BRUSHLESS ELECTRIC MOTORS:
A Third Year Study

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1. Statement of the Problem

In first year research a new type of an electric motor was invented, built, and tested. It is a reed switch based brushless motor. In the second year development, extra circuits with another electromagnet and/or reed switch were added to the original prototype. Different experiments demonstrated that these new motors were very reliable, stable, and powerful enough to be favorably compared to existing conventional motors.

But how would the prototype motor compare to other types of brushless motors, and how would these motors compare to each other?

2. Hypothesis

If different types of brushless motors will be built using the same design, it is believed that no motor will be the best in everything, but different motors will show best results in various categories such as speed, torque, and efficiency.

3. Project Objective

In this third year study it is planned to build eight different types of brushless motors based on the same design and technology:

- Motor #1 – The Original Reed Switch Based Brushless Motor
- Motor #2 – Double Reed Switch Motor Based On Push-Pull Operation
- Motor #3 – SCR Controlled Brushless Motor
- Motor #4 – Transistor Controlled Brushless Motor
- Motor #5 – Optocoupler Based Brushless Motor
- Motor #6 – Brushless Motor With Optical Control
- Motor #7 – Hall Effect Position Sensor Based Brushless Motor
- Motor #8 – Brushless Motor Based On Hall Effect IC

These motors will be tested and compared to each other in the following categories:

- Speed under different loads
- Torque under different voltages
- Maximum load
- Efficiency
- Reliability
- Stability
- Complexity
- Cost

4. Background Information

An electric motor is a device that converts electrical energy into mechanical force, based on the attraction or repulsion of magnets. A conventional electric motor consists of two main parts: the rotor, which is the coil, and the stator, which are the magnets and brushes. When current flows through the coil, it creates a magnetic field. The magnetic field of the rotor interacts with the magnetic field of the stator, and this causes the coil to spin.

The brushes in a conventional motor limit its life to a few thousand hours (Werninck, 1978). This is a big disadvantage of a conventional DC motor. There are other disadvantages of this type of a motor, such as a big noise.

To avoid these problems several types of brushless motors were invented (Werninck, 1978). Most of them consist of four elements: the rotor, the stator, electronic commutator, and the rotor position sensor. The stator contains the armature (coil), and the rotor has permanent magnets.

Advantages of a brushless motor are:

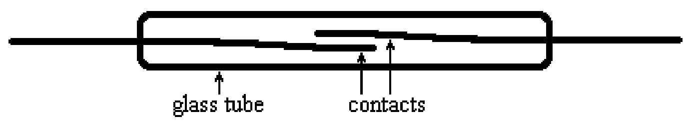
- The reduced the amount of friction increases motor life significantly.
- The brushless motor has high reliability and a fast response.
- The brushless motor is more efficient that the conventional motor.
- The brushless motor makes less noise.
- The brushless motor needs little or no maintenance, because there aren't any brushes.

There are some disadvantages of the brushless motor, mostly related to the price or complexity of it. The brushless motor is more expensive than the conventional motor, because it requires an additional sensor to determine the rotor position and send a signal to change the magnetic field.

Several types of sensors can be used in a brushless motor.

Reed Switches

Since the rotor consists of permanent magnets, a reed switch can be used for two purposes: to determine the position of the rotor and to serve as an electronic switch to alternate the magnetic field in a stator.



A reed switch consists of two magnetic contacts in a glass tube. When a magnet comes close to a reed switch the two contacts become magnetized and attract to each other and allow an electrical current to pass through. When the magnet is moved away from the reed switch the contacts demagnetize, separate, and move to their original position (Reed Electronics AG, 1997).

Most reed switches have normally open (NO) contacts. Reed switches with normally closed (NC) contacts are not very common. There are also reed switches that have three contacts, with one switching between the two. This type of reed switch is called a single-pole, double-throw reed switch.

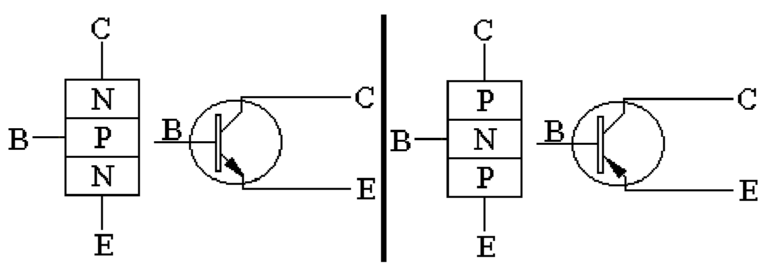
Reed switches are very reliable and last as long as 3 billion operations if used properly. However, they are designed for low currents, and a high current through the contacts causes an arc (spark), which may weld the contacts together after several hours of operation.

Separating the reed switch from the inductive coil may eliminate this problem. Several methods can be used. The most simple and common way is to use a transistor to switch the coil.

Transistors

In 1947, William Shockley, John Bardeen, and Walter Brattain developed the first transistor in Bell Laboratories (Bridgman, 1993).

Transistors are made from silicon. Boron atoms are added to silicon to create a P-type silicon layer (positive). Phosphorus atoms are added to silicon to create an N-type silicon layer (negative). A transistor consists of a stack of three layers. The arrangement, pnp or npn, determines which way electrons flow.



Transistors are devices with three leads, known as base (B), emitter (E), and collector (C). A very small emitter-base current will allow much larger emitter-collector current to flow.

There are two ways in which transistors are used. One is switching, and the other is amplifying a signal. Only the switching capability will be used in this project, so it is not described how transistors amplify signals.

“When the base of a transistor is grounded (0 Volts), no current flows from the emitter to the collector (the transistor is “off”). If the base is forward biased by at least 0.6 Volts, a current will flow from the emitter to the collector (the transistor is “on”). When operated in only these two modes, the transistor functions as a switch” (Mims, (Getting started in Electronics), p.50).

Transistors can be “burnt” very easily, and there are many parameters, which cannot be exceeded. The most important electrical parameters of a transistor for this project are:

I_C – Maximum collector current. High current flowing through the collector may cause the transistor to “burn”.

V_{CEO} and V_{CBO} – Maximum voltage between collector and emitter and collector and base respectively. High voltage may destroy the transistor.

P –Maximum power the transistor can dissipate. Power transistors require heat sinks to achieve the maximum ratings. If the transistor gets too hot, the connection wires may separate.

β - Current gain.

Beta (symbol Greek letter β) describes the amount of collector current flowing when the base has a certain current flow. The formula for beta is:

$$\beta = I_C / I_B$$

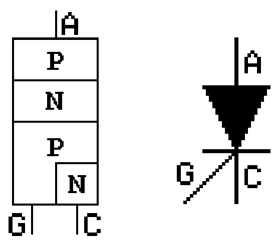
(R. J. Phagan, p.273).

Transistors are used in control circuits of conventional motors. “At low power (less than 50 kW) the transistor…is the most economical means of speed control. (Kamichik, p.82)”

Transistors are also widely used in brushless motors. “Transistors which make up the electronic commutator need signals or firing pulses, which are dependant upon the rotor position, to enable them to work at the correct time. Once the signal from the rotor position sensor has been removed from the base of the transistor it is switched off. The transistor stays in this state until the firing signal is applied again." (Werninck, p. 319)

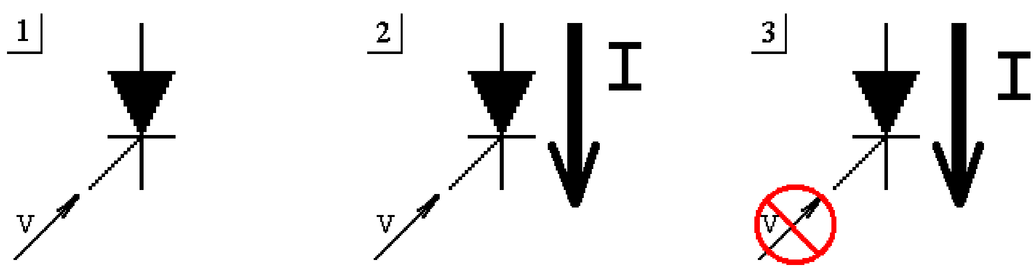
Silicon Controlled Rectifiers

Silicon Controlled Rectifiers or SCRs are a lot like transistors. They share the same operating principles, consist of P and N layers, and they act as switching devices. However, SCRs do not amplify signals and can be built to be very powerful.



"...SCR, also known as the thyristor, is a specialized type of device used for the control of current through its cathode-to-anode path. A gate is used to control the resistance between the cathode and anode. By applying a small voltage between the gate and the cathode, it is possible to control that resistance and, as a result, the amount of current flow through the device." (Miller, p.94) Here is a diagram showing this:

1. Small voltage applied to gate.
2. Large current may flow from anode to cathode.
3. Current continues to flow even when voltage to gate is removed.



This is why SCRs are unique from transistors. They stay on even if the voltage to the gate is turned off. The only way to turn SCRs off is to disconnect all power to it.

Optical Sensors and Optoisolators

"One method for determining the rotor position…is the use of photo transistors and LEDs…this method uses a wheel with a proper sequence of windows inserted between the light source and the photo-transistor. (Werninck, p. 320)"

LEDs, or Light Emitting Diodes, commonly serve as a source of light in optical interrupters and optical isolators. Normally in optical sensors they emit infrared light. "Light-Emitting Diodes switch off and on rapidly, are very efficient, and have a very long lifetime." (Mims, Forrest p. 9 (Optoelectronics Circuits)).

Phototransistors are like transistors, but are specially built to receive light. They "open" when there is light and "close" when there isn't any light. Usually they are used as detectors of the infrared light emitted by LEDs. "The most common phototransistor is an NPN transistor with a large, exposed base region" (Mims, (Getting started with Electronics) p.74)

Phototransistors are generally fabricated of Ge or Si in the same manner as conventional transistors, except that a lens or window is provided in the transistor to admit light at the base-collector junction (Fink and Christiansen, 1989, p. 11-79).

One of the best ways to separate the sensor (the reed switch) from the inductive load (the coil) is to use an optical isolator. It is very efficient and operates very silently.

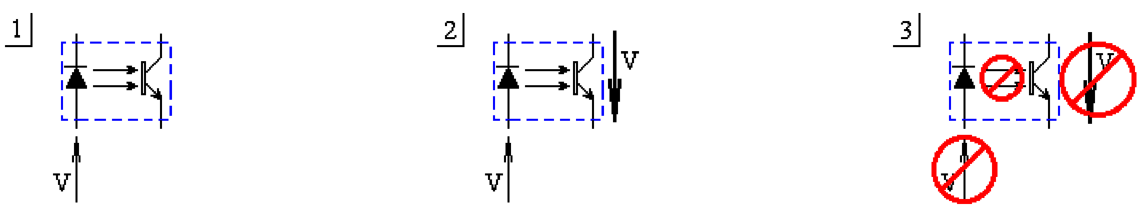
"An optical isolator is a device that is interposed between two systems to prevent one of them from having undesired effects on the other, while transmitting desired signals between the systems by optical means…

…An optical isolator is a very small four-terminal electronic circuit element that includes in an integral package a light emitter, and a light detector. The device is also known as an optocoupler." (McGraw-Hill Encyclopedia of Science and Technology, vol.12, p.422)

Optocouplers exist in two main forms:

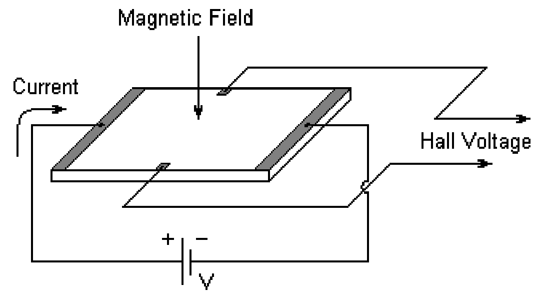
IC or as separate components

When voltage is applied to the LED of an optocoupler it emits light. The phototransistor receives this light, making it "open," and current may pass. If the voltage to the LED is shut off, it stops emitting light. Since the phototransistor does not receive any light, it turns off, and does not allow a current to flow.

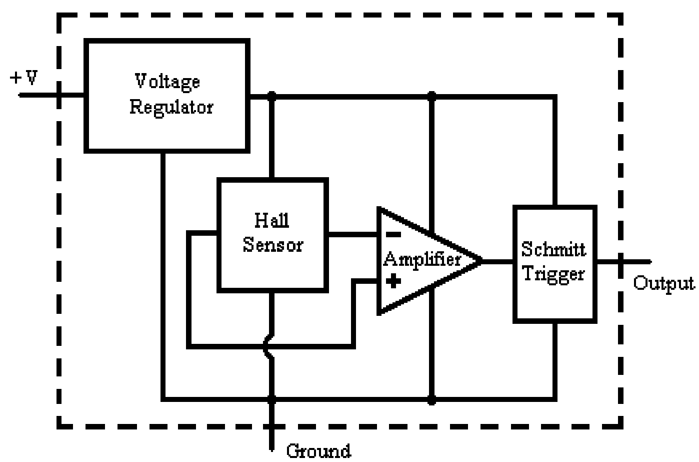


Hall Effect Switches

In October 1879, the physicist Edward Hall discovered the effect that bears his name. "Hall found that a strong magnetic field caused a voltage to appear across a thin film of gold through which an electrical current was flowing. This voltage is called the Hall voltage." (Mims, Forrest pg. 20 (Magnet and Magnet Sensor Project))."



Many new brushless motors have been developed using Hall effect sensors. "These motors use the main magnetic poles, or an auxiliary rotating permanent magnet that provides a rotating field for the stationary Hall generator (Werninck, p.320)."



Most Hall sensors are manufactured with a built-in amplifier or logic circuit to make them easier to use. (Mims, Magnet Sensor Projects, p.22) The Hall voltage is proportional to the applied magnetic field (p.23)

Hall sensors have only gained more popularity recently. They have many applications, and are inexpensive in manufacturing. They can be used instead of light sensors where the sensor may become dirty or exposed to bright light.

5. Principles Of Motor Operation

The Original Reed Switch Based Brushless Motor

This is the original reed switch based brushless motor. This motor was invented, built, and tested in the first year research, and then it was further developed in the second year development.

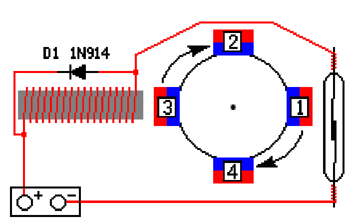
This brushless motor consists of the following components:

- Rotor with four magnets.
- Stator (electromagnet – 60' of 26 gauge insulated copper wire shunted with 1N914 diode. The diode protects from high voltage spikes that occur when the electromagnet is switched off).
- Reed switch with normally open contacts

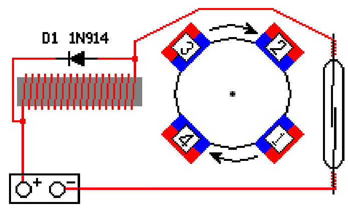
Motor operates fine on all tested voltages in the range from 2V to 11V DC.

This is how this motor works:

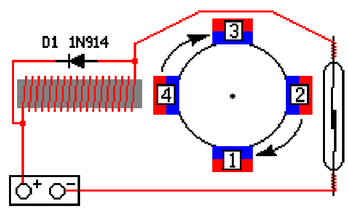
I. When magnet #1 gets close to the reed switch, the two contacts inside the glass tube get magnetized and touch each other. This causes the electromagnet to push magnet #3 away.



II. When the magnets spin away, the reed switch demagnetizes and gets disconnected. This creates an open circuit disabling the electromagnet.



III. The magnets continue to spin due to inertia until magnet #2 gets in working range of the reed switch. It becomes magnetized again and its contacts connect together making the electromagnet push magnet #4 away. The process continues until the power is disconnected.



Double Reed Switch Motor Based On Push-Pull Operation

The original reed switch based brushless motor uses repulsion of the magnets. It can be redesigned so at different moments it will push and pull the magnets on the rotor. That may significantly increase the power of the motor but it will also increase the consumed power.

Double reed switch motor based on push-pull operation uses two single-pole, double-throw reed switches. They are connected in a way allowing to switch the coil and therefore to change the direction of the current flowing through the electromagnet.

The arrows in these drawings indicate the direction in which electricity flows.

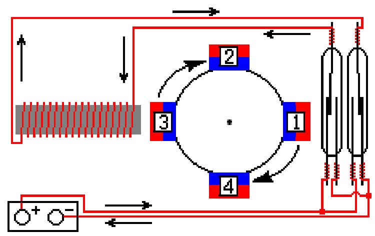
The double reed switch motor based on push-pull operation consists of the following components:

- Rotor with four magnets.
- Stator (electromagnet – 60’ of 26 gauge insulated copper wire).
- 2 single-pole, double-throw reed switches.

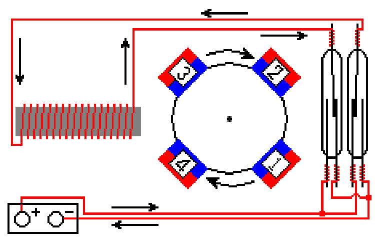
The motor worked only on voltages in the range from 2V to 5V DC.

