Using DC motors in fighting robots

V3.01 27-Jun-03

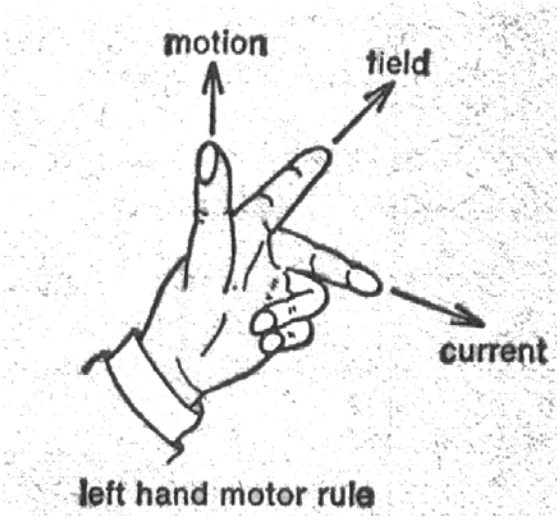
1. Introduction

This page describes how DC motors work, and how we can use them to build the traction system of a robot. It covers both permanent magnet motors, and series wound motors (such as car starter motors). If you are interested in converting a starter motor for use in a robot, see the separate page Converting starter motors.

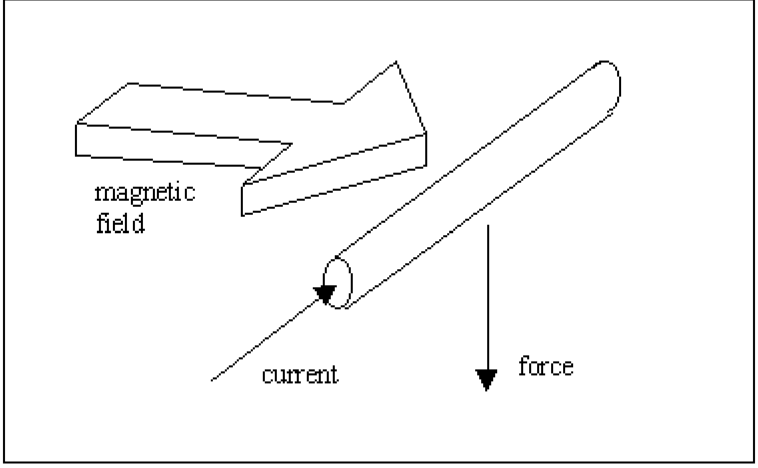
2 Motor principles

All motors require two magnetic fields, one produced by the stationary part of the motor (the *stator*, or *field*), and one by the rotating part (the *rotor*, or *armature*). These are produced either by a winding of coils carrying a current, or by permanent magnets. If the field is a coil of wire, this may be connected in a variety of ways, which produces different motor characteristics.

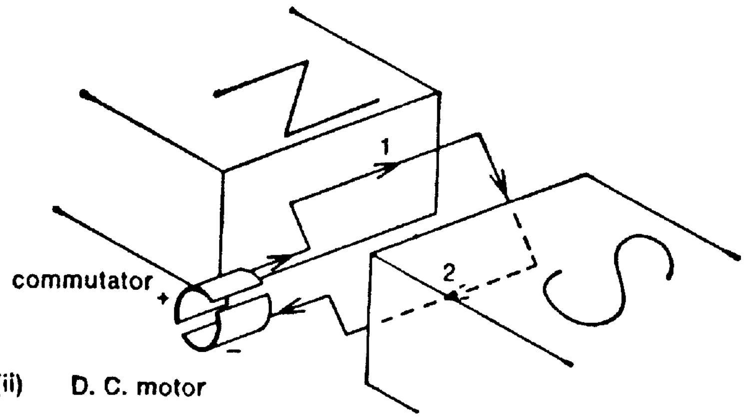
The basic law of a motor, the reason why they rotate, is governed by Fleming's left hand rule (see figure below). This tells you the direction of the force on a wire that is carrying current when it is in a magnetic field.



The next diagram shows the force acting on a wire carrying current, obeying the left hand rule:



If we now bend the wire round in a loop, and place it in a magnetic field caused by two permanent magnets, we have the situation shown in the diagram below. Here, both sides of the wire loop will have a force on them, trying to make the wire loop rotate. The current is applied to the loop through the *commutator*, which is shown as two pieces of metal formed into a ring in the figure. Current is applied to the commutator by stationary graphite blocks, called *brushes*, which rub against the commutator ring.



