Electronics for Model Railways

Chapter 2

Motors and DC controllers

By Davy Dick

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By Davy Dick

In memory of Margaret

Contents

Motors and DC loco controllers

There are three types of motor that can be used on model railways.

DC Motor

These provide continuous rotation, forward or reverse and are the mainstay of loco traction. They are also used for windmills, watermills, turntables, canal barges, road rollers , etc.

Servo

These rotate a spindle to defined positions within a defined arc (usually between 90° or 180° . These are used for points, semaphore arms, gates, animations etc., and are covered in the chapter on *'Point motors and servos'*.

Stepper

These also provide continuous rotation but only turn the spindle in very small defined steps at a time. They are used where accurate positioning is important, such as turntables and traversers. They are covered in the chapter on *'Animations'*.

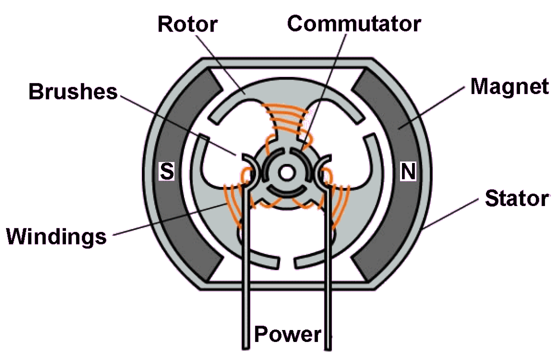
This chapter covers the range of DC motors, how they work, and how they are controlled.

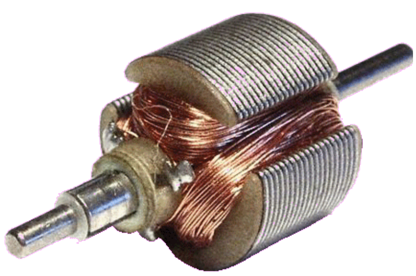
Brushed DC motor

This is by far the most common type of motor used on model railways.
The internet is full of explanations of how they work but here is a brief description of a very basic motor.
A DC motor has six main parts

- The axle – around which things spin.
- The rotor – the moving part (includes the axle, the coil and the commutator) .
- The stator – the fixed part of the motor (includes the case, the magnets) .
- The commutator – to transfer current from the stationary part of the motor to the rotating part.
- The brushes – transfers current from the external supply to the coil via the commutator segments.
- The magnets – to establish the permanent magnetic field.

A three pole motor is commonly used, as in this illustration. The commutator has three segments and there are three coils.
The rotor with its coils is able to rotate between the two magnets, and is sitting in a permanent magnetic field created by the magnets.

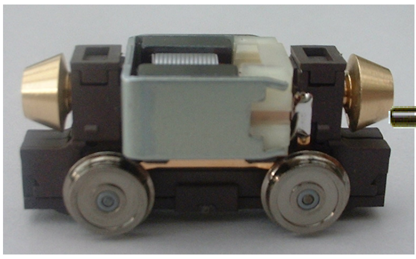


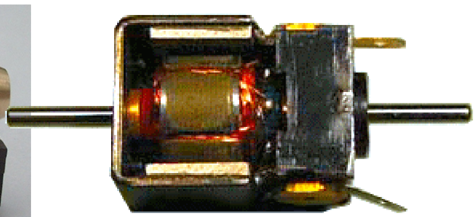


The ends of the coils connect to separate copper segments on the commutator. The brushes only contact two commutator segments at a time (i.e. only one coil can be activated at any one time).
Electric current is supplied to the coils by carbon brushes that rub against the commutator segments.

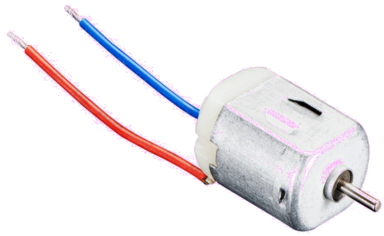
This current generates a magnetic field from the coil currently connected to the power. The design of the rotor, commutator and brushes create a misalignment between the magnet's magnetic field and that produced by that coil. The rotor responds by turning towards being aligned with the magnet's field.
At that point, the commutator has moved round and the electric current is now flowing through the next coil. And so the process continues as the axle rotates.
The magnet remains stationary while the rotor rotates.
For this reason they are sometimes referred to as *'permanent magnet motors'*.

Of course, there is more to it than that.





Iron/steel core motors are available with different constructions.
Here are two open frame motors, from Halling and from Tenshodo.



These three are '*can'* type motors, so-called because they are fully enclosed.