This is how this motor works:

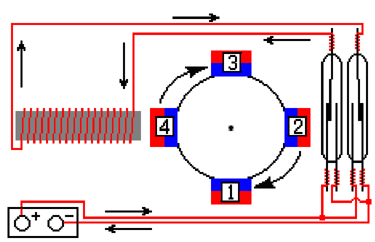
I. When magnet #1 gets close to the reed switches, the contacts get magnetized and touch each other. This causes the current to go through the coil and makes the electromagnet push magnet #3 away.



II. When the magnets spin away, the reed switches switch back to their original position. The current flowing through the coil changes direction. This makes the electromagnet attract magnet #4.



III. Once magnet #2 gets in working range of the reed switches again, their contacts become magnetized and connect together. This changes the direction of the current flowing through the coil, making the electromagnet push magnet #4 away. This process continues until the power is disconnected.



SCR Controlled Brushless Motor

The reed switch based brushless motor can be built using a Silicon Controlled Rectifier or SCR. The SCR significantly decreases the spark, which may damage the reed switch.

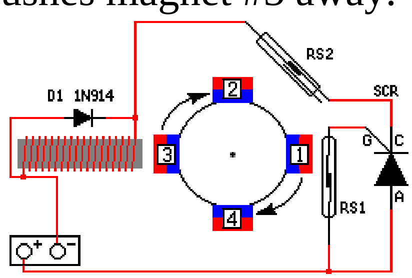
The SCR controlled brushless motor consists of the following components:

- Rotor with four magnets.
- Stator (electromagnet – 60' of 26 gauge insulated copper wire shunted with 1N914 diode. The diode protects from high voltage spikes that occur when electromagnet is switched off).
- SCR with I_{max} = 10 A, V_{max} = 200V.
- RS1 – Reed switch with normally open contacts
- RS2 – Reed switch with normally closed contacts oriented at 45° to RS1. NC contacts of a single-pole double-throw reed switch were used.

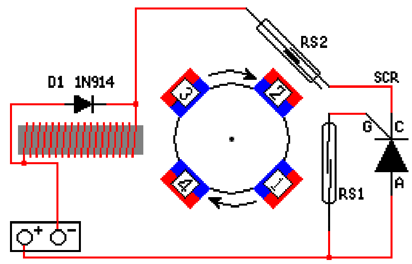
Motor operates fine on all tested voltages in the range from 2V to 13V DC.

This is how this motor works:

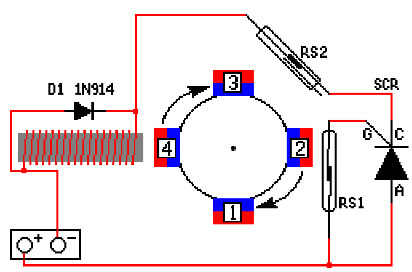
I. When magnet #1 gets close to reed switch 1, its contacts get magnetized and touch each other. This allows a small current to flow through the gate, which opens the SCR. Therefore, the main current starts to flow through the cathode to anode, then through RS2, and finally through the electromagnet. The electromagnet pushes magnet #3 away.



II. When the rotor spins away, RS1 opens. However, the SCR remains open and current continues to flow between the cathode and anode. When the rotor turns about 45°, magnet #2 approaches RS2, its normally closed contacts get magnetized and separate. This creates an open circuit, turns off the SCR, and disables the electromagnet.



III. The rotor continues to spin due to inertia. Magnet #2 moves out of the working range of RS2 and into the working range of RS1. The contact in RS2 demagnetizes and moves back to its original position. The contacts in RS1 become magnetized again, connect together, and turn the SCR on again. This allows the electromagnet to push magnet #4 away. The process continues until the power is disconnected.



Transistor Controlled Brushless Motor

The reed switch based brushless motor can be built using a power transistor. The transistor separates the reed switch from the inductive load. This eliminates the spark and decreases the current through the reed switch, which may increase the lifetime of the motor.

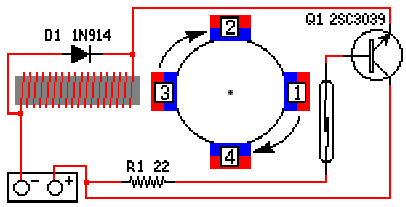
The transistor controlled brushless motor consists of the following components:

- Rotor with four magnets.
- Stator (electromagnet – 60’ of 26 gauge insulated copper wire shunted with 1N914 diode. The diode protects from high voltage spikes that occur when the electromagnet is switched off).
- NPN power transistor (2SC3039) with $I_C = 7A$, $V_{CEO} = 400V$.
- Reed switch with normally open contacts.
- 22 Ohm resistor. Used to lower the current flowing through the base of the transistor.

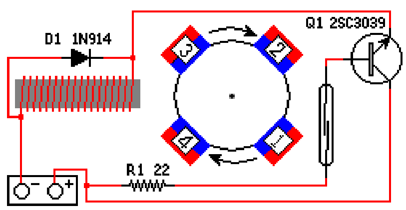
Motor operates fine on all tested voltages in the range from 2V to 10V DC.

This is how this motor works:

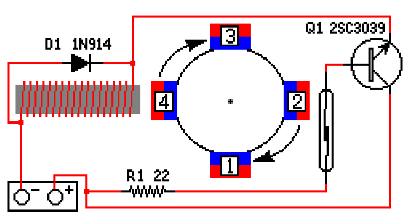
I. When magnet #1 gets close to the reed switch, the two contacts inside the glass tube get magnetized and touch each other. A small current flows through the base of the transistor. The transistor opens, and allows a bigger collector current to flow through the electromagnet. The electromagnet pushes magnet #3 away.



II. When the rotor spins away, the reed switch demagnetizes and the contacts move back to their original position. Since there is no more current flowing through the base, the transistor turns off. This disables the electromagnet.



III. The rotor continues to spin due to inertia until magnet #2 gets in working range of the reed switch. It becomes magnetized again and its contacts connect together. The transistor opens and allows a current to flow between the collector and emitter. The electromagnet turns on, and pushes magnet #4 away. This process continues until the power is disconnected.



Optocoupler Based Brushless Motor

The optocoupler IC can be used for even further separation of the reed switch from the electromagnet. This motor will still require a reed switch as a rotor position sensor and a power transistor as a control device. It also uses a separate +5V power source connected to the LED through the reed switch. This keeps the LED current the same and independent of voltage changes in the main circuit.

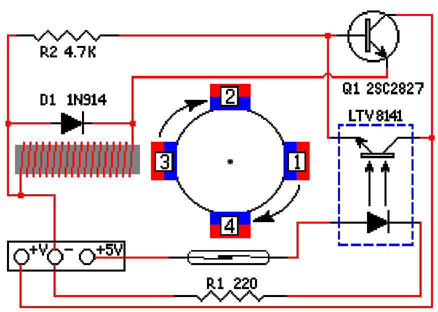
The optocoupler based brushless motor consists of the following components:

- Rotor with four magnets.
- Stator (electromagnet – 60' of 26 gauge insulated copper wire shunted with 1N914 diode. The diode protects from high voltage spikes that occur when the electromagnet is switched off).
- Optocoupler chip (LTV8141). The phototransistor within this chip is a Darlington transistor (two transistors connected together to increase β)
- NPN power transistor (2SC2827) with $I_C = 6A$, $V_{CEO} = 400V$.
- Reed switch with normally open contacts
- R1 – 220 Ohm resistor. Used to limit the current flowing through the LED.
- R2 – 4.7 K Ohm resistor. Used to lower the current flowing through the base of transistor Q1.

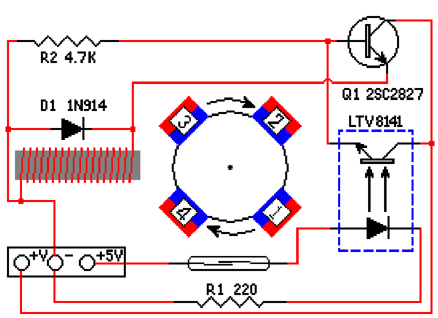
This motor works in a range from 2V to 12V DC. However, it could not lift any weight on 2 volts.

This is how this motor works:

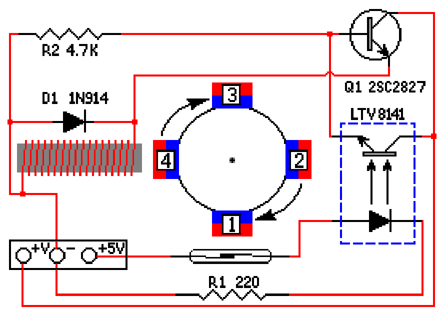
I. When magnet #4 gets close to the reed switch, the two contacts inside the glass tube get magnetized and touch each other. A small current flows through the LED, which emits light to the phototransistor. The phototransistor opens, allowing a current to flow through the base of power transistor Q1. It opens and allows a bigger collector current to flow through the electromagnet. The electromagnet pushes magnet #3 away.



II. When the magnets spin away, the reed switch demagnetizes and its contacts move back to their original position. This turns off the LED and then the phototransistor. Since there is no signal to the base, transistor Q1 gets turned off. This disables the electromagnet.



III. The magnets continue to spin due to inertia until magnet #1 gets in working range of the reed switch. The two contacts get magnetized and touch each other. A small current flows through the LED, which emits light to the phototransistor. The phototransistor opens, allowing a current to flow through the base of power transistor Q1. It opens and allows a bigger collector current to flow through the electromagnet. The electromagnet pushes magnet #4 away. This process continues until the power is disconnected.



Brushless Motor With Optical Control

The brushless motor with optical control represents a motor with a different type of sensor. It uses a slotted optointerrupter, or an optical pair. A disk with a proper sequence of windows, inserted between the LED and the phototransistor in the optointerrupter, was affixed to the rotor. This motor uses a separate +5V power source connected to the LED. It keeps the LED current the same and independent of voltage changes in the main circuit.

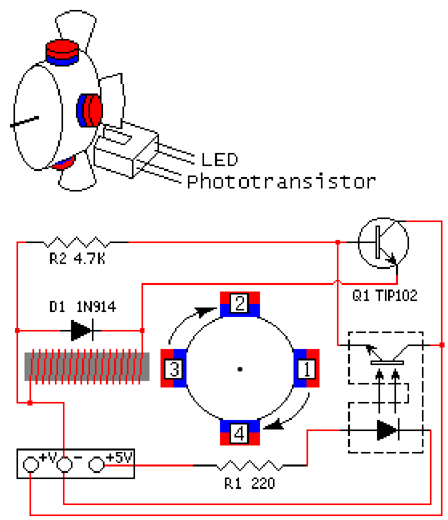
The brushless motor with optical control consists of the following components:

- Rotor with four magnets and an attached disk with four windows.
- Stator (electromagnet – 60’ of 26 gauge insulated copper wire shunted with 1N914 diode. The diode protects from high voltage spikes that occur when electromagnet is switched off).
- NPN Darlington power transistor (TIP102) with I_C = 8A, V_{CEO} = 100V (two transistors connected together to increase β). It was used because the output from the phototransistor is too small on certain voltages to fully open regular power transistors. Plus it simplifies the motor.
- Slotted optointerrupter (OPB867T55) consisting of an LED and a phototransistor.
- R1 – 220 Ohm resistor. Used to limit the current flowing through the LED.
- R2 – 4.7 K Ohm resistor. Used to lower the current flowing through the base of transistor Q1.

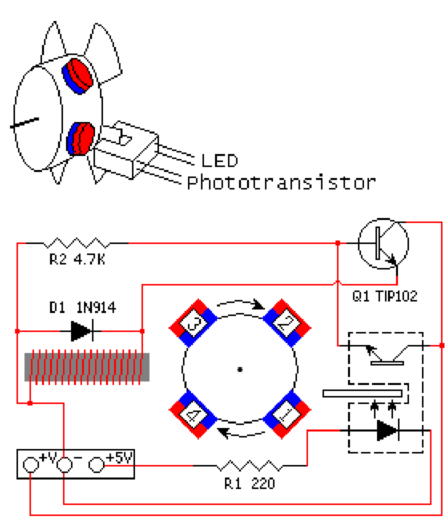
Motor operates fine on all tested voltages in the range from 2V to 12V DC.

This is how this motor works:

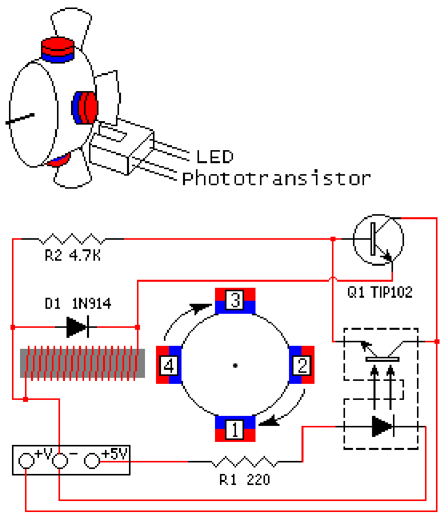
I. When the motor stops, the edge of the disk does not interfere with the channel between the LED and the phototransistor. So, when voltage is applied to the LED, it sends a constant signal to phototransistor. The phototransistor opens, allowing a current to flow through the base of power transistor Q1. It opens and allows a bigger collector current to flow through the electromagnet. The electromagnet pushes magnet #3 away.



II. When the magnets spin away, the disk moves between the LED and phototransistor. This interrupts the light signal to the phototransistor turning it off. Since the phototransistor is off, it turns off power transistor Q1. This disables the electromagnet.



III. The magnets continue to spin due to inertia until the disk moves out of the optointerrupter channel. The phototransistor opens, allowing a current to flow through the base of power transistor Q1. It opens and allows a bigger collector current to flow through the electromagnet. The electromagnet pushes magnet #4 away. This process continues until the power is disconnected.



Hall Effect Position Sensor Based Brushless Motor

The Hall effect position sensor based brushless motor represents a motor with a different type of sensor. It uses a Hall effect sensor that is utilized in industrial applications such as in the automotive industry. This motor requires a separate +5V power source connected to the Hall sensor as its working range is 4.5-5.5 volts.

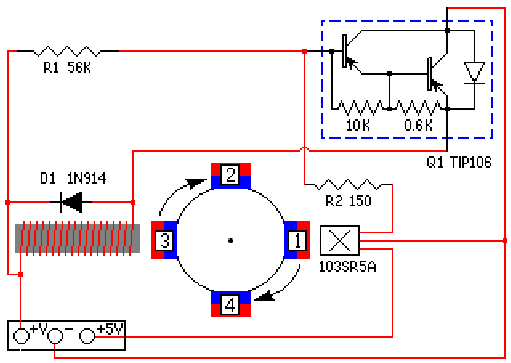
The Hall effect position sensor based brushless motor consists of the following components:

- Rotor with four magnets.
- Stator (electromagnet – 60' of 26 gauge insulated copper wire shunted with 1N914 diode. The diode protects from high voltage spikes that occur when electromagnet is switched off).
- PNP Darlington power transistor (TIP106) with I_C = 8A, V_{CEO} = 100V (two transistors connected together to increase β). It was used because the output from the Hall sensor is too small to fully open regular power transistors. Plus this simplifies the motor.
- Industrial Hall effect position sensor (103SR5A) with supply voltage $V_{min/max}$ = 4.5-5.5 V, output current I_{max} = 8 mA.
- R1 – 56 K Ohm resistor.
- R2 – 150 Ohm resistor. Used to limit the output current from the Hall sensor.

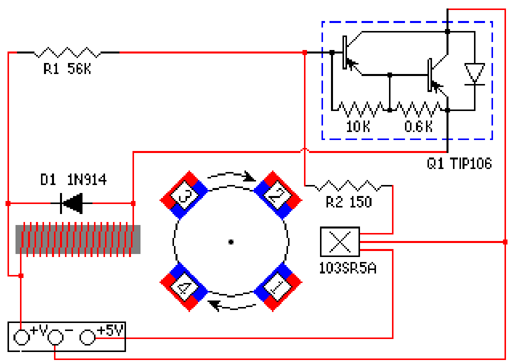
Motor operates fine on all tested voltages in the range from 2V to 13V DC.

This is how this motor works:

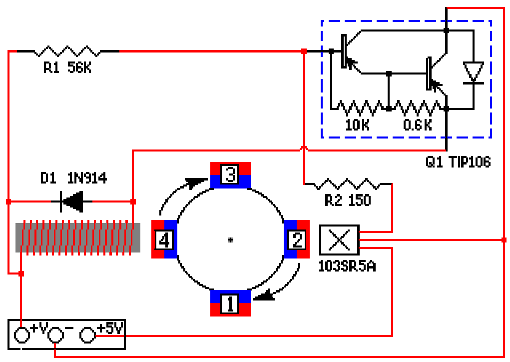
I. When magnet #1 gets close to the hall sensor, the sensor sends a signal to the base of power transistor Q1. The transistor opens, and allows a bigger collector current to flow through the electromagnet. The electromagnet pushes magnet #3 away.