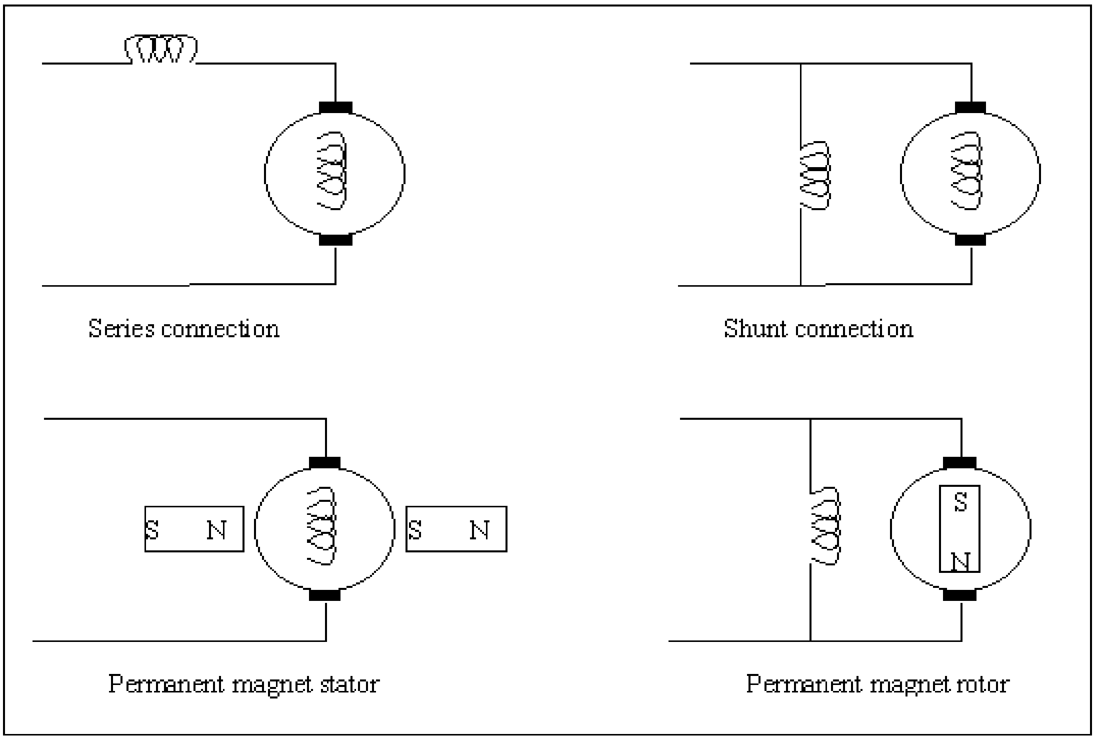
(ii) D. C. motor

The loop will continue to rotate anticlockwise (as we see it in the figure) until it is vertical. At this point, the stationary brushes won't be applying current around the loop any more because they will be contacting the gap between the commutator segments, but the inertia of the loop keeps it going a little more, until the DC supply reconnects to the commutator segments, and the current then goes around the loop in the opposite direction. The force though is still in the same direction, and the loop continues to rotate.

This is how DC motors work. In a real motor, there are many wire loops (*windings)* all at varying angles around a solid iron core. Each loop has its own pair of commutator segments.This block of core and wire loops is called the *rotor* because it rotates, or the *armature*.

The fixed magnets in the diagram above generating the field may be replaced by electromagnets which are generally more powerful. The elctromagnets are supplied by the same power supply as the armature winding, either in series (series connected) or in parallel (shunt connected) as shown in the diagram below.

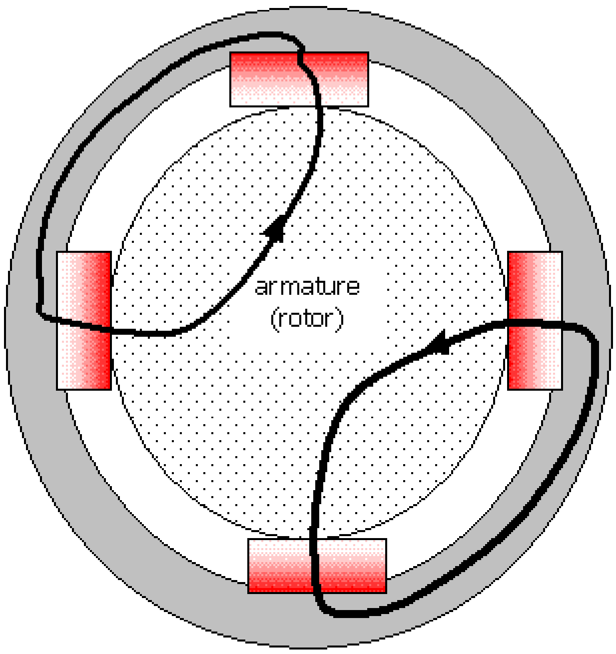
If permanent magnets are used, the motor is said to be a permanent magnet (PM) motor. DC motors can also have permanent magnets in the armature, and electromagnets for the stator coils. In this case, the stator windings must be switched in some way to make the permanent magnets in the rotor follow them to cause rotation. This connection is less common for small motors.

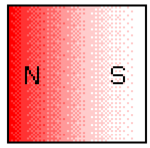


There may be more than just the two fixed magnets, called *poles*. In some motors there may be four poles (imagine one more coming from above and one more from below in the figure). There will always be an even number of poles, since there is an N pole for every S pole, and in the equations governing the motor, the number of poles is often quoted as *p*, the number of *pole pairs*. These magnets are called the *stator* because they are stationary, and the electromagnet coils are called the *field windings* because they generate the magnetic field.

