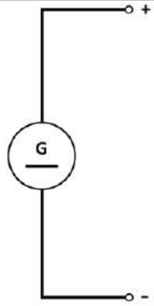
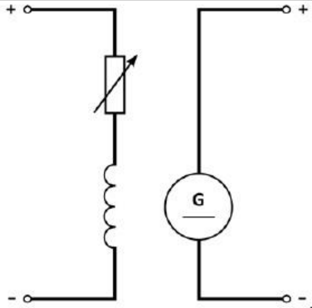


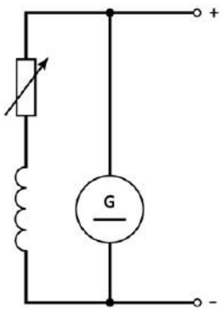
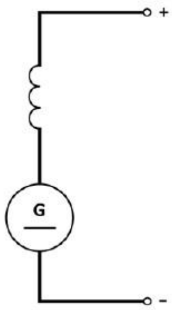
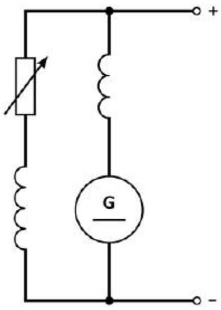
Method of Field Excitation

There are three methods of field excitation for d.c. generators, they are:

- Permanent magnet – no field current
- Separately excited – field current provided by external d.c. power source
- Self-excited – field current provided by voltage generated in the armature

Types of d.c. Generators		
Generator Type	**Circuit Diagram**	**Excitation Method**

<table>
<tr><td>Permanent Magnet</td><td>
</td><td>Excitation provided by permanent magnet field poles, instead of using field coils
No field current required</td></tr>
<tr><td>Separately Excited</td><td>
</td><td>Field coils connected to a separate d.c. supply, such as
A battery
Rectified a.c. power supply</td></tr>
</table>

Self-Excited	 Shunt connected	• Field current provided by the armature • Field coils connected in parallel with the armature
	 Series connected	• Field current provided by the armature • Field coils connected in series with the armature
	 Compound connected	• Field current provided by the armature • Contains two separate field windings wound on each pole piece • Shunt coils connected in parallel with the armature • Series coils connected in series with the armature

Compound Connected Generators

A compound generator has both a series field winding and a shunt field winding on each pole piece. The magnetic fields of the shunt and series fields can be oriented in the same direction to increase the total magnetic field strength. Alternatively their magnetic fields can oppose each other.

Compound generators are divided into 'cumulatively compounded' and 'differentially compounded' generator types. These labels refer to the relative direction of current through the shunt and the series fields, which affects the combined strength of the magnetic field.

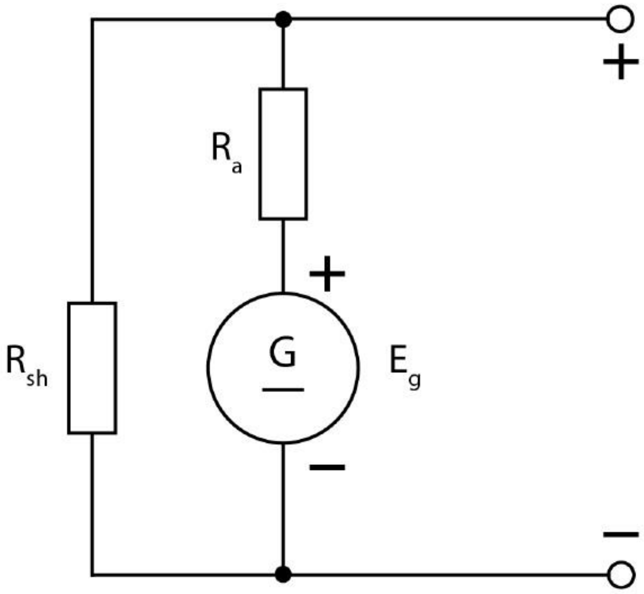
Compound Generators	
Cumulatively compounded	• Currents through the shunt field and series field are in the same direction • Shunt field flux and series field flux have the same polarity • Both fluxes combine to increase the strength of the total field flux

When a generator is connected to a load, current flow into the load produces an internal voltage drop across the armature winding resistance. This reduces the voltage available at the generator terminals. The higher the load current, the higher the internal voltage drop and the lower the voltage available at the generator terminals.

The generator equivalent circuit provides a way to analyse the operation of the generator when it is connected to a load.