II. When the rotor spins away, magnet #1 stops affecting the Hall sensor. Since the signal to the base of power transistor Q1 has been removed, it is turned off. This disables the electromagnet.



III. The rotor continues to spin due to inertia until magnet #2 moves into the working range of the Hall sensor. The Hall sensor sends a signal to the base of transistor Q1. The transistor opens, and allows a bigger collector current to flow through the electromagnet. The electromagnet pushes magnet #4 away. This process continues until the power is disconnected.



Brushless Motor Based On Hall Effect IC

The brushless motor based on Hall effect IC (integrated circuit) is very similar to the previous motor. It uses a Hall effect IC chip that is very small and widely used. The small Hall IC chip contains several components: the Hall sensor, voltage regulator, amplifier, and Schmidt trigger.

The Hall sensor IC used in this motor works with a supply voltage in a range from 3.8-24 V.

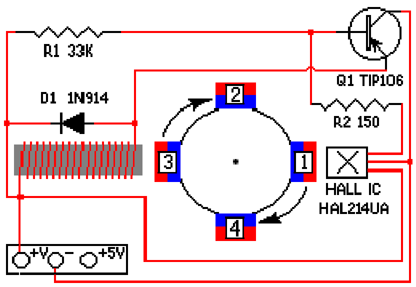
The Hall effect position sensor based brushless motor consists of the following components:

- Rotor with four magnets.
- Stator (electromagnet – 60’ of 26 gauge insulated copper wire shunted with 1N914 diode. The diode protects from high voltage spikes that occur when electromagnet is switched off).
- PNP Darlington power transistor (TIP106) with I_C = 8A, V_{CEO} = 100V (two transistors connected together to increase β). It was used because the output from the Hall sensor is too small to fully open regular power transistors. Plus this simplifies the motor.
- Industrial Hall effect position sensor (HAL504UA-E) with supply voltage $V_{min/max}$ = 3.8-24 V, output current I_{max} = 30 mA.
- R1 – 33 K Ohm resistor.
- R2 – 150 Ohm resistor. Used to limit the output current from the Hall sensor.

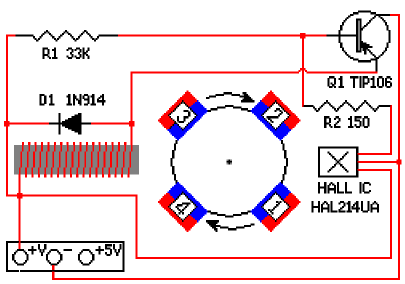
Motor operates fine on all tested voltages in the range from 4V to 13V DC.

This is how this motor works:

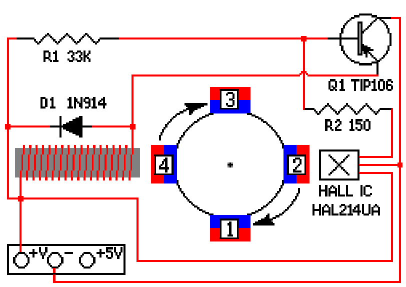
I. When magnet #1 gets close to the Hall IC, the sensor sends a signal to the base of power transistor Q1. The transistor opens, and allows a bigger collector current to flow through the electromagnet. The electromagnet pushes magnet #3 away.



II. When the rotor spins away, magnet #1 stops affecting the Hall IC. Since the signal to the base of power transistor Q1 has been removed, it is turned off. This disables the electromagnet.



III. The rotor continues to spin due to inertia until magnet #2 moves into the working range of the Hall IC. The Hall IC sends a signal to the base of transistor Q1. The transistor opens, and allows a bigger collector current to flow through the electromagnet. The electromagnet pushes magnet #4 away. This process continues until the power is disconnected.



6. Tools and Materials

All of the motors were built with the same tools and materials to make them identical. This allows a better and more accurate comparison of the data.

These are the tools that were used during the construction of the motors:

- Soldering iron
- Drill press
- Screwdrivers
- Table saw
- Bench grinder
- PVC cutter
- Pliers
- Knife
- Sandpaper

There are some materials that were common for all eight motors:

- Wire (70 feet of 26 gauge insulated copper wire)
- 4 Magnets with South pole marked
- Heavy-duty white board (approx. 5” x 5.5”)
- 4 Stands
- Rotor core with 4 flat surfaces for 4 magnets
- 4” Nail with tape for the electromagnet
- 2 Caps
- T-pin
- Wooden insert
- Pushpin
- Rubber plug
- Super glue
- Flux

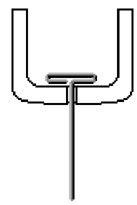
- Solder
- Small prototype circuit board
- Stands with matching screws

As the motors had different electronic circuits, they used different electronic components such as transistors, diodes, resistors, etc. Most of these components were listed for each motor in the previous chapter.

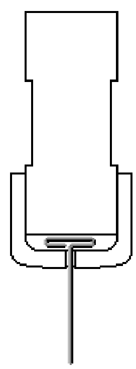
7. Building Instructions

The building instructions for all motors have several common steps required to assemble the rotor and stator. These steps will be shown in detail below.

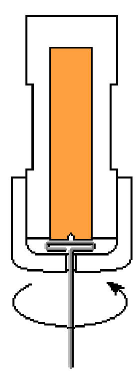
The T-pin was inserted into one of the caps.



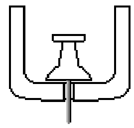
The rotor core was inserted into the same cap. Some pressure was apllied to push the rotor core approximately ½" into the cap.



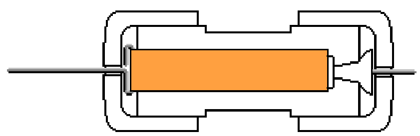
A wooden insert was put in. The side with the slit faced the T-pin. The T-pin was spun slowly until it snapped into the slit of the wooden insert. At this point insert started to rotate with the T-pin.



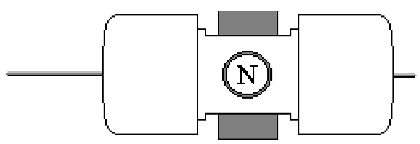
The pushpin was inserted into the other cap.



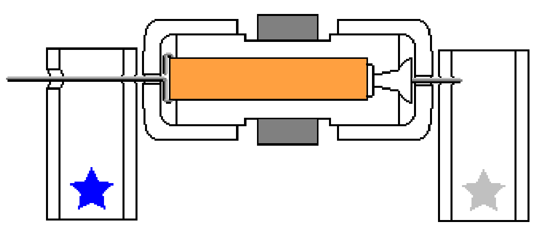
Everything was put together as shown below. The caps were pushed towards each other until they could not move any more. The T-pin was secured firmly.



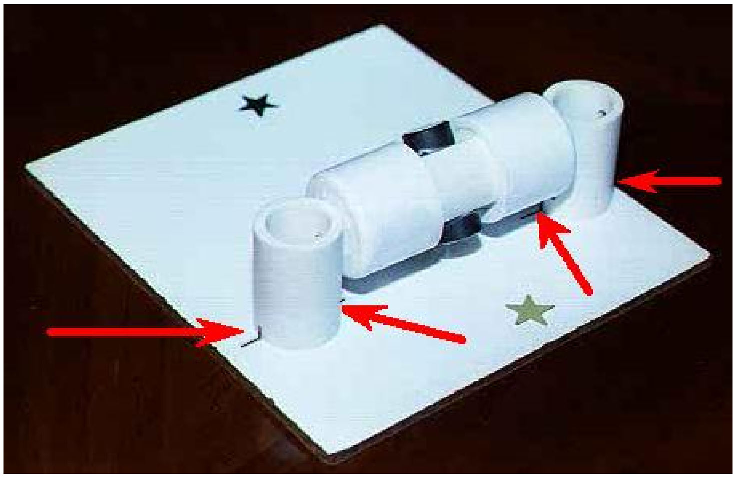
The magnets were glued to the flat surfaces of the rotor core.



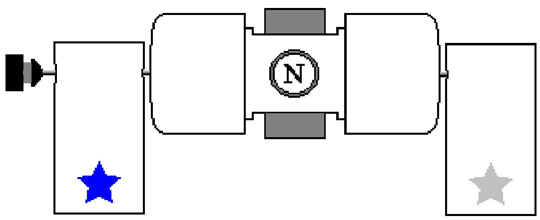
The rotor was inserted into the stands as shown below.



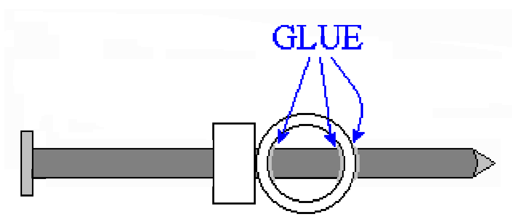
One stand was glued to the board. The marks were aligned on the stand with the line on the board as shown below.



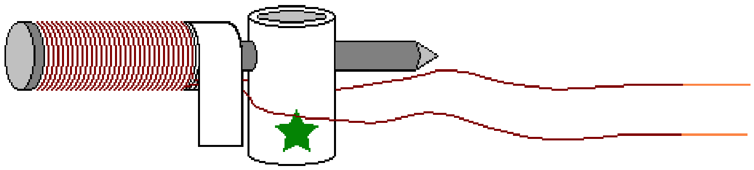
The rotor was inserted into the stand. Then it was glued to the board the same way as the first stand. A gap of about 1/16”(1/32” on each side) was left between the rotor and the stands. It was tested that the rotor spun freely.



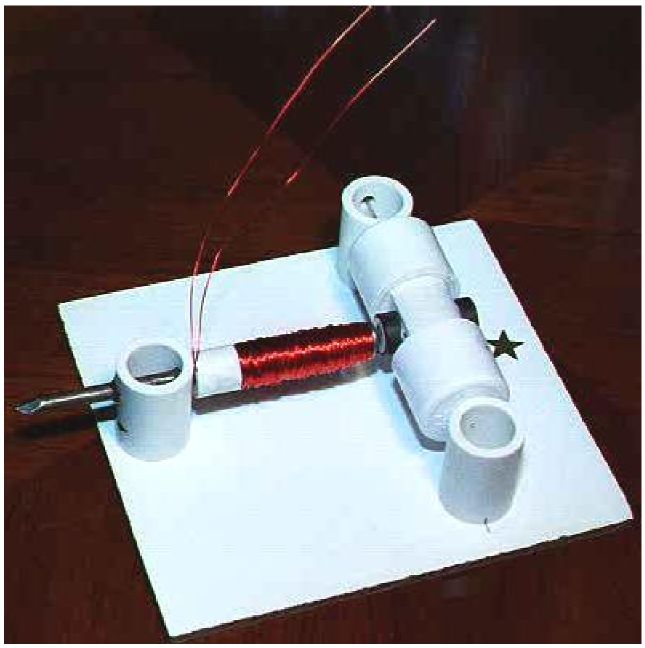
A nail was inserted into the stand with a big hole in it. Glue was apllied as shown below.



Wire was wrapped around the area between the tape and the head of the nail. The end and beginning of the wire was taped using the same tape and leaving open ends of wires about 6” long. About 1” of the wire tips was cleaned with fine sandpaper.



The electromagnet was glued to the board as shown below.



The reed switch wires were inserted as shown in diagram 1 below. The wires were twisted as shown below in diagram 2.

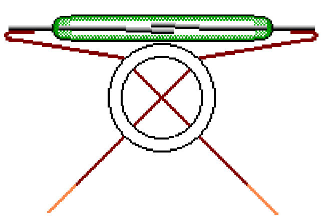


Diagram 1

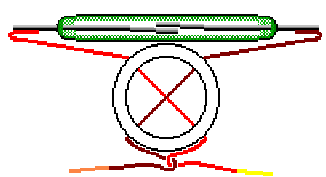
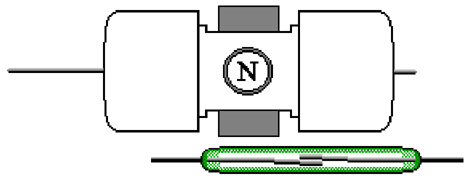
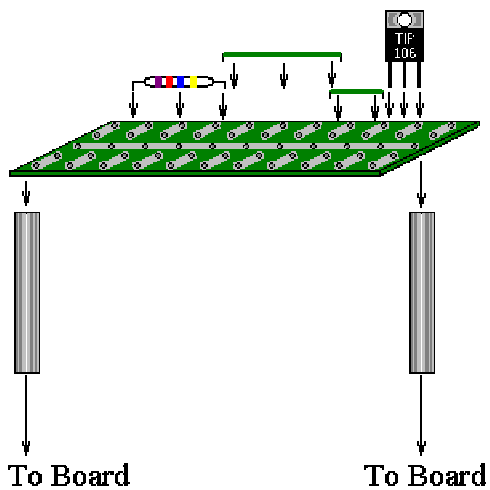


Diagram 2

The reed switch holder was glued to the base. It was located on a distance of about 1/8" from the closest magnet.



The necessary components and connecting wires were placed on the circuit board. Their arrangement was checked that it was correct. The contacts were then soldered to the board. The circuit board was then attached to the stands, which were attached to the main board. The wires from the reed switch, electromagnet, and battery were then also soldered to the circuit board.

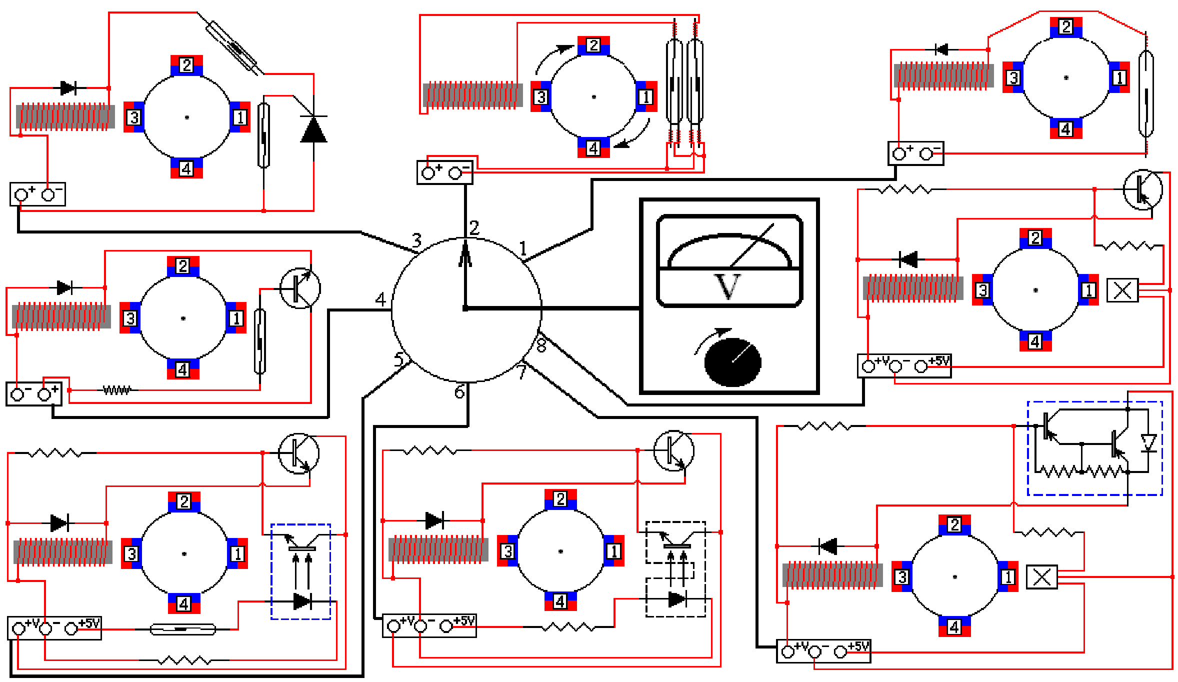


All motors had different electronic components, or different sensors were used instead or the reed switch, but most of the steps in assembling them remained the same.

8. Experiments

Eight different motors were placed on two long boards. Power to the motors was provided by a specially built and designed power supply. This regulated power supply had two built-in indicators for voltage (V) and current (A) with an output voltage in the range from 1.5 to 15 volts DC at a maximum current of 3 amperes. This device also had an overload protection circuit that after some time of work on high currents (over 0.5A) switched off the power supply. It was then necessary to wait until it cooled off.

The power supply was attached to a control box. This control box provided the ability to switch between eight different motors:



First year research clearly showed that the position of the sensor affected motor parameters. As a result of the experiments it was noted that the best position was opposite of the electromagnet. Thus, all of the sensors in this year research are exactly opposite the electromagnet and at the same level.

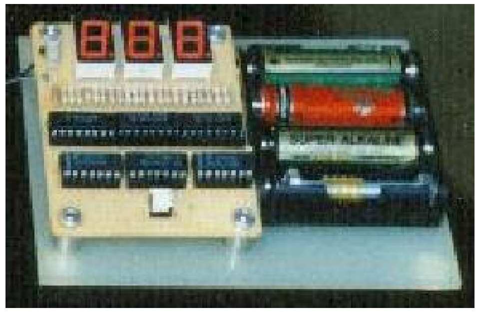
A major problem for the original motor, developed in the first year research, was the presence of the “dead spot”. The “dead spot” occurs when the rotor stops in a position where the magnets are outside the reed switch working range. In this case the motor can’t restart. Last year this problem was solved by completely redesigning all of the motors. This problem was not encountered this year as well.