Speed and torque

Motors for locos rotate at very fast speeds (often 10,000rpm or more) and use gears to reduce the speed at the wheels. Some can motors have a built in gearbox and have low rotational speeds (e.g. 5rpm or 15rpm) and are ideal for layout animations, turntables, etc.
Motor speed is dependent on the applied voltage and the load presented to it.
The load could be the gearbox friction, or often the combined weight of the rolling stock it has to pull. Ensuring good lubrication and free-running wheels makes a big difference.
Torque is the motor's ability to overcome friction. It varies with speed. At high speed, the torque is zero, while the torque is high at slows speeds.
At zero speed, torque is maximum. For example, more power is needed to start a stationary train than to keep it moving. The definition of stiction is

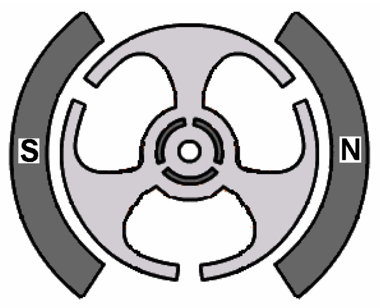
"static friction preventing stationary surfaces moving"

Modern motors

Many of you will probably have a collection of locos dating back a few decades, along with ones recently purchased. You have probably noticed a difference in performance between them. In some cases, it may be due to the permanent magnets becoming weaker with age. In most cases, it is the result of more efficient motors.
Older motors had relatively large gaps between the iron/steel poles on the armature, reducing efficiency and providing varying torque.
Modern motors use more powerful magnets (some using neodymium magnets) and benefit from improved design and improved engineering.
The result is smaller, more powerful motors, with reduced current requirements.

Cogging

If your loco does not respond well to the throttle, specially from stationary or at slow speeds, it is probably the result of cogging.
The metal core sits inside the permanent magnetic field and exhibits 'preferred' positions relative to the magnets.
The metal of an iron/steel cored motor is not uniformly present round the armature. There is a gap between each pole on the rotor, as shown in the illustration. This results in parts of the rotor being attracted to the nearest permanent magnet and being reluctant to be pulled away. It is the same effect you will have noticed when pulling a magnet off a sheet of metal; its stays put despite increased pulling, before suddenly being jerked off the material.

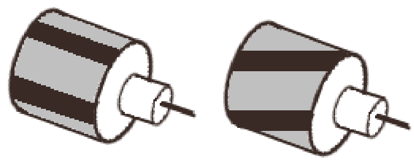


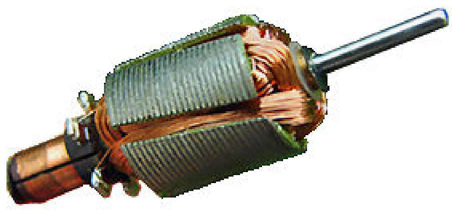
Cogging results in the motor rotating in jerky steps rather than being smooth, being more noticeable at slow speeds.

Improvements include '*skew wound'* construction and having extra poles on the motor.

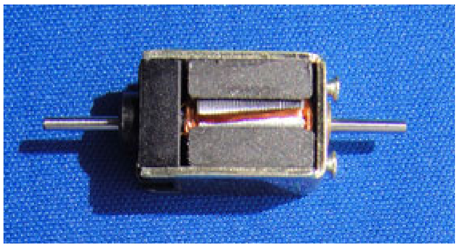
Skew wound

The illustrations show the standard motor on the left and the skew wound motor on the right. The non-metal gaps run the length of the standard rotor, while the gaps run at an angle with skew wound. Skew wound rotors have less pronounced gaps, when viewed on the horizontal axis, and this minimises cogging. As the end of one pole piece moves away from the magnet, the other end of the next pole moves in.





Here are examples of skew wound motors.



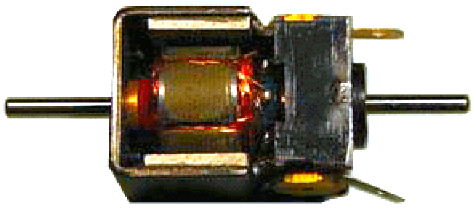
Adding flywheels to the motor, as in the Halling shown earlier, helps store momentum to reduce the effect of cogging at slower speeds.

5 pole motors

A three pole motor cogs six times every revolution, being the number of times the armature poles align with their preferred positions.
If we increase the number of poles on the armatures (they always go up in twos), then we increase the number of preferred positions and reduce the cogging effect.
So, for example, a five-pole motor would have ten cogging positions compared to six for the 3-pole motor.
This results in smoother running at slow speeds and a reduced risk of stalling. Five pole motor start at a lower voltage without loss of torque. It also allows the use of a lower gear ratio resulting in less loss of mechanical power.