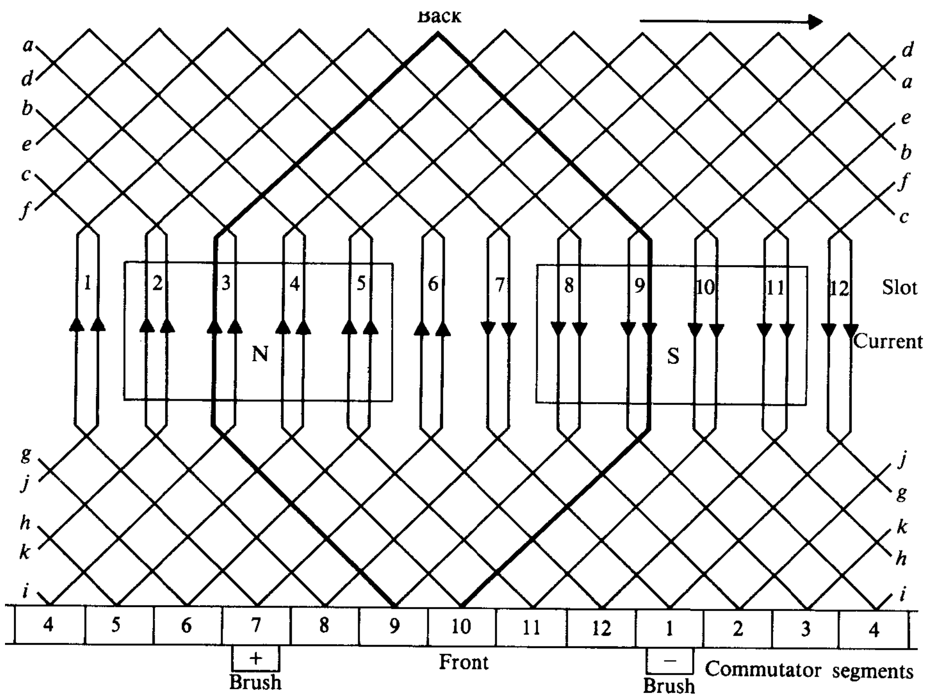
The supply is connected to the commutator segments through graphite *brushes*. These are held in little sockets with a spring behind them, so the brush is pushed onto the segments. This guarantees a good electrical connection (although there will be a fraction of an Ohm resistance across them). Eventually, these brushes wear down completely. If you get the motors from a scrap yard, the brushes may need replacing. New brushes should be available from automotive spares shops.

A four pole motor is shown in the diagram below. This shows how the magnetic field is generated by the poles and flows through the rotor:



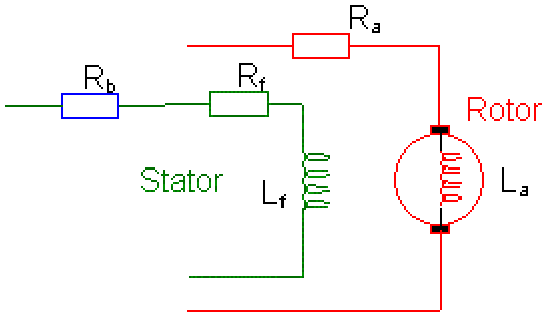


If you can imagine getting the cylindrical rotor of a starter motor, and unrolling it, the wires would look something like this:



In this diagram, the stator magnetic *poles* are shown underneath the rotor wires. You can trace the electrical current from the supply, through a commutator segment, through all the rotor wire loops, and back through a commutator segment. For a four pole motor (two pairs of poles), two pairs of commutator segments will be supplying current to the rotor wire loops

We can now draw a circuit diagram of the motor. The coils of wire will have a small resistance, and a quite large inductance. R_b represents the resistance through the brushes to the commutator. R_f is the resistance of the field windings, and R_a is the resistance of the armature (rotor) windings.



If the motor is has permanent magnets for the field, then of course R_b and R_f don't exist. Most starter motors use a serial connection. (For example values of these resistances and inductance, the starter motors I am using (from a Ford Fiesta) have an inductance, L_a, of 71µH, and resistances of R_b=0.008 Ohms, R_f=0.016 Ohms, and R_a=0.017 Ohms, giving a total, R_t, of 0.041 Ohms.

2.1. Back EMF

In the same way that a wire carrying a current in a magnetic field has a force acted upon it (left hand rule), conversely a moving wire in a magnetic field gets a voltage induced across it. This is called *Lenz's law*. In a motor, the consequence of this is that the supply voltage makes the rotor rotate, and the rotor generates a 'back emf' or reverse voltage, which nearly matches the supply voltage when the motor is rotating but not driving anything.

The resistance of the coils of wire that make up the field and armature are normally very low. So you would think that the motor would take a very large current (current = voltage ÷ resistance). However this back emf means that there is actually only a small voltage across the resistance of the coils, because the back emf, e_a, is nearly as large as the supply voltage, V_t. Therefore , the actual current taken is

$$i_a = \frac{(v_t - e_a)}{R_a + R_f + R_b} = \frac{(v_t - e_a)}{R_t}$$

Some typical values for a 900Watt starter motor are: R_t = 0.041 Ohms, V_t = 12V, e_a = 11.9v, so the motor current is 2.4 Amps.

The back emf is dependant on the speed of the motor, and is given by the equation

$$e_a = k\,\omega_m\,\varphi$$

where *k* is a constant for the motor, Ω_m is the speed of the motor, and Φ is the strength of the magnetic field generated by the field coils or magnets. From this equation you can see that when the motor starts, and its speed is zero, then the back emf will be zero, and so the current taken by the motor will be very large. This is also true when the motor is stalled.