The manipulated variable in the experiments was voltage. The results were taken at the following voltages: 2, 3, 4, 5, 6, 7, and 8 volts DC. Although the power supply could provide higher voltages and most of the motors would work on them, it was decided to use this range for consistent results during testing.

The controlled variable in this experiment was the amount of weight: No Weight (there are no restraints on the motor), Hooked (the motor is attached to the speed reducer), 0.5 lbs, 1 lbs, 1.5 lbs, 2 lbs, 2.5 lbs, 3 lbs, and 3.5 lbs. The motors were also tested to find the maximum load that they could lift on 2-8 volts. The maximum load that was used was 10 lbs.

The responding variables were the speed, measured in revolutions per minute and the current, measured in amperes.

In the first year research, for speed measurements, a 3-digit electronic decade counter was built. The spinning magnets on the rotor were used for calculating speed in revolutions per minute. To assist in finding the rpm value another reed switch was utilized. The signals from this reed switch were sent to the counter. This year, it was decided to replace the reed switch with a Hall effect switch. The Hall effect switch is more stable and provides more accurate measurements. Another digit was also added to the counter.



Although the counter shown on the previous page was built completely for these experiments only, it doesn't represent the main topic of this project, and therefore is not described here in details.

The speed in rpm was calculated as the ratio of the number of pulses in one minute displayed on the counter divided by the number of magnets on the rotor.

One of the biggest challenges of this project was the torque measurement. To achieve this task the motor was attached to a speed reducer. One end of the piece of thread was affixed to the axle of the speed reducer, while the other end contained a hook, which was holding a plate. As the motor spun the thread was slowly winding onto an axle; this lifted the plate. The speed reducer ratio was approximately 1:150, which means that the motor needed to make 150 revolutions to make the axle rotate one turn. The plate that has been lifted contained a specific number of weights, which were actually ceramic tiles. Three ceramic tiles weighed exactly 1 lb. To achieve 0.5 lb. increments, one tile was split in half. For example, 7 and one half tiles were equal to 2.5 lbs.

The speed reducer increased the power of the motor, but decreased its speed significantly.

All the experiments were done at least three times each to get accurate results, and the average data was calculated and used for comparisons and conclusions.

It is important to note that in motor #1 voltages in excess of 6 volts created a visible spark between the contacts inside the reed switch tube. In motor #2 even the voltage of 3 volts created a visible spark between the contacts inside the reed switch tubes. As it was mentioned earlier, sometimes this welds the contacts together. This problem was encountered many times during the testing, but only on these two motors. After a few hours of work on high voltage settings, these motors stopped working for a few moments, but restarted later. Heavy-duty reed switches were used in motors #1, #2, and #3 to reduce this problem.

9. Results

The results for all the experiments were recorded in the tables on the next pages. As mentioned earlier, the speed measurements were taken three times each to get accurate results. The average speed was then calculated.

The current represented the average value as due to the nature of the motors the current goes through the coil only when the reed switch is closed, or there is a signal from the sensor.

One of the columns shows the power in watts. It was calculated by multiplying the current, in amperes, by the voltage, in volts.

For visual representation of the data many different graphs were made. However, only the most significant are shown and described later in this chapter.

Motor #1

	Setting	Speed			Power W	Average Speed	Current A
2 Volts	No Weight	2014	2129	2148	0.2	2097.0	0.1
	Hooked	1018	936	987	0.2	980.3	0.1
	0.5 lbs	900	951	931	0.2	927.3	0.1
	1 lbs	797	764	783	0.2	781.3	0.1
	1.5 lbs	689	589	643	0.2	640.3	0.1
	2 lbs	519	572	537	0.2	542.7	0.1
	2.5 lbs	467	455	461	0.2	461.0	0.1
	3 lbs	339	328	334	0.3	333.7	0.15
	3.5 lbs	**X**	**X**	**X**			

	Setting	Speed			Power W	Average Speed	Current A
3 Volts	No Weight	2595	2940	2743	0.6	2759.3	0.2
	Hooked	1277	1255	1266	0.6	1266.0	0.2
	0.5 lbs	1265	1144	1213	0.6	1207.3	0.2
	1 lbs	758	736	732	0.6	742.0	0.2
	1.5 lbs	601	621	632	0.6	618.0	0.2
	2 lbs	589	576	598	0.6	587.7	0.2
	2.5 lbs	545	521	528	0.6	531.3	0.2
	3 lbs	401	412	406	0.6	406.3	0.2
	3.5 lbs	320	327	313	0.6	320.0	0.2

	Setting	Speed			Power W	Average Speed	Current A
4 Volts	No Weight	2960	2748	2970	1.2	2892.7	0.3
	Hooked	1613	1583	1598	1.2	1598.0	0.3
	0.5 lbs	1498	1500	1499	1.0	1499.0	0.25
	1 lbs	1324	1288	1293	1.0	1301.7	0.25
	1.5 lbs	1370	1345	1323	1.0	1346.0	0.25
	2 lbs	1289	1299	1294	1.2	1294.0	0.3
	2.5 lbs	1083	1083	1087	1.2	1084.3	0.3
	3 lbs	875	883	878	1.2	878.7	0.3
	3.5 lbs	357	353	354	1.0	354.7	0.25

	Setting	Speed			Power W	Average Speed	Current A
5 Volts	No Weight	2989	3005	2879	1.3	2957.7	0.25
	Hooked	1901	1900	1921	1.5	1907.3	0.3
	0.5 lbs	1827	1852	1834	1.5	1837.7	0.3
	1 lbs	1535	1474	1501	1.5	1503.3	0.3
	1.5 lbs	1586	1519	1521	1.5	1542.0	0.3
	2 lbs	1859	1909	1874	1.5	1880.7	0.3
	2.5 lbs	1207	1407	1336	1.3	1316.7	0.25
	3 lbs	1032	1067	1051	1.75	1050.0	0.35
	3.5 lbs	554	569	557	1.5	560.0	0.3

	Setting	Speed			Power W	Average Speed	Current A
6 Volts	No Weight	3195	3034	3063	2.1	3097.3	0.35
	Hooked	2109	2150	2143	1.8	2134.0	0.3
	0.5 lbs	1676	1673	1675	1.8	1674.7	0.3
	1 lbs	1402	1432	1428	1.8	1420.7	0.3
	1.5 lbs	1330	1308	1323	1.8	1320.3	0.3
	2 lbs	1581	1554	1568	2.1	1567.7	0.35
	2.5 lbs	1225	1172	1203	1.8	1200.0	0.3
	3 lbs	1165	1169	1167	1.8	1167.0	0.3
	3.5 lbs	813	801	807	1.8	807.0	0.3

	Setting	Speed			Power W	Average Speed	Current A
7 Volts	No Weight	3293	3372	3423	2.8	3362.7	0.4
	Hooked	2427	2438	2417	2.1	2427.3	0.3
	0.5 lbs	2217	2217	2221	2.1	2218.3	0.3
	1 lbs	1517	1455	1478	2.1	1483.3	0.3
	1.5 lbs	1494	1511	1503	2.1	1502.7	0.3
	2 lbs	2329	2102	2256	2.5	2229.0	0.35
	2.5 lbs	1011	1196	1131	2.1	1112.7	0.3
	3 lbs	1321	1376	1318	2.1	1338.3	0.3
	3.5 lbs	761	750	756	2.1	755.7	0.3

	Setting	Speed			Power W	Average Speed	Current A
8 Volts	No Weight	3542	3684	3864	2.8	3696.7	0.35
	Hooked	2822	2769	2793	2.8	2794.7	0.35
	0.5 lbs	2646	2686	2671	3.2	2667.7	0.4
	1 lbs	1780	1785	1769	2.4	1778.0	0.3
	1.5 lbs	1406	1433	1421	2.4	1420.0	0.3
	2 lbs	1395	1352	1327	2.8	1358.0	0.35
	2.5 lbs	1267	1264	1262	2.4	1264.3	0.3
	3 lbs	1157	1154	1156	2.4	1155.7	0.3
	3.5 lbs	665	618	679	2.4	654.0	0.3

Motor #2

	Setting	Speed			Power W	Average Speed	Current A
2 Volts	No Weight	3260	3510	3395	0.6	3388.3	0.3
	Hooked	1147	934	1122	0.7	1067.7	0.35
	0.5 lbs	1462	1242	1840	0.6	1514.7	0.3
	1 lbs	1573	1078	1075	0.6	1242.0	0.3
	1.5 lbs	X	X	X			
	2 lbs	X	X	X			
	2.5 lbs	X	X	X			
	3 lbs	X	X	X			
	3.5 lbs	X	X	X			

	Setting	Speed			Power W	Average Speed	Current A
3 Volts	No Weight	6129	6028	6121	0.9	6092.7	0.3
	Hooked	3021	3001	2976	1.2	2999.3	0.4
	0.5 lbs	2285	2358	2363	0.9	2335.3	0.3
	1 lbs	1644	1246	1610	0.9	1500.0	0.3
	1.5 lbs	X	X	X			
	2 lbs	X	X	X			
	2.5 lbs	X	X	X			
	3 lbs	X	X	X			
	3.5 lbs	X	X	X			

	Setting	Speed			Power W	Average Speed	Current A
4 Volts	No Weight	6598	7968	6028	1.4	6864.7	0.35
	Hooked	1595	1303	1481	1.6	1459.7	0.4
	0.5 lbs	2414	2063	2248	1.2	2241.7	0.3
	1 lbs	2408	2243	1502	1.2	2051.0	0.3
	1.5 lbs	1596	1978	1754	1.2	1776.0	0.3
	2 lbs	X	X	X			
	2.5 lbs	X	X	X			
	3 lbs	X	X	X			
	3.5 lbs	X	X	X			

	Setting	Speed			Power W	Average Speed	Current A
5 Volts	No Weight	8508	7566	7780	1.5	7951.3	0.3
	Hooked	X	X	X			
	0.5 lbs	X	X	X			
	1 lbs	X	X	X			
	1.5 lbs	X	X	X			
	2 lbs	X	X	X			
	2.5 lbs	X	X	X			
	3 lbs	X	X	X			
	3.5 lbs	X	X	X			

	Setting	Speed			Power W	Average Speed	Current A
6 Volts	No Weight	X	X	X			
	Hooked	X	X	X			
	0.5 lbs	X	X	X			
	1 lbs	X	X	X			
	1.5 lbs	X	X	X			
	2 lbs	X	X	X			
	2.5 lbs	X	X	X			
	3 lbs	X	X	X			
	3.5 lbs	X	X	X			

	Setting	Speed			Power W	Average Speed	Current A
7 Volts	No Weight	X	X	X			
	Hooked	X	X	X			
	0.5 lbs	X	X	X			
	1 lbs	X	X	X			
	1.5 lbs	X	X	X			
	2 lbs	X	X	X			
	2.5 lbs	X	X	X			
	3 lbs	X	X	X			
	3.5 lbs	X	X	X			

	Setting	Speed			Power W	Average Speed	Current A
8 Volts	No Weight	X	X	X			
	Hooked	X	X	X			
	0.5 lbs	X	X	X			
	1 lbs	X	X	X			
	1.5 lbs	X	X	X			
	2 lbs	X	X	X			
	2.5 lbs	X	X	X			
	3 lbs	X	X	X			
	3.5 lbs	X	X	X			

Motor #3

	Setting	Speed			Power W	Average Speed	Current A
2 Volts	No Weight	1360	1690	1333	0.1	1461.0	0.05
	Hooked	408	471	447	0.1	442.0	0.05
	0.5 lbs	X	X	X			
	1 lbs	X	X	X			
	1.5 lbs	X	X	X			
	2 lbs	X	X	X			
	2.5 lbs	X	X	X			
	3 lbs	X	X	X			
	3.5 lbs	X	X	X			

	Setting	Speed			Power W	Average Speed	Current A
3 Volts	No Weight	2429	2166	2233	0.2	2276.0	0.05
	Hooked	1293	1264	1286	0.2	1281.0	0.05
	0.5 lbs	1190	1186	1188	0.3	1188.0	0.1
	1 lbs	971	997	981	0.3	983.0	0.1
	1.5 lbs	637	658	646	0.3	647.0	0.1
	2 lbs	568	564	566	0.3	566.0	0.1
	2.5 lbs	530	564	531	0.3	541.7	0.1
	3 lbs	X	X	X			
	3.5 lbs	X	X	X			

	Setting	Speed			Power W	Average Speed	Current A
4 Volts	No Weight	2745	2619	2423	0.2	2595.7	0.05
	Hooked	1691	1699	1694	0.4	1694.7	0.1
	0.5 lbs	1446	1319	1374	0.4	1379.7	0.1
	1 lbs	1261	1274	1266	0.4	1267.0	0.1
	1.5 lbs	1085	1147	1101	0.4	1111.0	0.1
	2 lbs	1003	1002	1005	0.4	1003.3	0.1
	2.5 lbs	898	937	912	0.4	915.7	0.1
	3 lbs	1072	942	998	0.4	1004.0	0.1
	3.5 lbs	667	670	669	0.6	668.7	0.15

	Setting	Speed			Power W	Average Speed	Current A
5 Volts	No Weight	2758	2816	2824	0.3	2799.3	0.05
	Hooked	1846	1859	1852	0.5	1852.3	0.1
	0.5 lbs	1360	1360	1345	0.5	1355.0	0.1
	1 lbs	1481	1114	1221	0.5	1272.0	0.1
	1.5 lbs	1421	1336	1379	0.5	1378.7	0.1
	2 lbs	1145	1212	1173	1	1176.7	0.2
	2.5 lbs	1110	1134	1122	1.0	1122.0	0.2
	3 lbs	1051	1119	1071	1	1080.3	0.2
	3.5 lbs	873	909	889	1	890.3	0.2

	Setting	Speed			Power W	Average Speed	Current A
6 Volts	No Weight	2825	3272	3047	0.3	3048.0	0.05
	Hooked	2095	2089	2092	0.6	2092.0	0.1
	0.5 lbs	1757	1770	1762	0.9	1763.0	0.15
	1 lbs	1645	1687	1658	0.9	1663.3	0.15
	1.5 lbs	1588	1629	1596	1.2	1604.3	0.2
	2 lbs	1395	1447	1412	1.2	1418.0	0.2
	2.5 lbs	1268	1311	1279	1.2	1286.0	0.2
	3 lbs	1209	1278	1227	1.2	1238.0	0.2
	3.5 lbs	1085	1060	1072	1.2	1072.3	0.2

	Setting	Speed			Power W	Average Speed	Current A
7 Volts	No Weight	3334	3250	3145	0.7	3243.0	0.1
	Hooked	2597	2611	2603	0.7	2603.7	0.1
	0.5 lbs	2027	2082	2039	1.4	2049.3	0.2
	1 lbs	1816	1863	1834	1.1	1837.7	0.15
	1.5 lbs	1728	1618	1658	1.4	1668.0	0.2
	2 lbs	1619	1647	1623	1.4	1629.7	0.2
	2.5 lbs	1430	1441	1436	1.4	1435.7	0.2
	3 lbs	1340	1340	1356	2.1	1345.3	0.3
	3.5 lbs	1232	1232	1236	1.4	1233.3	0.2

	Setting	Speed			Power W	Average Speed	Current A
8 Volts	No Weight	3300	3473	3286	0.8	3353.0	0.1
	Hooked	2764	2691	2731	0.8	2728.7	0.1
	0.5 lbs	2152	2311	2254	1.6	2239.0	0.2
	1 lbs	1997	2094	2010	1.6	2033.7	0.2
	1.5 lbs	1795	1723	1754	1.6	1757.3	0.2
	2 lbs	1754	1749	1752	1.6	1751.7	0.2
	2.5 lbs	1639	1705	1668	1.6	1670.7	0.2
	3 lbs	1523	1584	1549	2.4	1552.0	0.3
	3.5 lbs	1482	1395	1449	2.0	1442.0	0.25

Motor #4

	Setting	Speed			Power W	Average Speed	Current A
2 Volts	No Weight	1354	1343	1347	0.2	1348.0	0.1
	Hooked	841	851	842	0.2	844.7	0.1
	0.5 lbs	544	546	548	0.2	546.0	0.1
	1 lbs	399	368	386	0.2	384.3	0.1
	1.5 lbs	357	359	365	0.2	360.3	0.1
	2 lbs	X	X	X			
	2.5 lbs	X	X	X			
	3 lbs	X	X	X			
	3.5 lbs	X	X	X			

	Setting	Speed			Power W	Average Speed	Current A
3 Volts	No Weight	1832	1821	1816	0.6	1823.0	0.2
	Hooked	1189	1212	1201	0.6	1200.7	0.2
	0.5 lbs	877	882	877	0.6	878.7	0.2
	1 lbs	732	748	752	0.6	744.0	0.2
	1.5 lbs	647	691	673	0.6	670.3	0.2
	2 lbs	563	581	570	0.6	571.3	0.2
	2.5 lbs	456	501	484	0.6	480.3	0.2
	3 lbs	362	383	361	0.8	368.7	0.25
	3.5 lbs	X	X	X			