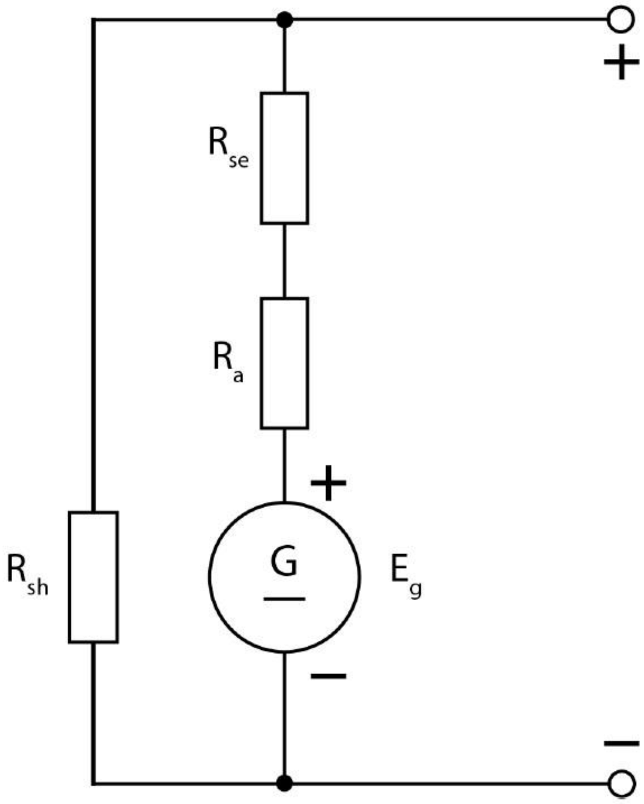
Shunt Generator Equivalent Circuit

This diagram shows the equivalent circuit for a shunt connected generator. The shunt field winding is replaced with its equivalent resistance value, R_{sh}. The armature circuit shows the open circuit generated voltage, Eg, connected in series with a resistor, labeled R_a, which represents the armature winding resistance.



Compound Generator Equivalent Circuit

This diagram shows the equivalent circuit for a compound connected generator. The shunt field winding resistance, R_{sh}, is connected in parallel with the armature circuit. The armature circuit consists of the generated voltage, Eg, in series with the series field resistance, R_{se} and the armature circuit resistance, R_a.



Calculating Generator Terminal Voltage

The equivalent circuit provides a way to calculate the generator operating parameters, such as the generated e.m.f. (E_g), the armature current (I_a) and field current (I_{sh}) when the generator is connected to a load.

This equation is used to calculate the generated e.m.f. when the generator is connected to a load.

$$E_g = V_t + I_a R_a$$

Where:

- E_g = generated e.m.f in volts (V)
- V_t = generator terminal voltage in volts (V)
- I_a = armature current in amperes (A)
- R_a = armature resistance in ohms (Ω)

Worked Example – calculating generator operating parameters

A shunt generator has an armature resistance of 0.05 Ω, and a shunt field resistance of 150 Ω. The generator is supplying a 10 kW load at 200 V d.c.

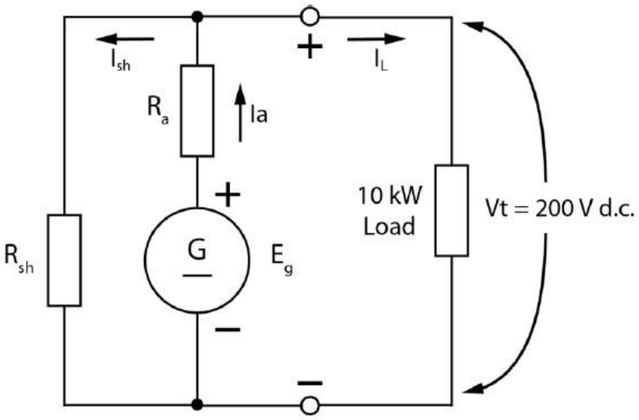
Calculate the following d.c. generator parameters:

(a) The line current

(b) The shunt field current

(c) The armature current

(d) The generated e.m.f.