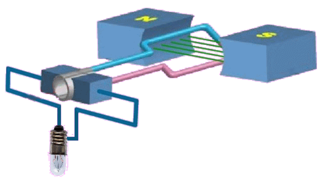
This image is of the Hornby X4026 five-pole motor that fits a wide range of their locos.

Improved design

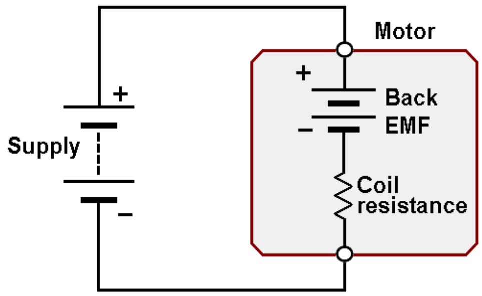


Older motors, like the one shown here, place magnets at each end of the stator assembly.   The magnetic field is not uniform at all points in the rotor's movement.
In some cases, there was an excessive gap between the rotor and the magnets, further reducing the efficiency.
Can motors have magnets that are shaped to almost complete encircle the rotor. This creates a more efficient motor, with reduced cogging and smoother running.

Back EMF

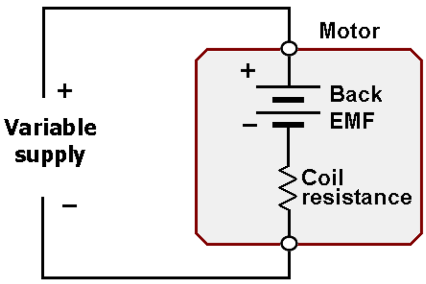


If we apply a voltage to a motor, it results in rotation.
However if we rotate a motor's shaft, the motor windings will generate a voltage (think car or cycle dynamo or hydroelectric power generation).
In reality, when your motor is turning, it is also generating a counter voltage at the same time.   This voltage opposes the supply voltage and is known as '*back EMF*' or shortened to *'emf'*.
It is the resultant voltage that determines the speed of the motor. The faster the motor spins, the greater the back EMF; a stationary motor produces no back EMF.



This diagram shows a battery supplying a motor.   The smaller battery, marked as 'Back EMF' represents the voltage which is effectively in series with the main supply, but with a reverse voltage.   The motor, therefore, is being run from the difference between the two voltages.

Now consider a motor being powered from a variable supply.

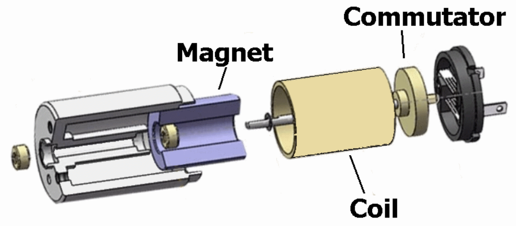


The motor has a much lower resistance and a higher current when stationary than when it is turning, due to the lack of any back EMF.   The increased current means less voltage being dropped across the motor. However, once the motor starts turning, back EMF occurs, the current drops and more voltage is developed across the motor.
The sudden voltage increase makes the loco surge forward.
Although this problem is worse when using old rheostat-based controllers, it occurs with most DC controllers.
Back-EMF is the voltage generated by the motor windings moving in the magnetic field of the motor's magnets.   Consequently, the faster the motor spins, the greater the amount of back-EMF, and vice-versa.   Put another way, the back-EMF is directly proportional to the loco speed at any one time.

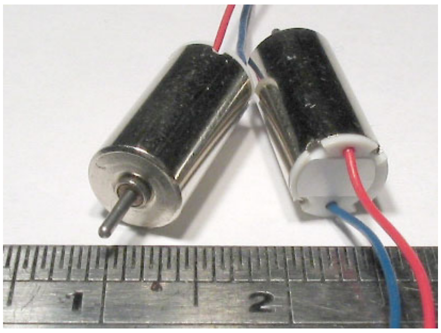
- When a loco comes to an incline, its speeds slows and its back-EMF reduces.
- When a loco hurtles down an gradient, its back-EMF increases.

In both cases, the current being drawn from the supply alters with the loco's speed – even though the operator has not touched the throttle control.

Coreless motors



These motors also have a stationary central magnet and rotating coil windings.
They do not have a metal core, hence their name.
They may also use aluminium wire instead of copper for the windings.
These both result is a smaller and lighter motor.



Their small size and weight means they are well suited for applications such cameras, quadcopters, barcode readers, pager motors, etc.

Here is the Portescap 17N78 which is typical of those to found in some modern locos.