	Setting	Speed			Power W	Average Speed	Current A
4 Volts	No Weight	2003	2062	2047	1.0	2037.3	0.25
	Hooked	1463	1483	1474	1.2	1473.3	0.3
	0.5 lbs	1156	1123	1142	1.2	1140.3	0.3
	1 lbs	965	1021	978	1.2	988.0	0.3
	1.5 lbs	921	901	935	1.2	919.0	0.3
	2 lbs	755	781	763	1.2	766.3	0.3
	2.5 lbs	701	662	680	1.2	681.0	0.3
	3 lbs	569	587	581	1.2	579.0	0.3
	3.5 lbs	389	412	408	1.4	403.0	0.35

	Setting	Speed			Power W	Average Speed	Current A
5 Volts	No Weight	2458	2432	2443	2.0	2444.3	0.4
	Hooked	1770	1798	1771	2.3	1779.7	0.45
	0.5 lbs	1483	1435	1466	2.3	1461.3	0.45
	1 lbs	1256	1187	1218	2.3	1220.3	0.45
	1.5 lbs	1158	1177	1162	2.3	1165.7	0.45
	2 lbs	951	1009	957	2.3	972.3	0.45
	2.5 lbs	882	878	897	2.3	885.7	0.45
	3 lbs	754	771	769	2.3	764.7	0.45

	Setting	Speed			Power W	Average Speed	Current A
6 Volts	No Weight	2587	2612	2600	3.3	2599.7	0.55
	Hooked	1885	1914	1911	3.6	1903.3	0.6
	0.5 lbs	1810	1758	1790	3.6	1786.0	0.6
	1 lbs	1475	1423	1457	3.6	1451.7	0.6
	1.5 lbs	1376	1393	1384	3.6	1384.3	0.6
	2 lbs	1231	1187	1213	3.6	1210.3	0.6
	2.5 lbs	1057	1044	1046	3.6	1049.0	0.6
	3 lbs	884	921	903	3.6	902.7	0.6
	3.5 lbs	874	823	847	3.9	848.0	0.65

	Setting	Speed			Power W	Average Speed	Current A
7 Volts	No Weight	2836	2872	2861	4.9	2856.3	0.7
	Hooked	2295	2334	2315	5.6	2314.7	0.8
	0.5 lbs	1935	1919	1920	5.6	1924.7	0.8
	1 lbs	1732	1741	1740	5.6	1737.7	0.8
	1.5 lbs	1648	1685	1658	5.6	1663.7	0.8
	2 lbs	1433	1496	1479	5.6	1469.3	0.8
	2.5 lbs	1299	1330	1326	6.0	1318.3	0.85
	3 lbs	1222	1252	1234	5.95	1236.0	0.85
	3.5 lbs	1121	1085	1094	5.95	1100.0	0.85

	Setting	Speed			Power W	Average Speed	Current A
8 Volts	No Weight	3085	3132	3124	7.2	3113.7	0.9
	Hooked	2498	2426	2465	7.6	2463.0	0.95
	0.5 lbs	2343	2299	2329	7.6	2323.7	0.95
	1 lbs	2265	2198	2223	7.6	2228.7	0.95
	1.5 lbs	1901	1998	1944	7.6	1947.7	0.95
	2 lbs	1672	1702	1691	7.6	1688.3	0.95
	2.5 lbs	1534	1600	1565	7.6	1566.3	0.95
	3 lbs	1457	1426	1433	7.6	1438.7	0.95
	3.5 lbs	1225	1189	1234	8	1216.0	1

Motor #5

	Setting	Speed			Power W	Average Speed	Current A
2 Volts	No Weight	X	X	X			
	Hooked	X	X	X			
	0.5 lbs	X	X	X			
	1 lbs	X	X	X			
	1.5 lbs	X	X	X			
	2 lbs	X	X	X			
	2.5 lbs	X	X	X			
	3 lbs	X	X	X			
	3.5 lbs	X	X	X			

	Setting	Speed			Power W	Average Speed	Current A
3 Volts	No Weight	1903	1887	1914	0.3	1901.3	0.1
	Hooked	1576	1542	1568	0.6	1562.0	0.2
	0.5 lbs	1145	1151	1159	0.6	1151.7	0.2
	1 lbs	788	804	793	0.6	795.0	0.2
	1.5 lbs	X	X	X			
	2 lbs	X	X	X			
	2.5 lbs	X	X	X			
	3 lbs	X	X	X			
	3.5 lbs	X	X	X			

	Setting	Speed			Power W	Average Speed	Current A
4 Volts	No Weight	2823	2765	2792	1.2	2793.3	0.3
	Hooked	2057	2106	2101	1.2	2088.0	0.3
	0.5 lbs	1574	1601	1606	1.2	1593.7	0.3
	1 lbs	1358	1312	1341	1.2	1337.0	0.3
	1.5 lbs	1119	1080	1111	1.2	1103.3	0.3
	2 lbs	952	974	947	1.4	957.7	0.35
	2.5 lbs	723	716	721	1.4	720.0	0.35
	3 lbs	612	584	603	1.4	599.7	0.35
	3.5 lbs	X	X	X			

	Setting	Speed			Power W	Average Speed	Current A
5 Volts	No Weight	3334	3289	3323	2.0	3315.3	0.4
	Hooked	2212	2256	2240	2.0	2236.0	0.4
	0.5 lbs	1901	1883	1873	2.0	1885.7	0.4
	1 lbs	1578	1580	1575	2.0	1577.7	0.4
	1.5 lbs	1227	1198	1215	2.0	1213.3	0.4
	2 lbs	1102	1075	1071	2.0	1082.7	0.4
	2.5 lbs	883	852	861	2.3	865.3	0.45
	3 lbs	699	722	697	2.5	706.0	0.5
	3.5 lbs	X	X	X	0		

	Setting	Speed			Power W	Average Speed	Current A
6 Volts	No Weight	3702	3668	3664	3.6	3678.0	0.6
	Hooked	2373	2391	2389	3.6	2384.3	0.6
	0.5 lbs	2294	2275	2288	3.6	2285.7	0.6
	1 lbs	1856	1865	1850	3.6	1857.0	0.6
	1.5 lbs	1685	1659	1664	3.6	1669.3	0.6
	2 lbs	1297	1321	1311	3.6	1309.7	0.6
	2.5 lbs	1150	1132	1149	3.6	1143.7	0.6
	3 lbs	832	889	861	3.9	860.7	0.65
	3.5 lbs	**X**	**X**	**X**			

	Setting	Speed			Power W	Average Speed	Current A
7 Volts	No Weight	3902	3874	3893	4.9	3889.7	0.7
	Hooked	3175	3137	3162	4.9	3158.0	0.7
	0.5 lbs	2485	2436	2477	4.9	2466.0	0.7
	1 lbs	2313	2236	2282	4.9	2277.0	0.7
	1.5 lbs	1835	1787	1797	4.9	1806.3	0.7
	2 lbs	1598	1613	1591	4.9	1600.7	0.7
	2.5 lbs	1187	1235	1205	5.3	1209.0	0.75
	3 lbs	978	1016	1039	5.25	1011.0	0.75
	3.5 lbs	797	765	817	5.25	793.0	0.75

	Setting	Speed			Power W	Average Speed	Current A
8 Volts	No Weight	4365	4336	4341	6.4	4347.3	0.8
	Hooked	3465	3534	3510	7.2	3503.0	0.9
	0.5 lbs	2934	2898	2929	7.6	2920.3	0.95
	1 lbs	2335	2365	2377	8.0	2359.0	1
	1.5 lbs	1985	2000	2016	8.0	2000.3	1
	2 lbs	1597	1603	1607	8.0	1602.3	1
	2.5 lbs	1367	1365	1354	8.0	1362.0	1
	3 lbs	1134	1175	1151	8	1153.3	1
	3.5 lbs	1054	1072	1066	8	1064.0	1

Motor #6

	Setting	Speed			Power W	Average Speed	Current
2 Volts	No Weight	846	853	838	0.1	845.7	0.05
	Hooked	225	222	211	0.2	219.3	0.1
	0.5 lbs	X	X	X			
	1 lbs	X	X	X			
	1.5 lbs	X	X	X			
	2 lbs	X	X	X			
	2.5 lbs	X	X	X			
	3 lbs	X	X	X			
	3.5 lbs	X	X	X			

	Setting	Speed			Power W	Average Speed	Current
3 Volts	No Weight	1101	1064	1062	0.3	1075.7	0.1
	Hooked	577	528	548	0.5	551.0	0.15
	0.5 lbs	453	470	461	0.3	461.3	0.1
	1 lbs	455	453	455	0.5	454.3	0.15
	1.5 lbs	328	291	303	0.5	307.3	0.15
	2 lbs	286	262	271	0.6	273.0	0.2
	2.5 lbs	X	X	X			
	3 lbs	X	X	X			
	3.5 lbs	X	X	X			

	Setting	Speed			Power W	Average Speed	Current
4 Volts	No Weight	1246	1292	1349	0.8	1295.7	0.2
	Hooked	678	640	661	0.8	659.7	0.2
	0.5 lbs	581	590	593	0.8	588.0	0.2
	1 lbs	576	603	581	0.8	586.7	0.2
	1.5 lbs	517	487	480	0.8	494.7	0.2
	2 lbs	480	455	473	0.8	469.3	0.2
	2.5 lbs	465	408	432	0.8	435.0	0.2
	3 lbs	373	376	378	1.0	375.7	0.25
	3.5 lbs	372	365	342	0.8	359.7	0.2

	Setting	Speed			Power W	Average Speed	Current
5 Volts	No Weight	1643	1519	1547	1.3	1569.7	0.25
	Hooked	874	757	813	1.5	814.7	0.3
	0.5 lbs	722	737	729	1.5	729.3	0.3
	1 lbs	667	687	673	1.5	675.7	0.3
	1.5 lbs	667	588	623	1.5	626.0	0.3
	2 lbs	645	616	609	1.5	623.3	0.3
	2.5 lbs	600	617	594	1.5	603.7	0.3
	3 lbs	611	589	583	1.75	594.3	0.35
	3.5 lbs	543	523	532	1.5	532.7	0.3

6 Volts	Setting	Speed			Power W	Average Speed	Current
	No Weight	1736	1728	1698	2.4	1720.7	0.4
	Hooked	1064	1096	1078	2.1	1079.3	0.35
	0.5 lbs	1039	1076	1021	1.8	1045.3	0.3
	1 lbs	1026	908	942	2.1	958.7	0.35
	1.5 lbs	872	882	864	1.8	872.7	0.3
	2 lbs	794	815	799	1.8	802.7	0.3
	2.5 lbs	655	685	658	1.8	666.0	0.3
	3 lbs	604	596	600	2.7	600.0	0.45
	3.5 lbs	585	574	568	1.8	575.7	0.3

7 Volts	Setting	Speed			Power W	Average Speed	Current
	No Weight	2595	2582	2625	3.2	2600.7	0.45
	Hooked	1318	1356	1367	2.8	1347.0	0.4
	0.5 lbs	1400	1390	1401	2.5	1397.0	0.35
	1 lbs	1226	1253	1237	2.8	1238.7	0.4
	1.5 lbs	1164	993	1054	2.5	1070.3	0.35
	2 lbs	950	929	941	2.5	940.0	0.35
	2.5 lbs	808	832	817	2.5	819.0	0.35
	3 lbs	699	741	721	2.8	720.3	0.4
	3.5 lbs	676	666	683	2.5	675.0	0.35

8 Volts	Setting	Speed			Power W	Average Speed	Current
	No Weight	3369	3370	3398	3.2	3379.0	0.4
	Hooked	1592	1651	1622	3.2	1621.7	0.4
	0.5 lbs	1537	1483	1503	3.2	1507.7	0.4
	1 lbs	1439	1470	1457	3.2	1455.3	0.4
	1.5 lbs	1337	1372	1352	3.2	1353.7	0.4
	2 lbs	1127	1003	1071	3.2	1067.0	0.4
	2.5 lbs	900	868	872	3.6	880.0	0.45
	3 lbs	821	838	821	3.2	826.7	0.4
	3.5 lbs	743	813	801	3.2	785.7	0.4

Motor #7

	Setting	Speed			Power W	Average Speed	Current
2 Volts	No Weight	765	801	783	0.4	783.0	0.2
	Hooked	X	X	X			
	0.5 lbs	X	X	X			
	1 lbs	X	X	X			
	1.5 lbs	X	X	X			
	2 lbs	X	X	X			
	2.5 lbs	X	X	X			
	3 lbs	X	X	X			
	3.5 lbs	X	X	X			

	Setting	Speed			Power W	Average Speed	Current
3 Volts	No Weight	2511	2301	2283	0.3	2365.0	0.1
	Hooked	1584	1547	1526	0.3	1552.3	0.1
	0.5 lbs	1244	1222	1234	0.3	1233.3	0.1
	1 lbs	796	853	812	0.3	820.3	0.1
	1.5 lbs	615	650	640	0.3	635.0	0.1
	2 lbs	X	X	X			
	2.5 lbs	X	X	X			
	3 lbs	X	X	X			
	3.5 lbs	X	X	X			

	Setting	Speed			Power W	Average Speed	Current
4 Volts	No Weight	3024	2768	2810	0.8	2867.3	0.2
	Hooked	2206	2302	2304	0.8	2270.7	0.2
	0.5 lbs	1924	1826	1923	0.8	1891.0	0.2
	1 lbs	1561	1618	1581	0.8	1586.7	0.2
	1.5 lbs	1336	1357	1341	0.8	1344.7	0.2
	2 lbs	1159	1158	1201	0.8	1172.7	0.2
	2.5 lbs	818	782	797	0.8	799.0	0.2
	3 lbs	810	760	783	0.8	784.3	0.2
	3.5 lbs	627	616	821	0.8	688.0	0.2

	Setting	Speed			Power W	Average Speed	Current
5 Volts	No Weight	3116	3053	3245	1.3	3138.0	0.25
	Hooked	2661	2696	2567	1.5	2641.3	0.3
	0.5 lbs	2163	2325	2273	1.3	2253.7	0.25
	1 lbs	2060	2013	2113	1.5	2062.0	0.3
	1.5 lbs	1700	1650	1673	1.3	1674.3	0.25
	2 lbs	1590	1478	1543	1.5	1537.0	0.3
	2.5 lbs	1279	1221	1251	1.3	1250.3	0.25
	3 lbs	1050	1052	1032	1.75	1044.7	0.35
	3.5 lbs	782	868	813	1.5	821.0	0.3

	Setting	Speed			Power W	Average Speed	Current
6 Volts	No Weight	3345	3425	3601	2.1	3457.0	0.35
	Hooked	2869	2912	2749	2.1	2843.3	0.35
	0.5 lbs	2488	2554	2503	2.1	2515.0	0.35
	1 lbs	2362	2435	2402	2.1	2399.7	0.35
	1.5 lbs	2084	2041	2018	2.1	2047.7	0.35
	2 lbs	1797	1853	1823	2.4	1824.3	0.4
	2.5 lbs	1581	1496	1532	1.8	1536.3	0.3
	3 lbs	1270	1059	1156	2.1	1161.7	0.35
	3.5 lbs	993	802	735	1.8	843.3	0.3

	Setting	Speed			Power W	Average Speed	Current
7 Volts	No Weight	3727	3724	3734	2.8	3728.3	0.4
	Hooked	3196	3051	3080	2.8	3109.0	0.4
	0.5 lbs	2629	2779	2692	2.1	2700.0	0.3
	1 lbs	2054	1857	1943	2.8	1951.3	0.4
	1.5 lbs	1863	1829	1843	2.5	1845.0	0.35
	2 lbs	1668	1735	1708	2.5	1703.7	0.35
	2.5 lbs	1634	1580	1621	2.5	1611.7	0.35
	3 lbs	1314	1312	1389	2.5	1338.3	0.35
	3.5 lbs	981	820	851	2.5	884.0	0.35

	Setting	Speed			Power W	Average Speed	Current
8 Volts	No Weight	3818	3770	4010	3.2	3866.0	0.4
	Hooked	2793	2734	2732	3.2	2753.0	0.4
	0.5 lbs	2273	2246	2261	2.8	2260.0	0.35
	1 lbs	2103	2141	2123	3.2	2122.3	0.4
	1.5 lbs	2051	2041	2031	2.8	2041.0	0.35
	2 lbs	1782	1746	1748	3.2	1758.7	0.4
	2.5 lbs	1634	1678	1682	2.8	1664.7	0.35
	3 lbs	1514	1500	1532	3.2	1515.3	0.4
	3.5 lbs	1463	1434	1475	2.8	1457.3	0.35

Motor #8

	Setting	Speed			Power W	Average Speed	Current
2 Volts	No Weight	X	X	X			
	Hooked	X	X	X			
	0.5 lbs	X	X	X			
	1 lbs	X	X	X			
	1.5 lbs	X	X	X			
	2 lbs	X	X	X			
	2.5 lbs	X	X	X			
	3 lbs	X	X	X			
	3.5 lbs	X	X	X			