(a) Line current

$$I_L = \frac{P_L}{Vt}$$

$$I_L = \frac{10{,}000}{200}$$

$$\underline{I_L = 50\ A}$$

-

(b) Shunt field current

$$I_{sh} = \frac{V_t}{R_{sh}}$$

$$I_{sh} = \frac{200}{150}$$

$$\underline{I_{sh} = 1.33\ A}$$

(c) Armature current

$$I_a = I_L + I_{sh}$$

$$I_a = 50 + 1.33$$

$$\underline{I_a = 51.33\ A}$$

(d) Generated e.m.f.

$$E_g = V_t + I_a R_a$$

$$E_g = 200 + (51.33 \text{ x } 0.05)$$

$$\underline{E_g = 202.57\ V}$$

Residual Magnetism

In every self-excited generator, some residual magnetism in the field poles is required for it to start to generate an e.m.f.

Self-excited generators, such as shunt generators and compound generators, derive their field current from the generated e.m.f. in the armature. Without residual magnetism in their field poles they are unable to generate an e.m.f.

When the armature of a self-excited generator starts to rotate, its armature conductors cut through the flux of the residual magnetism in the field poles. This generates a small e.m.f. in the armature causing current to flow through the field windings. This current increases the flux in the field poles, which subsequently increases the generated e.m.f. in the armature.

This process continues, as increased field current causes an increase in the field flux, which increases the generated voltage, and so on causing the generated voltage to build up to its maximum designed voltage. The process stops when the field poles saturate at maximum flux density and the maximum voltage is generated.

Flashing a Generator

If a generator loses its residual magnetism, it will produce very low or no output voltage. This problem can be fixed by 'flashing' the motor, which involves applying a momentary voltage across the field coils to re-magnetise the core.

Reverse Polarity

To reverse the polarity of the voltage at the generator terminal, the polarity of the generated e.m.f. in the armature must be reversed.

Reversed Polarity – Separately Excited Generator

The polarity of a separately excited generator can be reversed by either:

- Reversing the direction of rotation of the armature, or
- Reversing the direction of current through the separately excited field

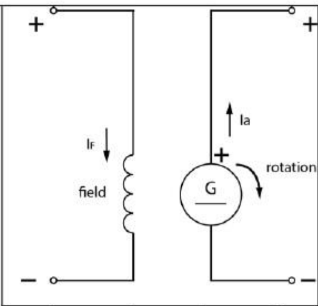
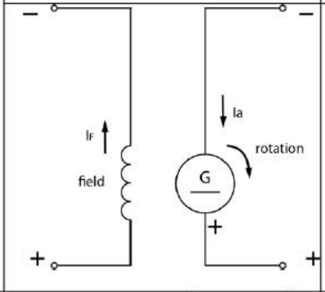
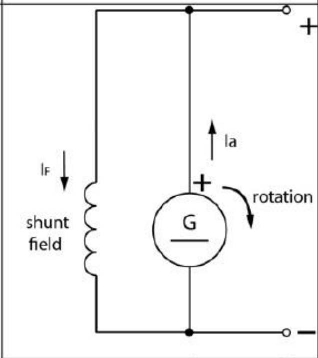
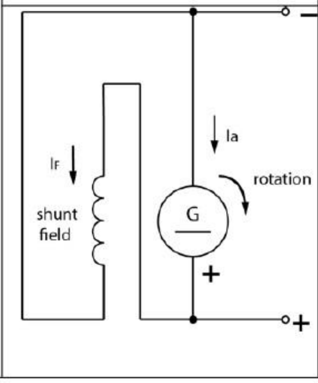
Note: to reverse the polarity you must do one or the other, but not both together!

Reversed Polarity – Self-excited Generator

If a self-excited generator is driven in the reverse direction it will fail to 'excite' as the residual field magnetism will be destroyed.

To reverse the direction of a self-excited generator the armature circuit connections must be swapped to reverse the terminal voltage polarity, but not the direction of current through the field windings.

This table show how to reverse the polarity of separately excited and self-excited generators. In each case the direction of rotation of the armature is not changed, only the direction of the generated e.m.f. of the armature.

Reversed Polarity – Separately Excited and Self Excited Generators		
Separately Excited		• Current through the field is top to bottom • Rotation clockwise • Vt positive is at the top
		• Current through field has reversed and now is bottom to top • Rotation remains clockwise • Vt positive is at the bottom • Generated voltage polarity has reversed
Self-excited		• Current through field is top to bottom which assists the residual magnetism • Rotation clockwise • Armature current is bottom to top • Vt positive is at the top
		• Current through field is maintained top to bottom (to assist residual magnetism • Rotation remains clockwise • Armature connections have been reversed • Armature current is now top to bottom (i.e. reversed) • Vt positive is now at the bottom • Generated voltage polarity has reversed

Introduction

Electric motors convert electrical energy into mechanical energy. The power applied at the input terminals of a d.c. motor creates a torque in the armature windings causing the shaft to rotate which is able to drive other machinery.