When a load is put on the motor, the speed drops, and so the back emf drops, and so the current drawn from the battery will increase.

2.2. Torque

The torque produced by a permanent magnet or shunt wound motor is given by the equation:

$$T = k_f \Phi i_a$$

The torque produced by a series motor is given by the equation

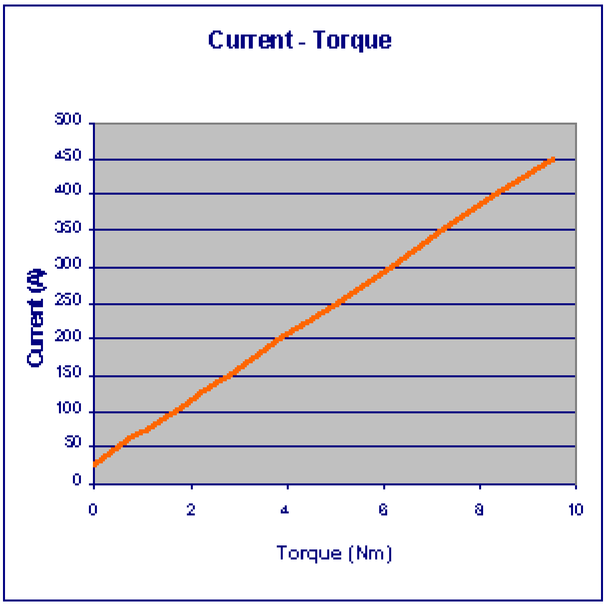
$$T = k_f i_a^2$$

where k_f is a constant for the motor, and i_a is the current, and Φ is the field strength. A series wound motor generates its field from the same armature current, so Φ increases as the motor draws current. Therefore the torque is proportional to the square of the current. This means that doubling the current that we put through a series wound motor quadruples the torque. This is a distinct advantage of series wound motors.

2.3 Current

When you read a DC motor datasheet, it will sometimes (if you are lucky!) have some characteristic graphs that tell you how the motor is likely to respond. These mostly have Load Torque as the bottom x-axis, and plot motor current, speed, power, and sometimes efficiency as they relate to the load torque. Sometimes they may have motor current on the bottom axis instead of load toruqe. In this case the graphs are still almost the same shape because the motor current is almost directly proportional to the load torque in all DC motors. Different types of field windings produce different shapes for these graphs.

For a permanent magnet or shunt wound DC motor, the current drawn by the motor increases linearly with load torque:



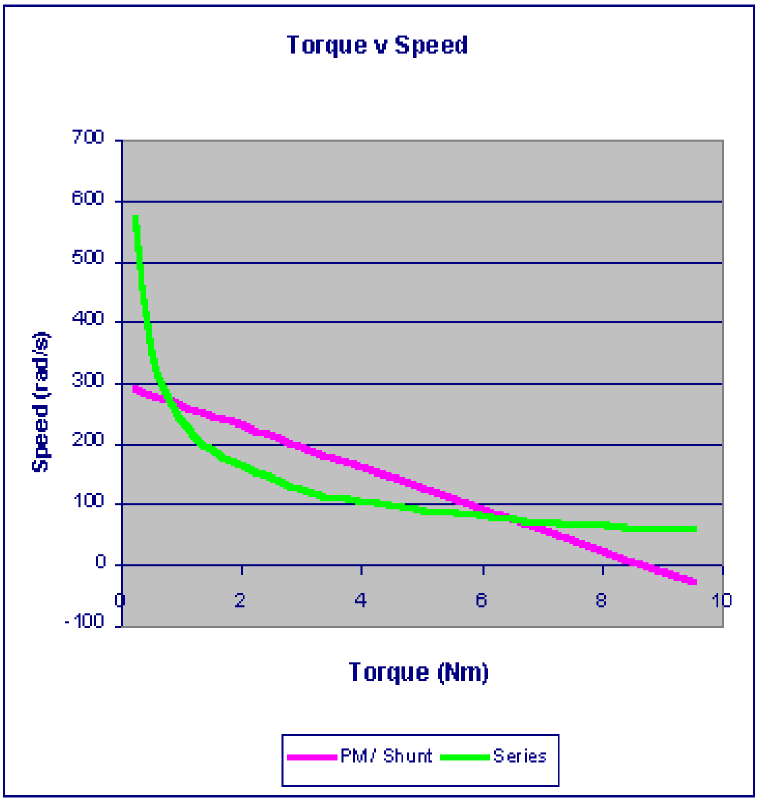
Notice that the line does not intersect the (0Nm / 0A) origin point. The zero torque point intersects at 25 Amps for this motor (an Iskra 900W starter motor). This means that the motor will not even start to turn until it is pulling 25 Amps!

2.4. Speed

For all DC motors, the speed is nearly proportional to the supply voltage, except for the effect of the armature resistance:

PM / Shunt: $\omega_m = \dfrac{V}{k\phi} - \dfrac{R_a T}{(k\phi)^2}$ Series: $\omega_m = \dfrac{V}{\sqrt{kT}} - \dfrac{R_a}{k}$

The values R_a and k_f are constant for any particular motor. It can be seen that the speed will drop off as the load torque increases, but differently for each type of motor:



From this graph, and the equation, it can be seen that the speed of a series motor with no load torque will rise to infinity! This doesn't happen in practice because there is always a little load torque because due to friction in the motor. It can also be seen that as a little load torque is added to a series wound motor, the speed drops off very quickly to start with, but then drops off less quickly.