	Setting	Speed			Power W	Average Speed	Current
3 Volts	No Weight	2428	2435	2419	0.6	2427.3	0.2
	Hooked	1282	1271	1292	0.6	1281.7	0.2
	0.5 lbs	1015	1001	1009	0.6	1008.3	0.2
	1 lbs	924	900	934	0.6	919.3	0.2
	1.5 lbs	753	776	749	0.6	759.3	0.2
	2 lbs	636	626	621	0.6	627.7	0.2
	2.5 lbs	537	521	551	0.6	536.3	0.2
	3 lbs	496	508	481	0.6	495.0	0.2
	3.5 lbs	X	X	X			

	Setting	Speed			Power W	Average Speed	Current
4 Volts	No Weight	2891	2913	2876	1.2	2893.3	0.3
	Hooked	1646	1661	1632	1.2	1646.3	0.3
	0.5 lbs	1410	1398	1401	1.2	1403.0	0.3
	1 lbs	1293	1308	1281	1.2	1294.0	0.3
	1.5 lbs	1085	1101	1071	1.2	1085.7	0.3
	2 lbs	929	903	941	1.2	924.3	0.3
	2.5 lbs	833	811	839	1.2	827.7	0.3
	3 lbs	741	712	721	1.2	724.7	0.3
	3.5 lbs	638	602	657	1.2	632.3	0.3

	Setting	Speed			Power W	Average Speed	Current
5 Volts	No Weight	3288	3303	3281	2.0	3290.7	0.4
	Hooked	2020	2051	2001	2	2024.0	0.4
	0.5 lbs	1740	1756	1712	2.0	1736.0	0.4
	1 lbs	1482	1503	1461	2	1482.0	0.4
	1.5 lbs	1302	1298	1287	2.0	1295.7	0.4
	2 lbs	1202	1198	1181	2	1193.7	0.4
	2.5 lbs	1048	1056	1036	2.0	1046.7	0.4
	3 lbs	958	934	975	2	955.7	0.4
	3.5 lbs	924	904	934	2.0	920.7	0.4

	Setting	Speed			Power W	Average Speed	Current
6 Volts	No Weight	3752	3764	3739	3.0	3751.7	0.5
	Hooked	2447	2456	2435	3	2446.0	0.5
	0.5 lbs	2040	2051	2048	3.0	2046.3	0.5
	1 lbs	1861	1848	1863	3	1857.3	0.5
	1.5 lbs	1701	1734	1685	3.0	1706.7	0.5
	2 lbs	1575	1579	1586	3	1580.0	0.5
	2.5 lbs	1403	1387	1712	3.0	1500.7	0.5
	3 lbs	1331	1315	1349	3.3	1331.7	0.55
	3.5 lbs	1193	1212	1201	3.3	1202.0	0.55

	Setting	Speed			Power W	Average Speed	Current
7 Volts	No Weight	4092	4103	4086	4.2	4093.7	0.6
	Hooked	2707	2688	2696	4.2	2697.0	0.6
	0.5 lbs	2428	2434	2421	4.2	2427.7	0.6
	1 lbs	2245	2249	2222	4.2	2238.7	0.6
	1.5 lbs	1919	1924	1910	4.2	1917.7	0.6
	2 lbs	1726	1712	1754	4.2	1730.7	0.6
	2.5 lbs	1623	1632	1612	4.6	1622.3	0.65
	3 lbs	1533	1525	1554	4.55	1537.3	0.65
	3.5 lbs	1248	1237	1259	4.9	1248.0	0.7

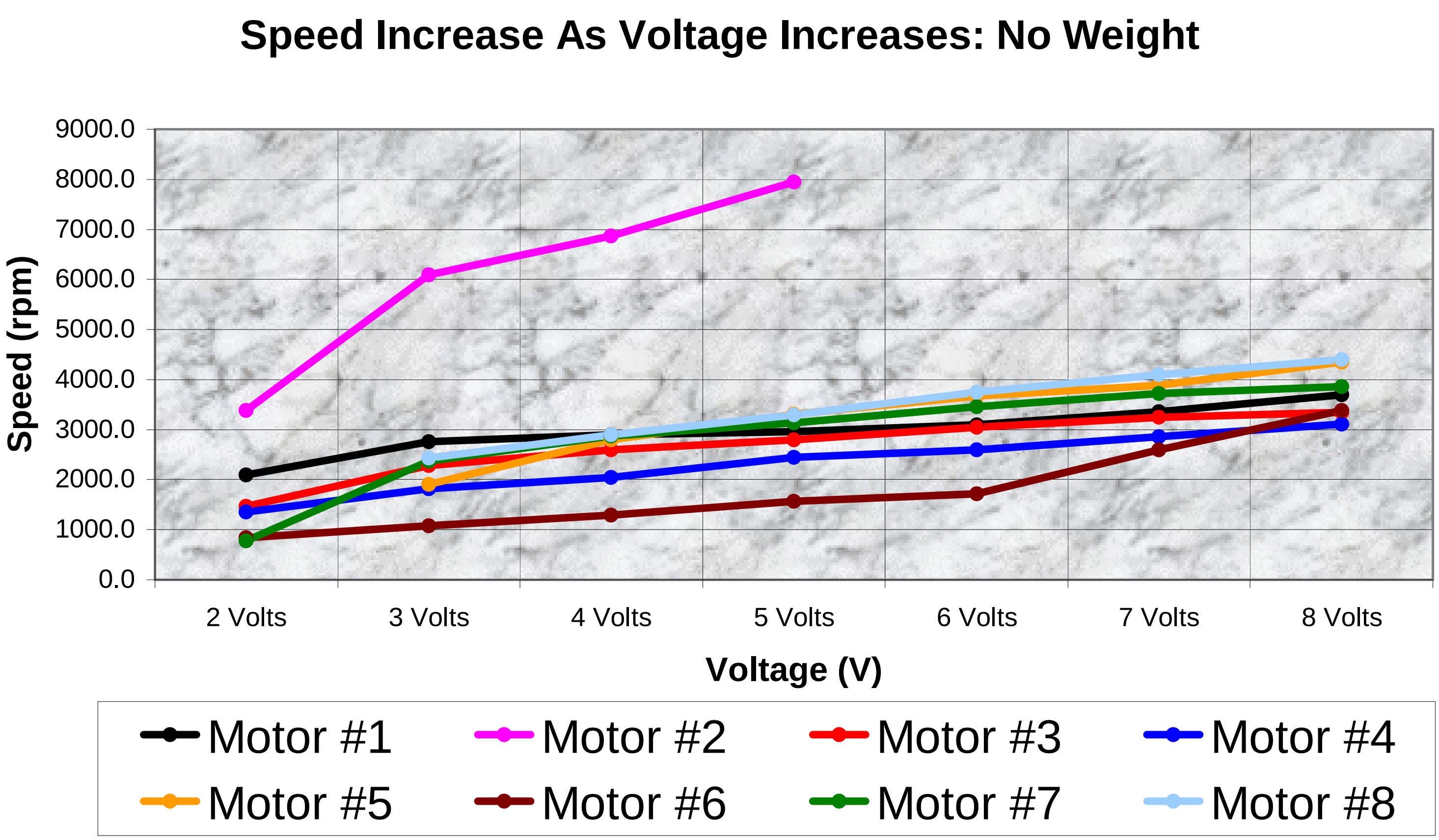
	Setting	Speed			Power W	Average Speed	Current
8 Volts	No Weight	4412	4395	4406	5.2	4404.3	0.65
	Hooked	3287	3301	3282	5.6	3290.0	0.7
	0.5 lbs	2786	2767	2776	5.6	2776.3	0.7
	1 lbs	2600	2566	2561	6	2575.7	0.75
	1.5 lbs	2364	2353	2357	6.4	2358.0	0.8
	2 lbs	2213	2186	2195	6.8	2198.0	0.85
	2.5 lbs	2098	2159	2120	6.8	2125.7	0.85
	3 lbs	2002	2013	2049	7.2	2021.3	0.9
	3.5 lbs	1918	1902	1940	7.2	1920.0	0.9

Maximum Load

The table below represents experimental data that shows the maximum load for each motor on different voltages. The maximum weight that was used in this experiment was 10 lbs.

Some of the motors were unable to lift any weight on certain voltages, such as 2 volts. Motor #2 did not work on voltages higher than 5 volts. Motor #8 was able to lift more than 10 lbs on higher voltages. However, the actual number was not recorded, because it was not necessary for comparison purposes.

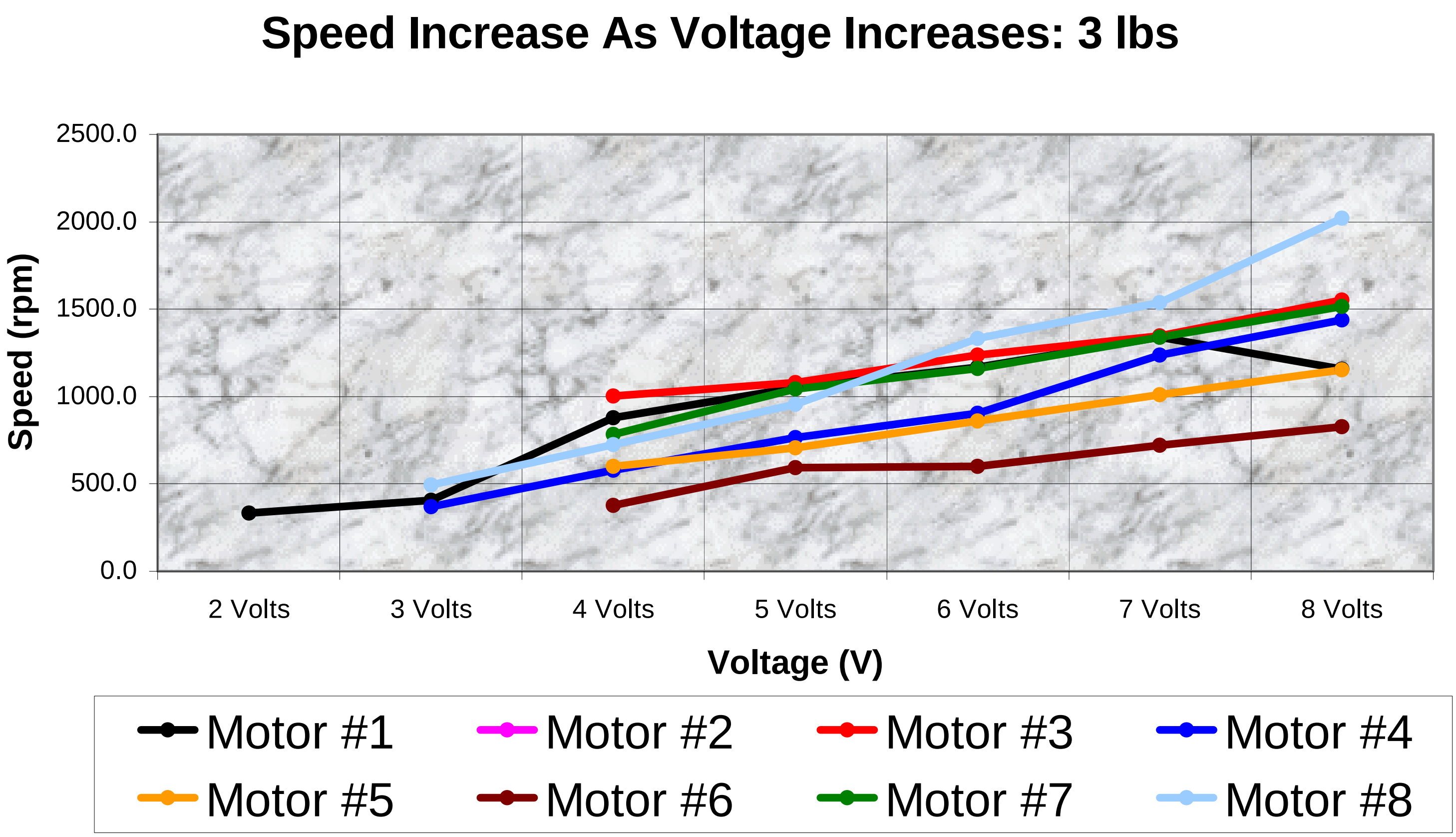
	Motor #1	Motor #2	Motor #3	Motor #4	Motor #5	Motor #6	Motor #7	Motor #8
2 Volts	3	1	X	1.5	X	X	X	X
3 Volts	4.5	1	2.5	3	1	2	1.5	3
4 Volts	6	1.5	3	6	3	3.5	2.5	6
5 Volts	7.5	X	4.5	7.5	3	5	4.5	9
6 Volts	8.5	X	6	8	3	6.5	6	10
7 Volts	9	X	7.5	9	4.5	7.5	7	>10
8 Volts	9.5	X	8	10	5	9	8	>10



This graph demonstrates how the speed increases with the voltage growth for all 8 motors. The motor was not attached to the speed reducer for this testing.

Motor #2 was not able to work beyond 5 volts, because the spark in the glass tube welded the contacts together. Although it could not operate at those voltages, this motor provided the best results in speed testing. It is also notable that motor #5 and #8 were not able to start working on 2 volts, but they provided very positive results on higher voltages. The rest of the motors had very similar results, while motor #6 under performed in this test.

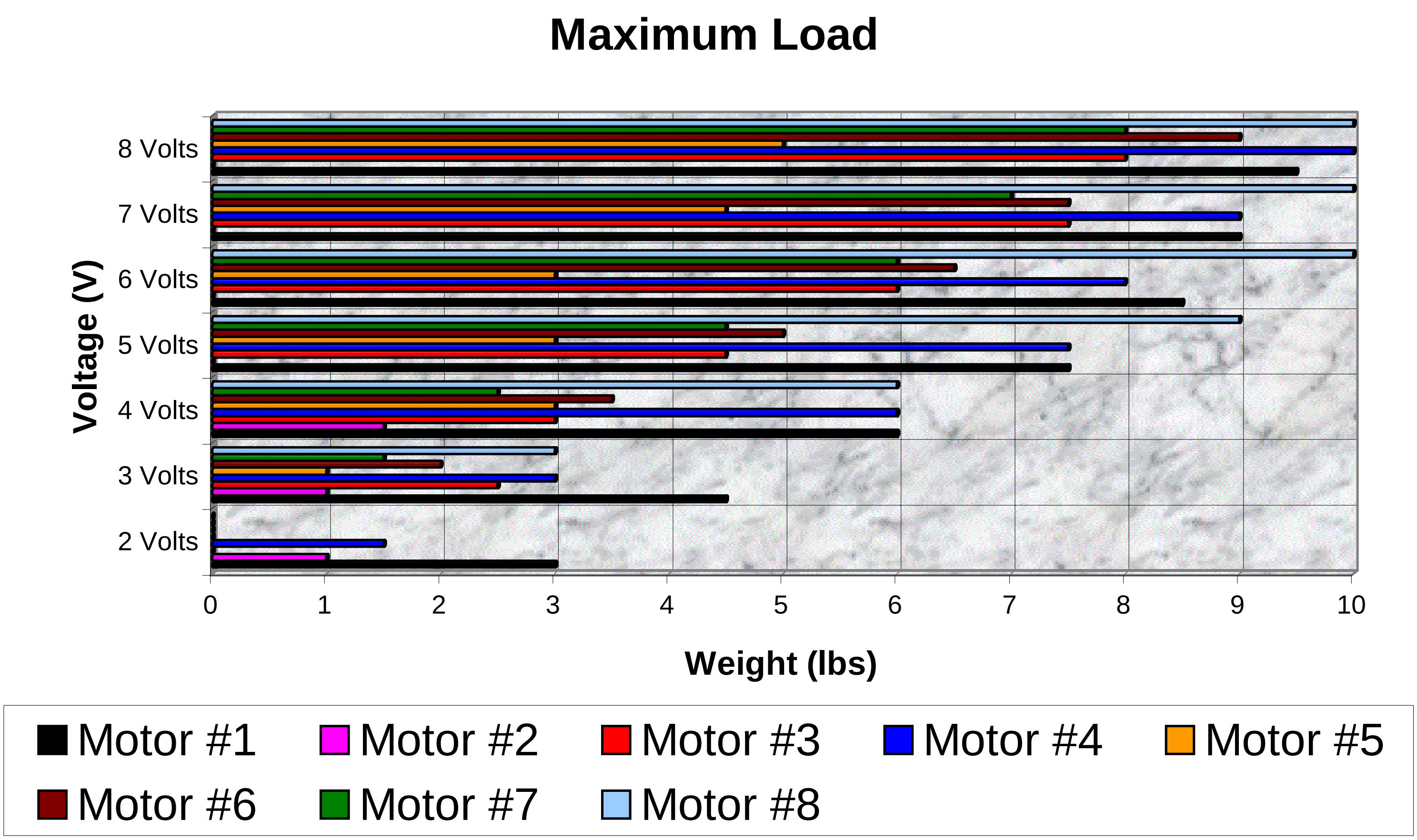
The speed changed dramatically from 783 rpm on 2 volts on motor #7, to 7951 rpm on 5 volts on motor #2.