This topic will help you develop your understanding of the types of d.c. motors, their methods of field excitation, how torque is developed, the back e.m.f. of a motor, how to reverse a d.c. motor and their load characteristics

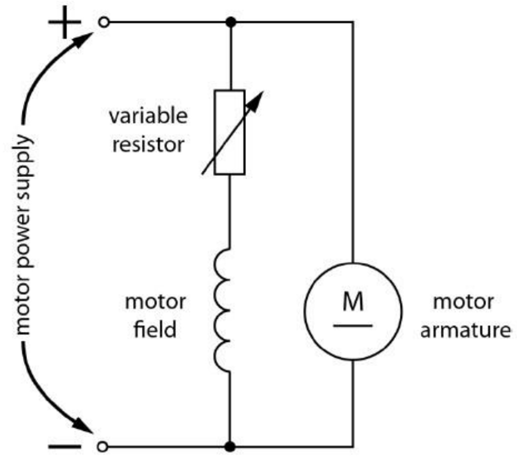
Types of d.c. Motors

When direct current is applied to the terminals of a d.c. motor a torque is developed in the armature windings due to the interaction between two magnetic fields; the motor field windings magnetic field and the armature windings magnetic field.

D.c. motors are classified according to how the motor field is connected in relation to the armature.

d.c. Motor Circuit Diagram

This diagram represents a typical circuit diagram for a shunt connected d.c. motor using Australian Standard symbols. The motor is a 'shunt' connected motor, because the motor field is connected in parallel with the motor armature. The variable resistor enables the field current to be adjusted, thereby controlling the motor speed.



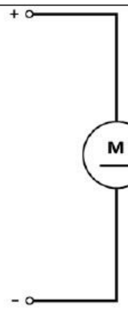
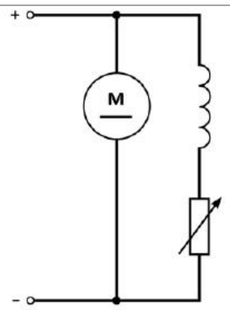
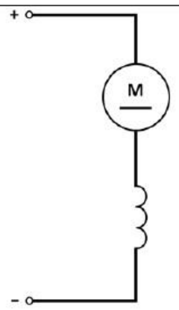
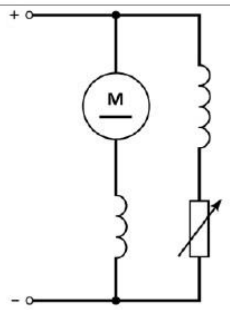
Motor Field Excitation

Common methods of motor field excitation for d.c. motors, include:

- Permanent magnet – no field current
- Shunt connected – motor field connected in parallel with the armature
- Series connected – motor field connected in series with the armature
- Cumulatively compound connected – motor field connected in series-parallel with the armature

Note: Differentially compound connected motors are not used, because they have no practice use.

Types of d.c. Motors

Motor Type	Circuit Diagram	Motor Field Connection
Permanent Magnet		• No field coils • Motor field excitation provided by permanent magnet field poles
Shunt connected		• Motor field connected in parallel with the armature • Variable resistor enables adjustment of motor field current
Series connected		• Motor field connected in series with the armature
Compound connected		• Motor field consists of two windings on each pole pieces • Shunt winding connected in parallel with armature circuit • Series winding connected in series with armature

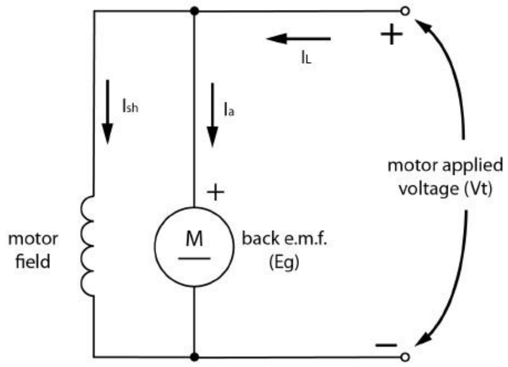
Applications for d.c. Motors

The range of applications for d.c. motors in modern industry is limited because of the wide spread use of a.c. induction motors. This table provides typical applications for d.c. motors.