With both motor field types, eventually, when the load torque becomes even larger, say when a stronger robot is pushing us backwards, the motor speed becomes negative (the motor starts rotating backwards).

In practice, the speed line for a PM or shunt wound motor may not be a straight due to frictional loads which are not linearly dependant on speed.

The torque speed graph of a DC motor when it is being driven by a speed controller with current limiting can be found in the speed controllers section.

2.5. Power and efficiency

The power a motor is taking from the battery is

$$P = [V - E_a]i_a \text{ or } P = [V - E_a]^2/R_a$$

The power the motor is putting into the load is

$$P = T\Omega$$

When the motor is running with no extra load other than its friction, then the load torque is zero, and so the output power is zero. The input power is small also because the back emf is almost equal to the supply voltage. The only power drawn from the battery is driving the loss torque:

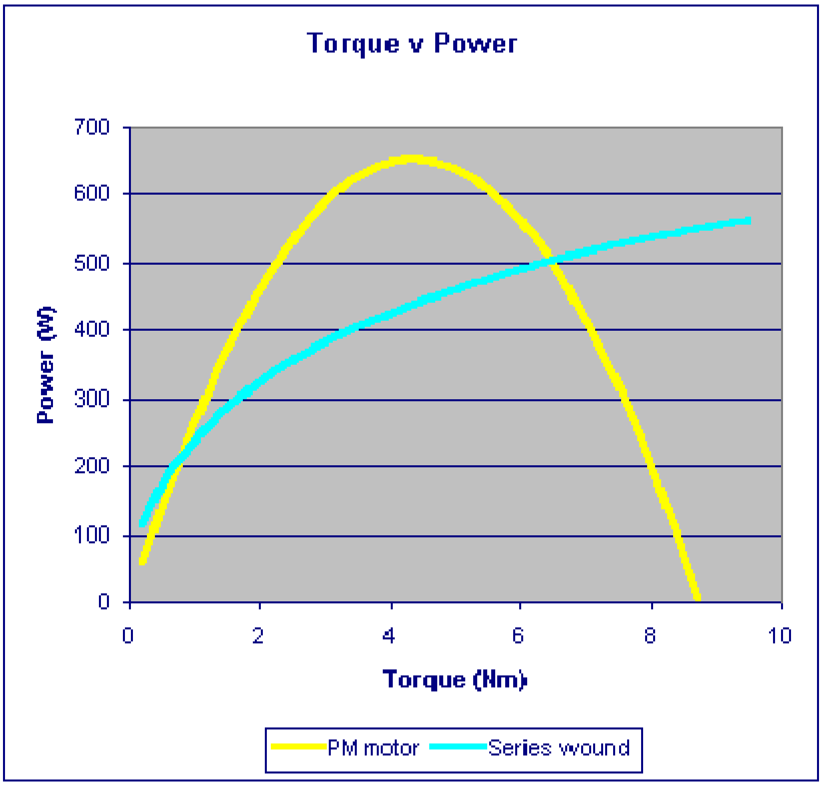
$$P_{loss} = T_{loss}\Omega$$

When the motor is driving such a large torque that it has stalled, then the back emf is zero, and the input power is very large:

$$P = V^2/R_a$$

and the output power is zero because the speed is zero.

At some point in between, the output power is at a maximum. If we plot the product of the torque and speed, we will have the graph for power:

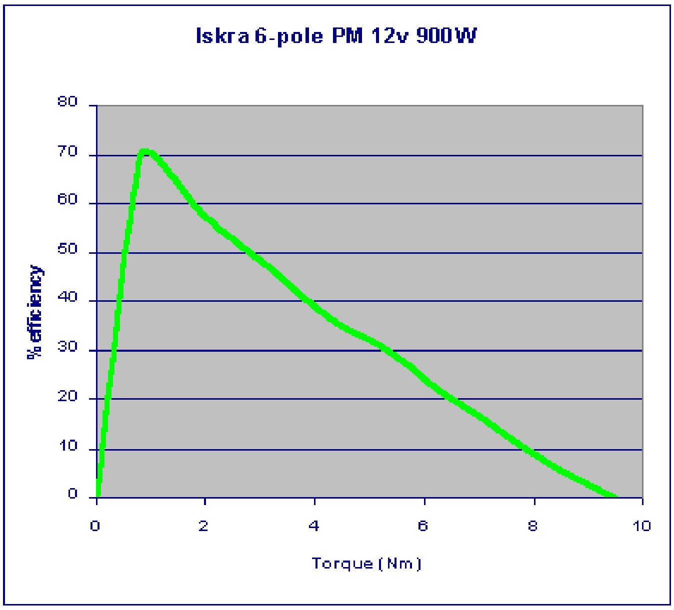


The power versus torque graph is a quadratic curve, with a maximum which the manufacturer specifies as the power rating of the motor. For a starter motor on a small car, this is typically around a kilowatt.