This graph is similar to the one on the previous page. It demonstrates how the speed increases with voltage growth for all 8 motors when the motors were lifting 3 lbs.

Some motors were only able to perform on certain voltages, while motor #2 couldn't work at all. Motor #1 was the only motor that was able to lift this weight on 2 volts. Once again, motor #6 under performed in this test. It is notable that motor #8 provided the best results, while motors #3 and #7 also performed well.

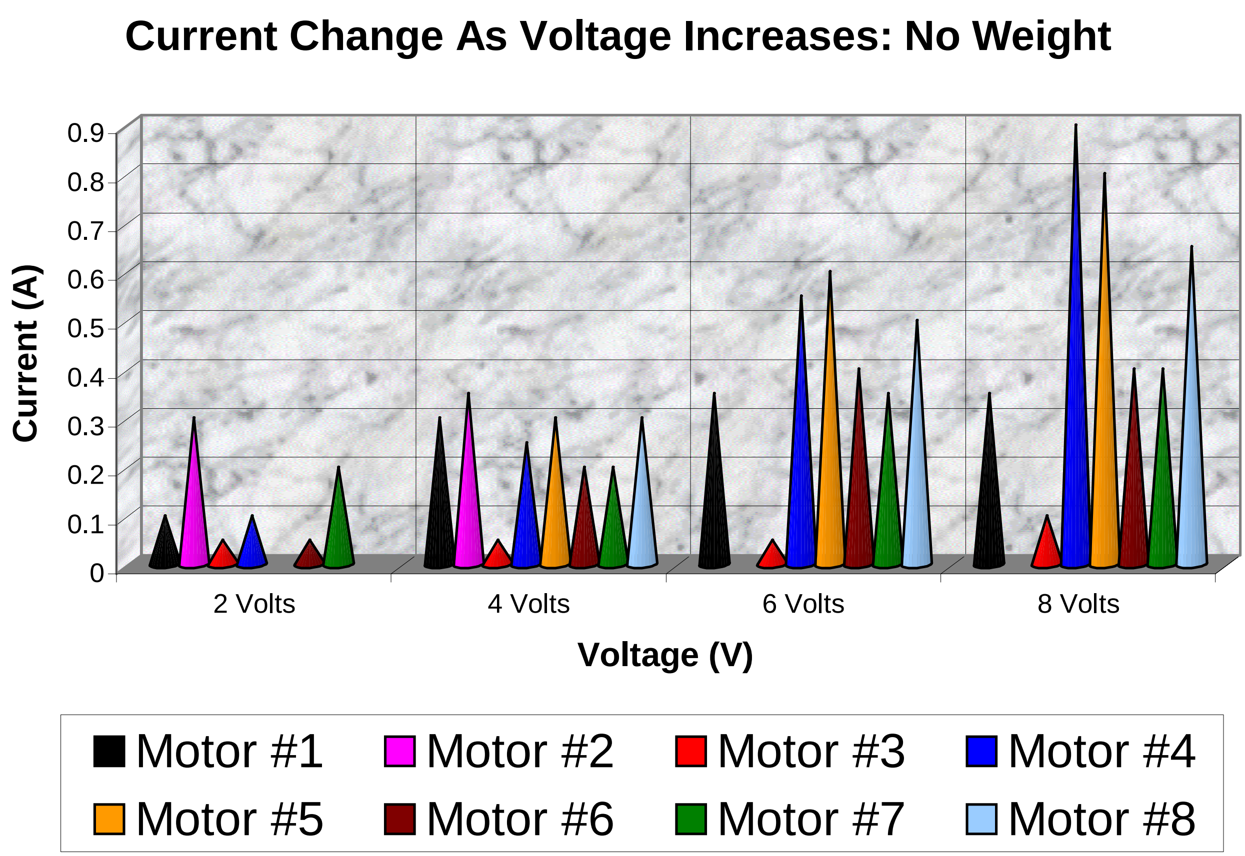
The registered speed was in the range from 333 rpm for motor #1 on 2 volts to 2021 rpm for motor #8 on 8 volts.



This graph shows how much weight each motor can lift on all the different voltage settings. It is easy to see that the voltage growth increases the power of each motor.

Motor #8 showed the best results, while motor #1, #4, and #6 also performed well. Motor #2 under performed in this test because it was not able to work on voltage settings higher than 4 volts and could not lift more than 1.5 lbs. Motor #5 also showed lower results. Some of the motors were not powerful to lift any weights on certain voltage settings such as 2 volts.

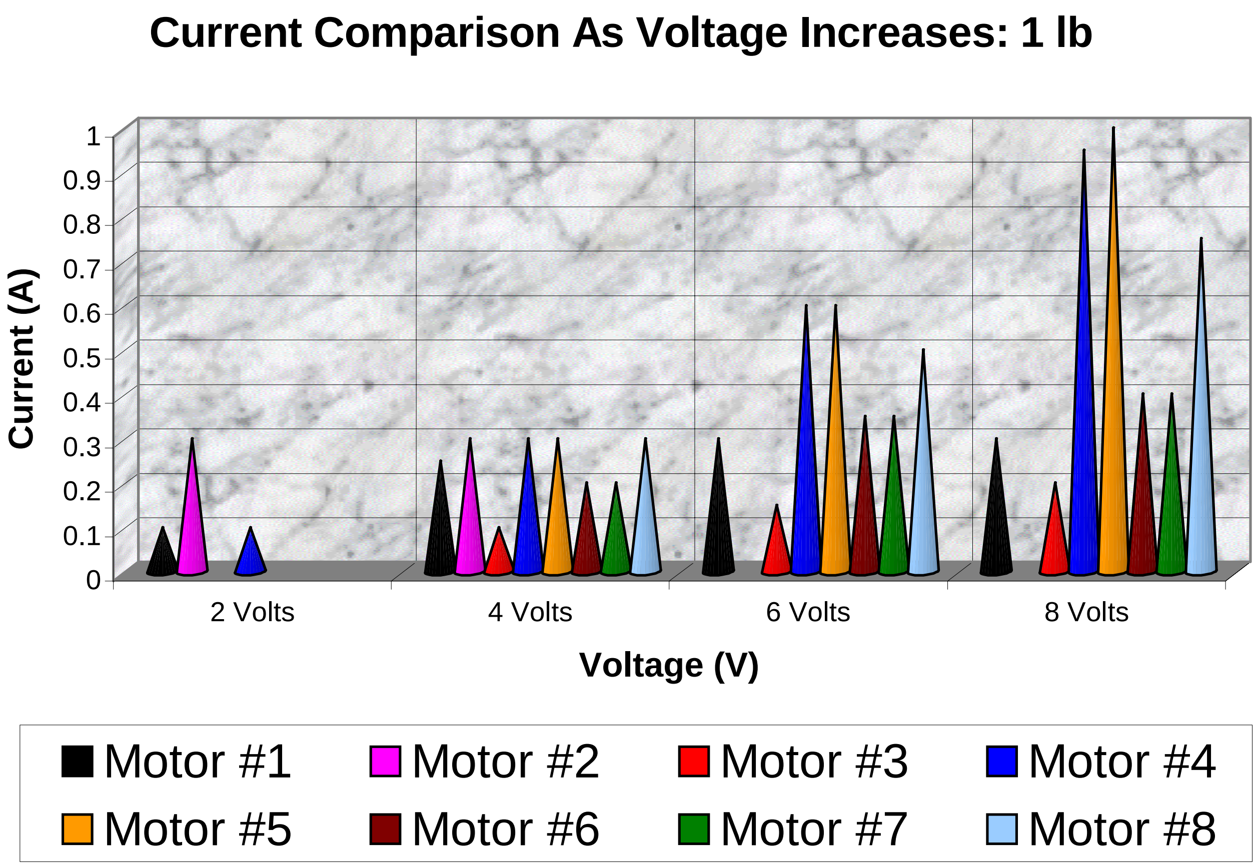
The maximum weight that was used was 10 lbs. Motor #8 was the only one to go beyond this number on high voltages, however the actual measurement was not taken as the data was collected for comparison purposes only.



This graph demonstrates how the current increases with voltage growth for all 8 motors. No load was attached to the motor during this testing. Only 2, 4, 6, and 8 volts used to make this graph.

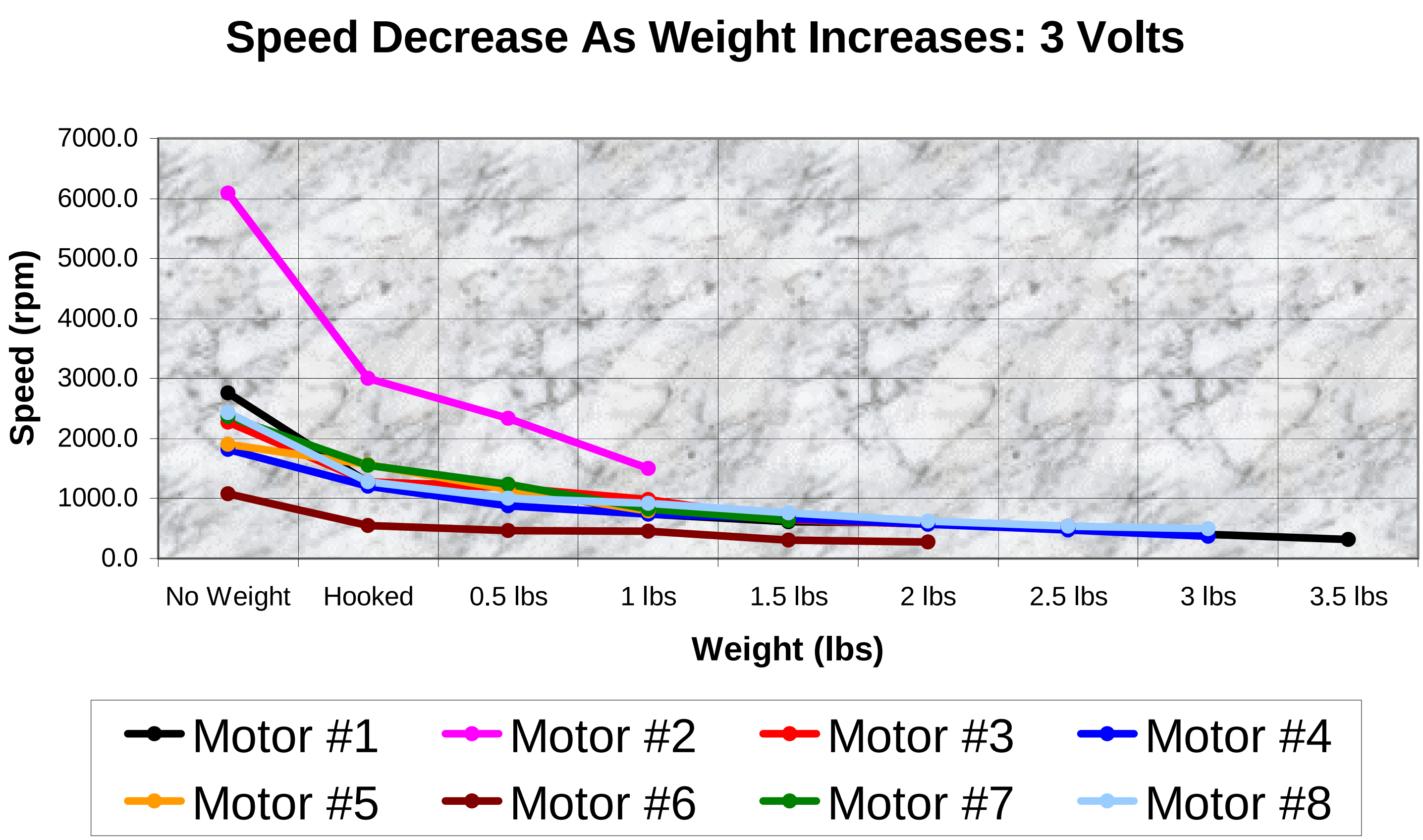
The growth of current was recorded for most of the motors. It is also visible that motor #3 consumed less current than any other motor. This means that motor #3 outperformed significantly in this testing, however motors #1, #6, and #7 also showed good results.

Motors that consume less current, and therefore electric power, to do the same work, are more efficient.



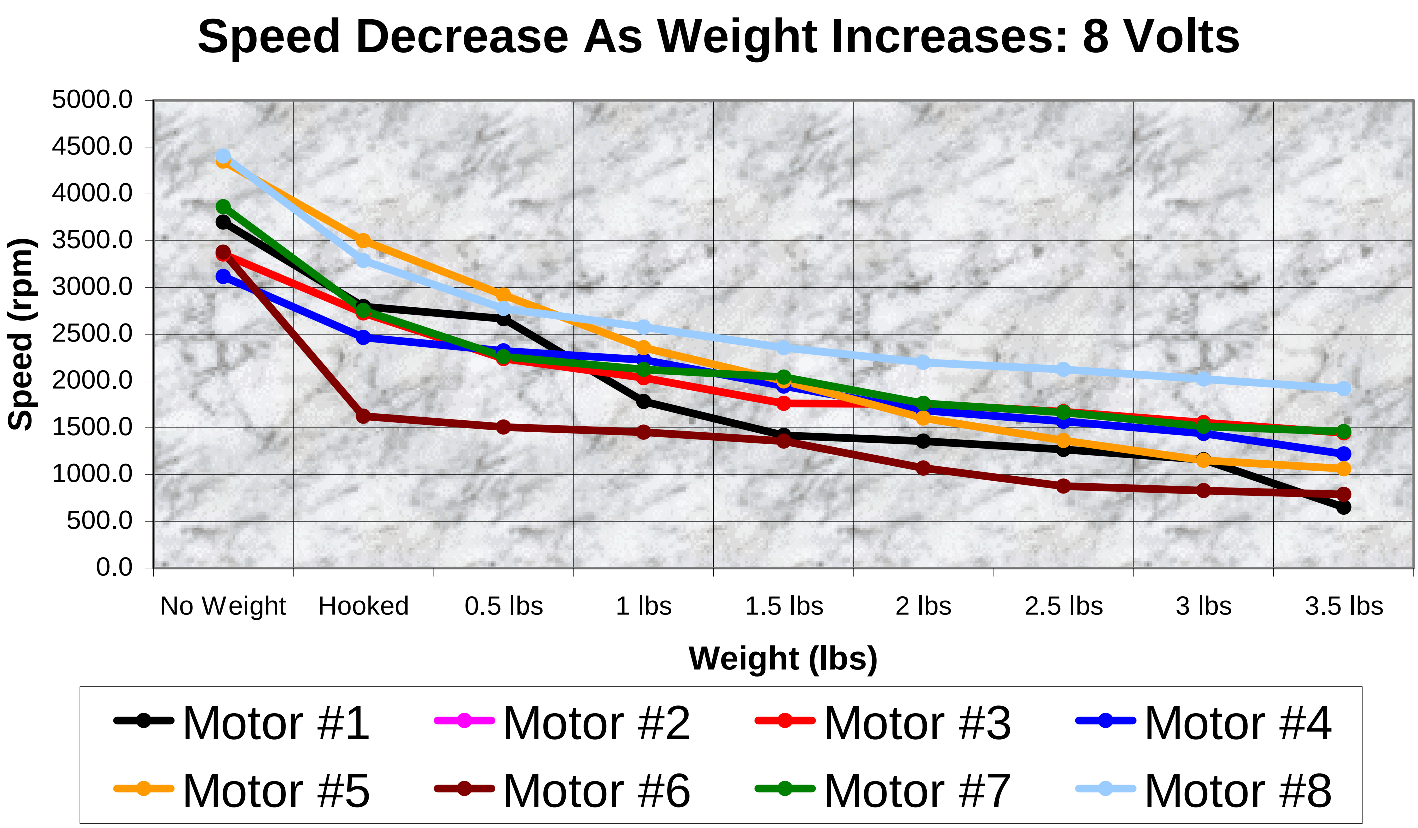
This graph is similar to the one on the previous page. It also demonstrates how the current increases with voltage growth for all 8 motors. In this case the motors were attached to the speed reducer. This added a significant load. In this experiment there were three tiles on the platform, or 1 pound. The friction generated by the decelerator made the motor consume more current to keep running.

Once again, motor #3 outperformed the other motors, because it consumed less current. Motors #1, #6 and #7 also performed well. It is notable that some motors were not able to perform on 2 volts, because there was too much load. Motor #2 did not work on voltages higher than 5 volts.



This line graph shows the decrease of speed with the increase of load for the 8 motors. The measurements were taken on 3V.