Applications for d.c. Motors

This diagram of a shunt motor shows the motor line current I_L flowing into the motor. The line current divides into the armature current I_a and the shunt field current I_{sh}.

The polarity of the back e.m.f. opposes the applied voltage, Vt.



Effect of Back e.m.f. in a Motor

The effect of back e.m.f is to limit the armature current in the motor.

At standstill, the back e.m.f. is zero and the motor starting current can be very high due to the low armature resistance (approximately 0.05 Ω).

As the motor speed increases, the back e.m.f. starts to increase, which opposes the applied voltage and limits the armature current. The armature current is proportional to the difference between the applied voltage and the back e.m.f., divided by the armature resistance, as shown in this equation.

$$I_a = \frac{V_t - E_g}{R_a}$$

Where:

- I_a = armature current in amperes (A)
- V_t = motor applied voltage in volts (V)
- E_g = back e.m.f. of the motor in volts (V)
- R_a = armature resistance in ohms (Ω)

Note: this equation is for explanation purposes only; you are not required to calculate the armature current using this equation in this unit.

Power Output of a d.c. Motor

The output power of a d.c. motor, measured in watts, is directly proportional to the speed and torque of the motor, as shown in this equation.

$$P_O = \frac{2\pi nT}{60}$$

Where:

- P_O = motor output power in watts (W)
- n = speed of the motor in r.p.m.

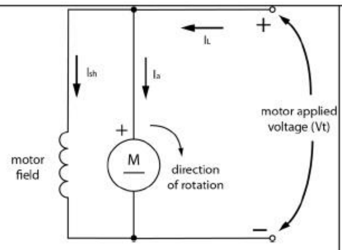
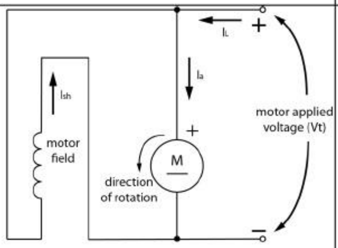
- T = torque in the motor in newton-metres (Nm)

Worked Example – calculating the power output of a d.c. motor
Calculate the power output of a d.c. motor operating at a speed of 1175 r.p.m. if the torque developed by the motor is 85 Nm.
$P_O = \frac{2\pi n T}{60}$
$P_O = \frac{2 \times \pi \times 1175 \times 85}{60}$
$\underline{P_O = 10.46\ kW}$

Reversing Direction of Rotation

To reverse the direction of rotation of a d.c. motor, the direction of either the motor field current or the armature current must be reversed, but not both. This has the effect of reversing the direction of force (torque) on the conductors in the armature.

This table shows how to reverse the direction of rotation in a shunt motor.

Reversed Direction of Rotation – Shunt Motor		
Forward direction		• Current through the motor field and armature is top to bottom • Direction of rotation is clockwise • Back e.m.f. opposes the applied voltage
Reverse direction		• Current through the armature is top to bottom • Current through the motor field is bottom to top • Direction of rotation is now anti-clockwise • Back e.m.f. continues to oppose the applied voltage

Iron losses (constant loss)	Hysteresis loss	• Due to hysteresis of the magnetic circuit • Occurs in the armature core
	Eddy current loss	• Due to eddy currents induced into the armature laminations
Mechanical losses (constant loss)	Friction loss	Due to • Friction in the bearings • Friction between the brushes and the commutator
	Windage loss	• Due to the armature rotating in air • Increases when a fan blade is attached to the shaft to ventilate the motor

No-load Test

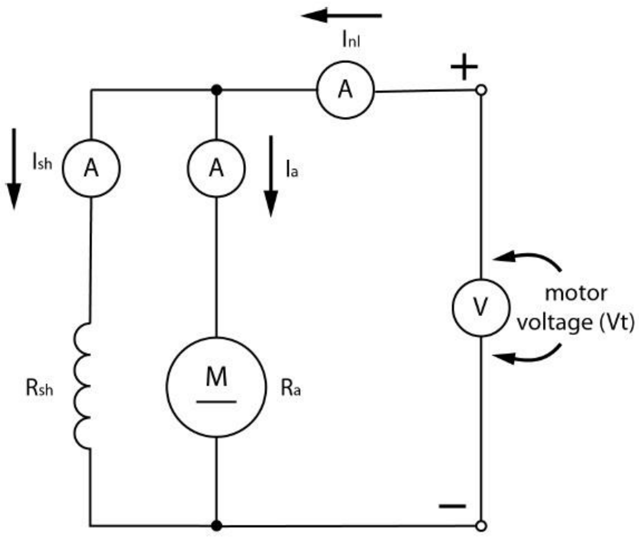
The no-load test is used to measure the constant losses and the no-load copper losses in a d.c. machine. The copper losses are variable losses, and increase as the load on the machine is increased.