The efficiency of the motor is defined as the amount of mechanical power you are getting out of the motor divided by the amount of electrical input power you are putting in, so:

$$efficiency = \frac{power\_out}{power\_in} = \frac{T\omega}{i_a(V - E)}$$

The efficiency can also be plotted against load torque. Here is the efficiency graph for an Iskra shunt wound starter motor:



Just because the maximum efficiency is at around 1Nm doesn't mean that you have to run the motor at that torque though!

There is a section about the power rating of DC motors in the spinning disks chapter here.

2.6. Characteristic graphs for some motors

Most of the graphs presented above were based on example values. Let's look at the characteristic graphs for some real motors:

Iskra 12 Volt 900 Watt shunt wound starter motor
Bosch GPA750
Lynch 12V
Lynch 24V
Scott 4BB-02488 motor (datasheet)
Scott 4BD-1460 motor datasheet.

The Bosch GPA750 has the following nameplate values:

Parameter	Value
Nominal voltage	24 V
Nominal power	750 W
Nominal current	40 A
Nominal speed	3300 rpm
Continuous torque	2.2Nm
Stall torque	11 Nm

Graphs for other motors, and sometimes the same motors at different voltages can be found at the following sites:

Lynch (LEMCO) motors
Iskra motors
Scott motors

[Bosch motors](#)

3. Testing

When designing your robot, it is very useful to know how fast the motors will be going under various load conditions. Basically, this means knowing the exact shape of the speed-torque graph described in section 2.4. This will tell us how fast the motors will go on no-load, and how much torque they will develop when they are starting or stalled. With the gearing information and wheel sizes, this will tell us how much force your robot will be able to push, and give us an idea of the maximum speed of the robot.

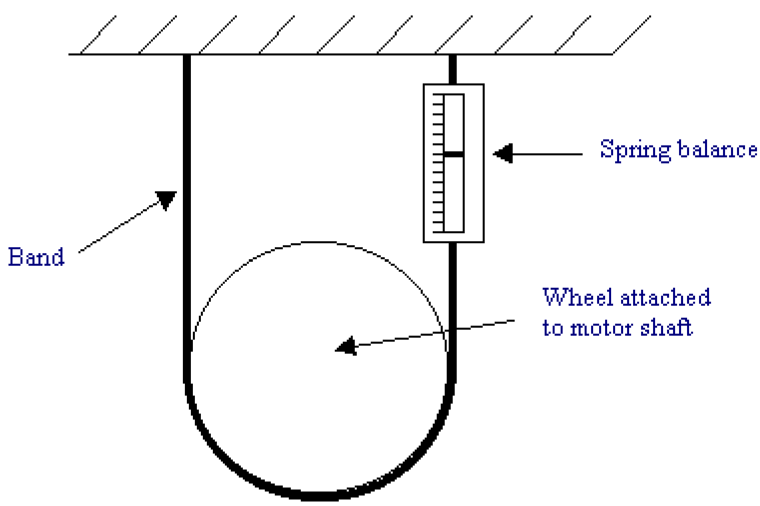
To fully test the motor, you will need the following equipment:

- Speed measuring device
- Spring balance (cheaply available from angling shops)
- load band
- digital voltmeter (with 0-2V range) and ammeter (0-10A)

The speed measuring device must be able to tell you the RPM of the motor. This may be the hardest piece of equipment to get hold of. Stroboscopes used for adjusting the timing of car engines are generally not of any use, since they require a reference pulse from the spark plugs. Here are some methods that you could use to perform this:

- Independant stroboscope with dial reporting flash frequency. A chalk mark is made on the shaft of the motor. When the motor is rotating, adjust the frequency of the stroboscope upwards from its lowest setting until the chalk mark appears to be stationary. Then read off the frequency from the stroboscope dial. The rpm is the frequency x 60.
- Home made LED stroboscope.
- Frequency counter. Attach a piece of card to the end of the motor shaft with a single slot (or two diametrically opposite if just one slot causes the card to become unbalanced and fly off) cut in it, similar to the speed measuring device described in the speed controllers page here. The rpm is then given by the frequency read from the frequency counter, multiplied by 60 and divided by the number of slots cut in the card.

Spring balances are available from general hardware stores, and angling shops. They are normally used for weighing. The load band is a tough piece of material that wraps around the wheel (which must be attached to the motor), that won't disintigrate too quickly. A piece of old seat belt from a car in the scrap yard is ideal. Here is the test setup:



Fit the motor into the apparatus as shown. There must be a means of adjusting the height of the motor so that band can be tightened. Start it off with the band stretched slightly tightened (but not too tight). Run the motor, and record the speed it is going at (call this w_1). The spring balance should change reading a little (if it doesn’t then the band is not tight enough, so move the motor and wheel downwards a little), record the spring balance reading (call this F_1).

Now move the motor and wheel further down (tightening the band further) and repeat. make sure that the speed and spring balance reading have changed appreciably - enough to see the difference, but not so much that it stalls the motor. Record the speed (w_2) and spring balance readings (F_2) again.

The spring balance reading must be converted to Newtons before we can use it. The speed must be converted to radians per second also. The following table will help you do these conversions.