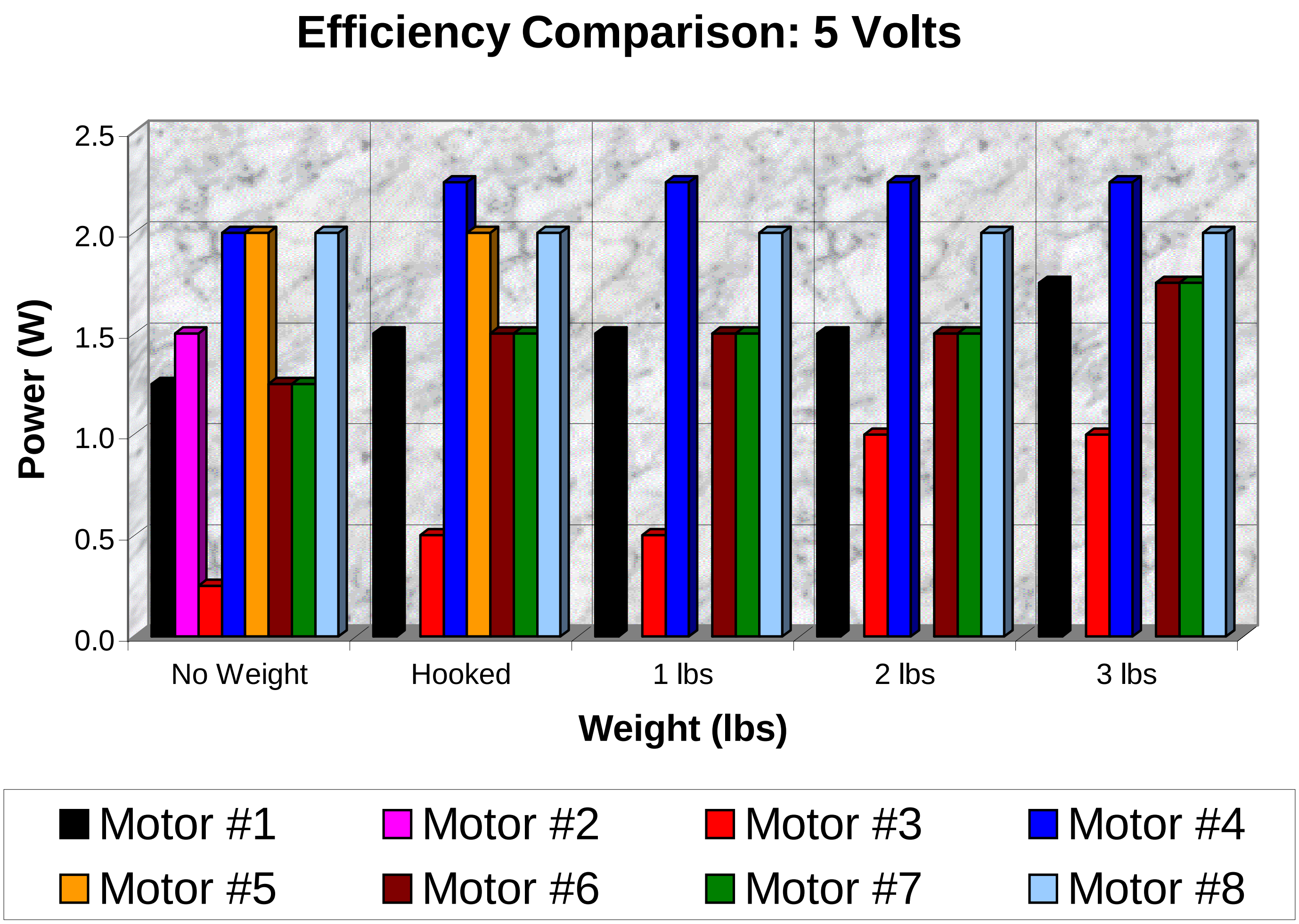
A big decline in speed occurs when the motor is connected to the speed reducer. The friction of the gears within it added a significant load to the motor. This can be seen very well on motor #2. This motor was very fast in the beginning, but could not lift more than 1 pound. It is also visible that motor #6 under performed in this test. The rest of the motors had quite similar results. The decrease of speed slowed down after about 0.5 pound for most motors.



This graph is similar to the one on the previous page. The measurements were taken on 8V.

Once again a big decline in speed occurs when the motors are connected to the speed reducer. Motor #8 was the best in this testing as it had the fastest speed and lowest speed decrease. Motors # 3 and #7 also performed well, while motor #6 under performed. Most of the motors had results similar to each other.

Motor #2 is not represented on this page, as it does not work on this voltage.



It is known that the efficiency of a motor is the ratio of its useful output to its total input. Input power is the electrical power these motors consume. It was calculated in the tables at the beginning of this chapter. The output power is proportional to the torque of the motor. Therefore, the motor that lifts the most weight and consumes less power to do it is proven to be more efficient.

This graph, taken at 5 volts, clearly demonstrates the efficiency comparison. Only the measurements for No Weight, Hooked, 1 lb, 2 lbs, and 3 lbs were used. It shows that motor 3 is the most efficient, because in all measurements it consumed less power to do the same work. Motor #1, motor #6, and motor #7 also had good efficiency, while other motors showed only satisfactory results in this test.

For example, in order to lift 1 lb., motor #3 consumed 0.5 watts of electricity (0.1 A at 5V). This motor showed the best results using 1 watt to lift 3 lbs. (0.2 A at 5V). The rest of the motors used much more electrical power; their consumed power was in the range from 1.3 to 2.0 watts.

From the last year research it is known that motor #1 is very efficient: it worked non-stop over 50 hours on one 1.5 Volts AA size battery under no load. This result could be better for motor #3 and should be comparable for motors #6 and #7.

The table below represents the summarized ranking of 8 motors using all experimental data. Most of the data for this table is based on the tables and graphs on the previous pages.

Most of the motors were very stable, except motor #2, what is reflected in the table.

Reliability of the reed switch based motors is determined to be lower than Hall effect based motors because of the spark problem.

The number and types of parts in each motor's circuit determines complexity and cost.

Motor Classification

Motor #	Speed	Speed Under Load	Torque @ 3V	Efficiency	Max. Load	Stability	Reliability	Complexity	Cost	Overall Rank
Motor #1	5	4	1	2	3	1	7	1	1	2.8
Motor #2	1	8	7	8	8	8	8	2	2	5.8
Motor #3	6	2	4	1	5	1	6	4	4	3.7
Motor #4	7	5	3	6	2	1	4	3	3	3.8
Motor #5	3	6	8	7	7	1	5	5	7	5.4
Motor #6	8	7	5	2	4	1	3	8	5	4.8
Motor #7	4	3	6	2	6	1	2	6	8	4.2
Motor #8	2	1	2	5	1	1	1	6	6	2.8

The motor classification table clearly shows that no one motor outperformed in each category.

Motor #1 had one of the best overall scores. It outperformed all other motors in torque testing. It is the simplest motor with lowest cost. It also was very stable and showed good results in maximum load testing.

Motor #8 had the same overall score as motor #1. It clearly was the best in maximum load testing, had the highest speed under load and was the most reliable motor.

Motor #3 was the next best. Since it consumed significantly less power than all other motors, it was the most efficient motor. It was also very fast under load and stable.

Motor #4 had an overall rank close to motor #3. It was also quite simple and inexpensive. This motor was more reliable than motor #1 as the reed switch was separated from the inductive load. This motor was also very powerful.

Motor #7 showed satisfactory results. It was the second most reliable motor. It was very efficient and fast under load. However, this motor was the most expensive.

Motor #6 also showed satisfactory results. It was third most reliable motor and had good efficiency. However, this motor was the most complex and took more time to build it.

Motor #5 on an overall scale under performed. It showed good speed without load. However, it showed worse results in torque, efficiency, and maximum load testing.

Motor #2 had the overall worst results in nearly every category. However, it was the fastest motor without load and one of the simplest and cheapest.

10. Conclusion

In the first year research a new simple inexpensive brushless DC motor based on a reed switch was invented, built, and tested. In the second year development, extra circuits with another electromagnet and/or reed switch were added to the original prototype. Different experiments demonstrated that these new motors were very reliable, stable, and powerful enough to be favorably compared to existing conventional motors.

The third year study was devoted to the development and comparison of eight different types of brushless motors:

- The Original Reed Switch Based Brushless Motor
- Double Reed Switch Motor Based On Push-Pull Operation
- SCR Controlled Brushless Motor
- Transistor Controlled Brushless Motor
- Optocoupler Based Brushless Motor
- Brushless Motor With Optical Control
- Hall Effect Position Sensor Based Brushless Motor
- Brushless Motor Based On Hall Effect IC

All of these motors were designed and built using the same technology to get reliable and accurate comparison. The motors were tested and compared in different categories, such as speed under different loads, torque under different voltages, maximum load, efficiency, reliability, stability, cost, and complexity.

The manipulated variable in the experiments was voltage. The controlled variable was the weight in torque testing. The responding variables were the speed, measured in revolutions per minute, and the current, measured in amperes.

According to the charts and graphs based on the experimental data, this year hypothesis that no motor will be the best in everything, but different motors will show best results in various categories such as speed, torque, and efficiency, was proven. The original reed switch based brushless motor and brushless motor based on Hall effect IC had the best overall rank. SCR and transistor controlled motors also showed good results. Other motors demonstrated satisfactory performance, except the double reed switch motor, which under performed in most experiments.

All motors shared the same design, were tested many times, and worked well under different conditions. The new improved design eliminated many problems encountered in the past two years. Very reliable and innovative methods were used to measure speed and estimate torque of the motors. When attached to the speed reducer, the motors were tested in a real application. All these are the strengths of the experiments.

There were some weaknesses. Some factors were not taken into consideration because of their complexity or little influence on this experiment. These factors include the friction in the speed reducer, differences in a sensors position, and movement of the motor while being attached to the speed reducer.

In future development it is planned to design small portable versions of the best performing brushless motors to be used in real life applications, for example in toys. Some other suggested areas for the future usage may include notebooks, cameras, and other portable electronic devices, because of their efficiency requirements. Brushless DC motors can be used for almost any application where high stability, reliability, and efficiency are required.

The original reed switch based brushless motor was successfully used as an educational kit to demonstrate principles of electricity and magnetism. Other motors developed this year may serve the same purpose to help explain the basics of electronics.

11. Acknowledgements

This project represents many hours of hard work and could not have been done without the help of many experts for whose time, knowledge, patience, and enthusiasm I am most grateful.

First of all I would like to thank my dad for spending a tremendous amount of his time helping me with this project. He helped me to go all the way from my initial ideas to the present stage of this task. I need to credit my dad for the following:

- He taught me how to select and use the correct tools for the right task when building the motors.
- My dad helped me to build the power supply and control box.
- In first research my father designed an electrical counter, explained to me the principles of its operation, and helped me to assemble it. I soldered most of it myself! I used this counter in last year's project. This year he helped me to improve it.
- My dad insisted on making me redo any step that was not perfect (or close to it).
- And finally he was always there to support me when I needed it.

I would like to thank Professor Gosney from Southern Methodist University and Mr. DiRenzo from Texas Instruments who suggested using transistors and Hall effect switches in my research.

And finally I appreciate all the comments I received from many visitors to my web page where I published the results of my first and second year development. Their suggestions helped me to improve my project.

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13. Appendix: Application of the original reed switch based brushless motor

The results of the first year research were published on the Internet. The web site (http://members.tripod.com/simplemotor) explained how the original reed switch based brushless motor works and provided detailed instructions for building it. Since June 1999 thousands of people around the world built this motor successfully. Many educational organizations used it in teaching the basics of electricity and magnetism.

As of 03/16/00 these schools and universities used the original reed switch based brushless motor in their educational process:

1. Carnegie Mellon University (Department of Civil and Environmental Engineering) – Pittsburgh, Pennsylvania.
2. University of Notre Dame (Minority Engineering Program) – Notre Dame, Indiana.
3. University of North Carolina (ECT598 Senior Project) – Greensboro, North Carolina.
4. University of Nebraska – Lincoln, Nebraska.
5. University of Tennessee – Knoxville, Tennessee.
6. Eastern New Mexico University – Portales, New Mexico.
7. Weber State University – Ogden, Utah.
8. Oxley College – Bowral, NSW, Australia.
9. Shrewsbury High School – Shrewsbury, Massachusetts.
10. Coulterville High School, Coulterville, Illinois.
11. South Lewis High School, Turin, New York.
12. California Middle School, Sacramento, California.
13. Tate’s School of Discovery, Knoxville, Tennessee.

The original idea of using a reed switch in the electric motor was very successful. Some of the user's responses are listed below.

Engineering Your Future

Electrical and Computer Engineering

Summer 1999

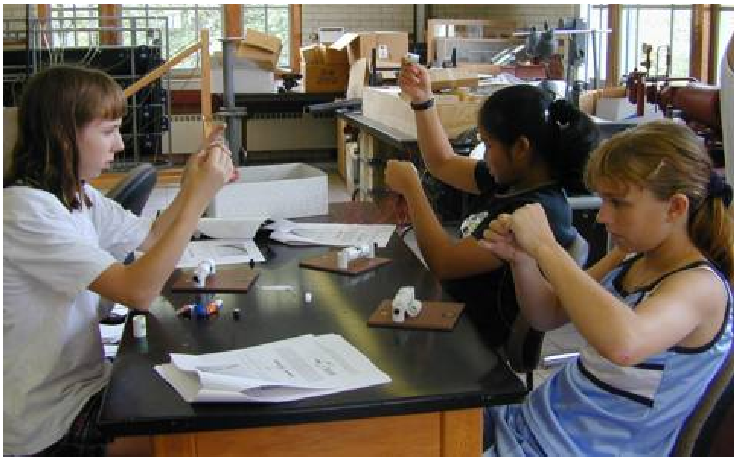
Carnegie Mellon University

As part of the Engineering Your Future program at Carnegie Mellon University, high school girls spent a day building battery-powered DC motors. After a short discussion about current, magnets, motors and generators, each girl got a kit containing the parts for her motor. The kits were made by an 8th grader in Texas who did a prize-winning science project about motors. For more information on the motors (and how to get a kit for yourself), see his web page.

The high school girls worked in teams so that they could help each other out. They they built a rotor with two permanent magnets on it, and they made an electromagnet by winding copper wire around a large nail. Connecting the electromagnet through the reed switch to the battery was the most difficult part. Some of the motors worked the first time, but a lot had to be checked for loose connections, friction in the rotor, and weak electromagnets. Each girl got to take her motor home with her.

Assembling the Rotors


Coiling the Wire for the Electromagnet

Assembling the Reed Switch and Closing the Circuit



http://www.ce.cmu.edu/~sfinger/eyh/

From: Joy Jeanette Vann-Hamilton [Joy.J.Vann.2@nd.edu]
Sent: Wednesday, September 15, 1999 2:57 PM

I am interested in the most complete kits. We plan to use them in our pre-college engineering program as a family engineering event. Each family will take home a kit and construct the project.

Look forward to hearing from you.

Joy J. Vann-Hamilton
Director, Minority Engineering Program
224 Cushing Hall
Notre Dame, IN 46556
(219) 631-6039 (Phone)
631-6678 (Fax)

Category1: Motor you built yourself
Category2: Suggested Improvements
Name: Rebecca Preston
Email: tateslab16@icx.net
Date: 25 Feb 2000
Time: 10:03:32
Remote Name: 216.82.33.209

Comments:

Super job on the motor - I've been looking for something to build easily and your design looks great. I am a computer teacher at an elementary school right now (I have 20 years of experience with computers from my electrical engineering work) and I am teaching electricity in science class to our fifth graders. We are going to use a small PLC (Programmable Logic Controller) I have to turn on some motorized toys and launch some rockets. Thanks again for your great design and wonderful web site!!
Rebecca Preston
Tate's School of Discovery
tateslab16@icx.net
in Knoxville, TN

Source:

How do Motors Work by Marshall Brain which I found from askjeevesforkids.com

Category1: My idea about this motor
Category2: Suggested Improvements
Name: Michael Amenson
Email: Amenson@ExecPc.Com
Date: 20 Feb 2000
Time: 13:38:52
Remote Name: 152.163.207.61

Comments:

I like your motor design and its operation. Your descriptions are easy to read and easy to understand. I teach Basic DC and Basic AC Theory for the Navy's Advanced Electronics Technical Core at Great Lakes Naval Base, Illinois. You've given me some new ideas for different approaches to an old subject. Thank You!

Source:

www.howstuffworks.com

Category1: This web site
Category2: Additional experiments
Name: Maurie Jenkinson
Email: bandmj@itfusion.com.au
Date: 28 Aug 1999
Time: 22:32:39
Remote Name: 203.18.50.13

Comments:

As a teacher of Industrial Arts in Hervey Bay, Queensland, Australia this project is just what I have been looking for as a basis for a design exercise for my 13 -14 year old students doing a metalwork based subject. They will be able to use metal turning lathes and other machinery to fabricate components of their own design. i am hoping they will be able to develop their own experiments and applications.
Thanks Maurie

Category1: Other
Category2: Suggested Improvements
Name: Chris O'Byrne
Email: chrisobyrne@hotmail.com
Date: 01 Feb 2000
Time: 19:24:11
Remote Name: 24.10.168.220

Comments:

Excellent job. I'm a physics teacher in Minnesota and I'm having my 8th graders design their own motor. We'll use your site as a reference. Thanks.