The iron losses and the mechanical losses are constant and don't change when the load increases.

To determine the constant losses and the no-load copper losses, the machine is run at rated speed, without a load connected and the field, armature and no-load line currents are measured.

This diagram shows a no-load test being used to measure the iron, mechanical and no-load copper losses in a shunt connected d.c. motor. The motor is run without load and a voltmeter and ammeters are connected to measure the:

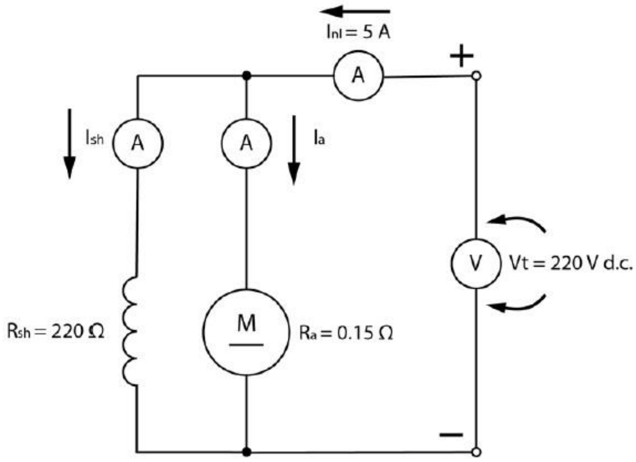
- Motor voltage, V_t
- No-load line current, I_N
- Armature current, I_a
- Field current, I_{sh}



Calculation of Constant Losses and No-Load Copper Losses

Worked Example – calculating constant losses and no-load copper losses

Calculate the no-load copper losses and the constant losses (iron and mechanical losses) in a 220 V d.c. shunt motor, if the no-load current is 5 A, the armature resistance is 0.15 Ω, and the shunt field resistance is 220 Ω.



(a) No-load input power, P_{NL}

$$P_{NL} = V_t \times I_{nl}$$

$$P_{NL} = 220 \times 5$$

$$\underline{P_{NL} = 1{,}100\ W}$$

(b) Shunt field copper loss, P_{sh}

$$I_{sh} = \frac{V_t}{R_{sh}}$$

$$I_{sh} = \frac{220}{220}$$

$$I_{sh} = 1\ A$$

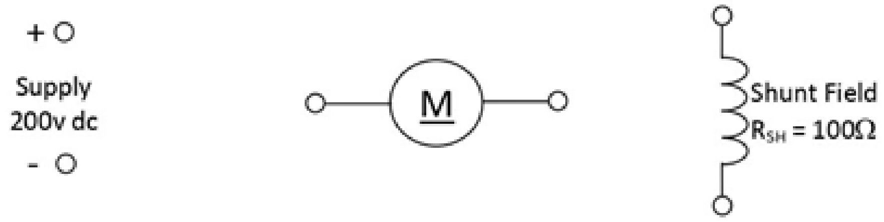
$$P_{sh} = I_{sh}^2 \times R_{sh}$$

$$P_{sh} = 1^2 \times 220$$

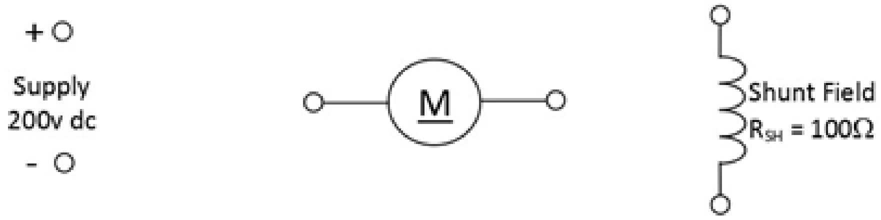
$$\underline{P_{sh} = 220\ W}$$

dc electric motor circuit connection and analysis

a. Using the electrical machine schematic drawing symbols below, draw the connections for the machine to operate as a dc shunt motor:



b. Redraw the dc shunt motor connections shown above so that the motor will now run in the reverse direction:



c. For the dc shunt motor drawn above,

the current in the shunt field winding will be = ________ Amps

Show your calculations here...