To convert	to	multiply by
kg	N	9.81
g	N	0.00981
lb	N	4.45
oz	N	0.278
rpm	rad/s	0.105
revs/sec	rad/sec	6.28

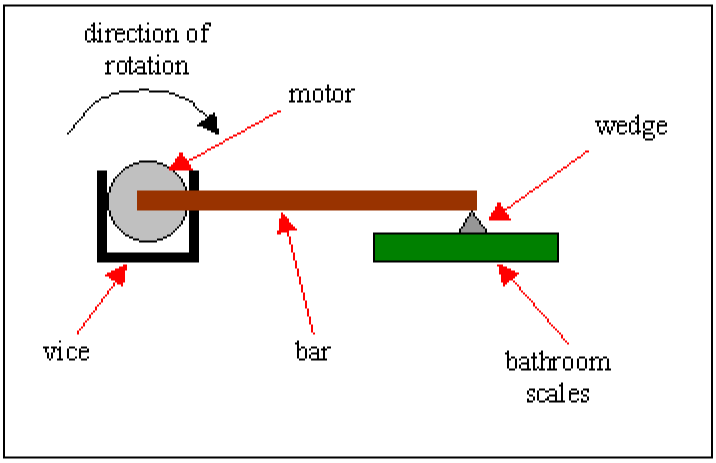
The load torque on the motor in the tests is $F \times r$ where F is the force in Newtons read by the spring balance, and r is the radius of the wheel (in metres).

By gradually tightening the band, the shape of the torque-speed graph can be established. For a PM or shunt motor, we already know the graph is almost a straight line, so if we knew the stall torque, and the no-load speed, we can just draw a straight line between them. For series motors, the band must be tightened gradually to obtain several readings so the curve can be plotted.

This apparatus is useful if you need to match more than one motor for your robot. If you have two motors and are running them with open-loop speed control, then if they are not sufficiently matched for torque-speed characteristics, then your robot will tend to swerve when you are trying to drive it in a straight line.

3.1. Stall torque

The band appartus described above may not be suitable for measuring the stall torque, since this can be quite large. An alternative is to fix (weld / bolt or whatever) a bar to the end of the motor shaft, perpendicular to the shaft. Mount the motor in a vice horizontally. The bar should preferably be at least half a meter long. Rotate the bar so it is horizontal, and place bathroom scales underneath the end of it. You may have to place a wedge between the bar and the scales so you you know the exact length of the bar between the motor shaft and the scales.



Now power up the motor so it will be forcing the bar downwards onto the scales (make sure you have the direction correct and it won't flip upwards!), and read the scales. Do not keep the motor powered up for long as it will be taking a very large current.

The stall torque can now be calculated:

$T_{stall} = 9.81 \times W \times L$

where W is the weight in kg and L is the length of the bar.

3.2. Maximum speed

We can get some idea of the maximum speed of the robot now. Since we don't know how much friction there will be in the gearing, and in the robots transmission from wheels to ground, we'll have to guess that! If, for example, the gearing is set to reduce the speed by a ratio 4:1, and the wheels are 30cm in diameter, then the road speed of the robot will be:

no load speed (rads/sec) ÷ gear reducing ratio × wheel radius - speed loss due to friction

If the no load speed is 200 rads/sec, say, and the speed loss due to friction is 2 metres per second, then the road speed will be 200 ÷ 4 × 0.15 - 2 = 5.5 metres per second, which is about 12 miles per hour.

To measure the speed of the motor, you will need a tachograph or Stroboscope . Projects to build both of these are given in the circuits section of this web site. Click on the names above to go to them.

3.3. Motor resistance

The motor resistance tells us how much current the motor will take when it is stalled or when it is just starting up. For PM and shunt motors, this is the sum of the brush resistance and the armature resistance. For series motors, this will also include the series field resistance. The resistance is normally very small (generally less than 0.1 Ohms), and so cannot be measured with a simple digital or analogue multimeter. There are several ways that it can be done.

3.3.1. Low resistance meter

This is a measuring instrument specially designed for measuring very low resistances. It may also be an LCR bridge which can measure the inductance also. Fix the rotor tight so it cannot rotate (so no back emf is induced), then use the instrument to measure the terminal resistance. I used one of these to get the following results for a Ford Fiesta starter motor:

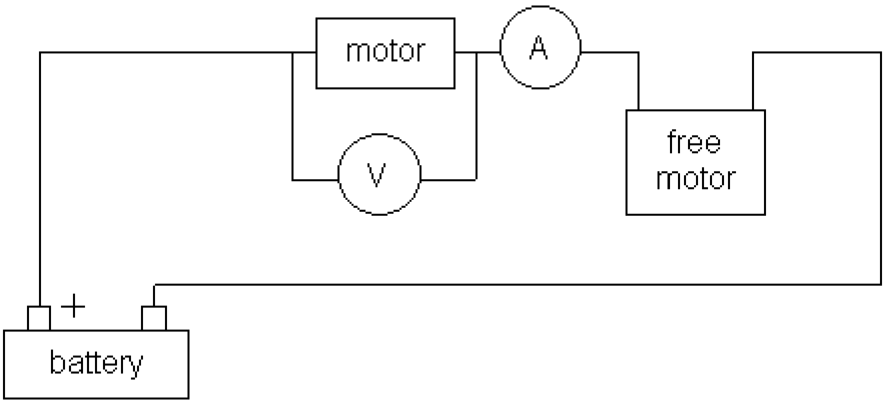
$$R_{total} = 0.041\text{Ohms}$$

$$L_{total} = 200\mu H$$

You can build your own low resistance meter. Some circuits are presented here.

3.3.2. Use another load in series

This is probably the easiest way if you can’t do (1). There are several easy methods. What we are trying to do is pass an appreciable current through the motor so we can measure the voltage dropped across it. The rotor of the motor under test must be fixed.



This requires two motors. One is the motor under test with its rotor fixed, and one is allowed to run freely. To pass current through the motor under test, simply apply a load to the free running motor (trying to slow it down). As its load increaes, it will take more current, and the voltage drop across our motor under test will increaese. You want as large a current as you can measure with your ammeter, so that the voltage is large enough to measure.

3.3.3. Use a clamp meter.

These are meters that can be clamped onto or around wire, and measure the current flowing in the wire by the magnetic effect. AC current is measured using a single coil in the meter as the secondary of a current transformer. To measure DC current, the meter measures the voltage of a Hall effect device in the meters clamp.

Maplin sell one for £100 (part number LD17T), which also includes all the normal ranges of a DMM. If you do not already have a DMM, it may be worth investing in this one. It also has a frequency measurement range up to 20kHz which would be useful when measuring motor rpm. Note that the other similar cheaper meters to this one in Maplins range do not measure DC current, only AC and so are not suitable.

If you already have a DMM, you can buy a clamp attachment which just plugs into your DMM. These can be quite expensive (well over £100 just for the probe, but CPC supply one (order code IN00710) made by Tenma (model number 72-6174) for £30.

4. How much current will my motor take?

I'm often asked this question, so here's a whole section just to answer it!

It's impossible to say how much current they will take on average, because it depends completely on what the motor is doing at the time.

An ideal electric motor (this doesn't exist of course but it is what motor manufacturers aim for), will convert 100% of the input electrical power into output mechanical power. This means that if the motor is not required to deliver any mechanical power - for example the vehicle is rolling at constant speed and there's no friction (I did say it's the ideal case!) - then it will draw no electrical power.

The mechanical power output is the load torque, 'T' (how much the vehicle is resisting the motor going round) multiplied by the rotational speed of the motor, 'ω'. The electrical input power is the voltage across the motor, 'V', multiplied by the current drawn by the motor, 'I'. In this ideal situation, the mechanical power equals the electrical power:

$$P_m = P_e$$

so

$$T\omega = VI$$

Therefore, if the load torque is zero, Pm is zero. The voltage will still be across the motor, so I will be zero - the motor takes no current.

Of course the world is not ideal - there will always be friction in real life - the wheel bearings, any gearing you have, the wheels against the floor, the bearings in the motor itself etc, and so T will never be zero. It follows therefore that 'I' will never be zero either. There will always be a little bit of current required to drive the vehicle even on a flat surface. For starter motors, this can be reasonably large. The problem with starter motors is that they are designed to do a quick dirty job for a few seconds. Their main design consideration is cost - they must be cheap for the car manufacturers. Most do not have proper roller bearings, but use a phosphor bronze sleeve bearing. The shaft of the motor simply rubs against the very hard bronze. This obviously causes a lot more friction that a roller bearing, but the car manuafacturers don't really care about that - it doesn't matter much for them. I have heard that it can take up to 20 Amps just to overcome this friction, although I have not experienced that myself. One alternative which is quite easy and inexpensive if you have welding equipment is to remove the bronze sleeves, and replace them with roller bearings. A roller bearing shouldn't cost any more than £2 (US$3). This should reduce the frictional current to a couple of amps at most.

As for the maximum current that the motor can take, this is governed by the resistance of its coils and brushes inside. Going back to an ideal motor, this would have zero resistance. When this ideal motor is stalled, it will take an infinite current, which will produce an infinite torque, and push whatever blockage is out of the way. In a real motor, the torque it can produce is not infinite, it is limited by the maximum current that can flow through the motor. The maximum current is simply the voltage applied to it divided by the motor's internal resistance... Imax = V / R. This is often called the stall current because it is the current the motor will take when it is not rotating, but full voltage is applied (i.e. it is stalled). A typical small car starter motor may have an internal resistance of 0.04 Ohms, so at 12V the stall current will be 12 / 0.04 = 300 Amps. Using our old equation Tw = VI, this maximum current corresponds to a maximum torque, which is often called the stall torque, and is how hard the motor will twist if you hold the shaft stationary. The motor is not rated to take this current for any length of time. Typically it will be rated for continuous use at about a quarter of this stall current.

In between these two currents, the motor may take any current, which will depend on the mechanical load. When accelerating the vehicle or pushing against an opposing force, it will take more, when decelerating or going downhill, it may take zero current.

5. Links

Theory of starter motors. Quite a good page.
http://www.apra.org/publications/electrical/fordther.htm

Controlling voltage spikes (motor suppression). SGS Thomson Acrobat document.
http://us.st.com/stonline/books/pdf/docs/1703.pdf

Using car windscreen wiper motors
http://www.geocities.com/sprite-midget/wipers.htm

5.1. Motor manufacturer's sites

Lynch electric motor company

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