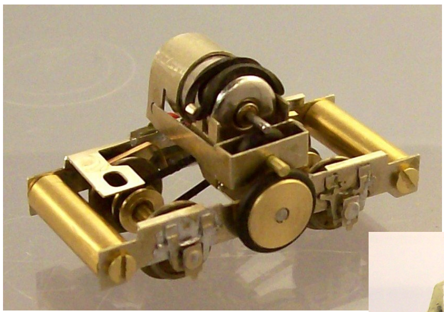
As the magnet is always in close proximity to the coil, it creates a very uniform and strong magnetic field. The coil is skew wired and, as there are no metal poles, there are no cogging problems. Without the metal in the armature, the motor responds faster to voltage changes. Also, due to no longer needing to be continually magnetising and demagnetising the poles, there is a saving on current (and wasted heat).

Pros

- Faster acceleration/deceleration
- No cogging
- Low starting voltage
- Less current
- Less electrical noise
- Less arcing, longer brush life

Cons

- No iron core to dissipate heat
- Heats up quickly
- Can't handle overloads
- Danger of damage if stalled
- Cannot be used on a DCC track without a DCC decoder.
- Can't use with DCC in 00 configuration



The 20HP WD Simplex chassis

Without the iron/steel core to conduct the heat away, the windings are exposed to dangers from overheating. They rely on the fast rotation of the rotor to keep the coils cool.
If the motor jams or is stalled, it will quickly overheat and could burn out the windings.
Without the back emf to limit the current to a safe value, the coils will overheat and burn out if the stall remains for any length of time.

Coreless motors can be used with DCC decoders, as long as they are high frequency types. Manufacturers recommend frequencies above 20KHz.

Here are warnings, quoted in full, of the danger of using coreless motors incorrectly with DCC.

This warning from Kato about their HO P42

> *"With the new HO P42, because of its coreless motor design, this locomotive* ***CAN NOT*** *be operated on a DCC system in "00" - doing so will irreparably damage the motors and void the warranty."*

The source is:

https://www.katousa.com/HO/P42/maintenance.html

This can be found on the DCC Wiki:

> *"Coreless motors and other low inductance types of motors should not be used on a DCC powered track (unless a DCC decoder is installed).*
> *Normally, current flow is limited by the back EMF that a motor generates when it is spinning, but the DCC waveform is full voltage all the time, even when address 00's throttle is closed, the zero stretching is at a minimum, and the motor is stopped.*
> *The waveform is not high enough in frequency for the low inductance to limit the current flow when there is no back EMF, so the windings look like a short.*
> *They lack the iron core to sink the heat generated by excessive current flow, which will kill them very quickly.*
> *Coreless motors are very expensive."*

The source is:

https://dccwiki.com/Zero_Stretching

Coreless motors were initially used in smaller gauges, such as this Meridian Model MDP18 with its 18mm wheelbase.

They are now to be found in more general use as these examples show:

Graham Farish

Bachmann

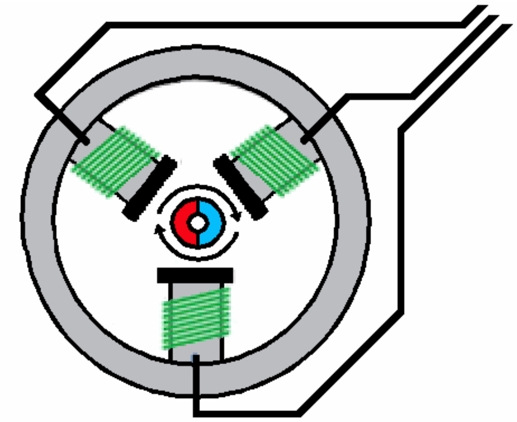
Kato

You can find a short video clip of a cored and coreless motor being stripped down for caparison at:

https://www.youtube.com/watch?v=SBaiLTleOs0

Brushless motors

This motor differs from the previous two types in that the coils remain stationary while the magnet rotates.



The other motors use brushes rubbing on the commutator segments to systematically direct the current through one coil to the next.
With brushless motors, each coil is switched electronically. The coil current is switched using position sensors (mostly Hall Effect types).
You already use these in your computer, for the cooling fan and in your disc drives.

Main features

- Faster speed for same voltage (less friction)
- Higher torque to weight ratio than brushed motors
- Lower current
- Longer life (nothing to wear out except the bearings)
- Low noise (no commutation noise)
- No sparks (no commutator and brushes)
- Compact size
- Light weight (no heavy metal poles)

Their absence of sparking brushes make them suitable for use in hazardous environments (mines, munitions factories).
Their long life makes them useful for installation in remote locations.

The motors in disc drives are run at a constant speed, with a built-in sensor checking the speed to keep the rotation constant.
Some computer fans run at a fixed speed, while others (those with built-in sensors) are able to have their speed altered to control the temperature inside the computer case.

Brushless motors tend to be the most expensive.

These types of motor are not to common on model railways.
Here is a Marklin loco that uses one.

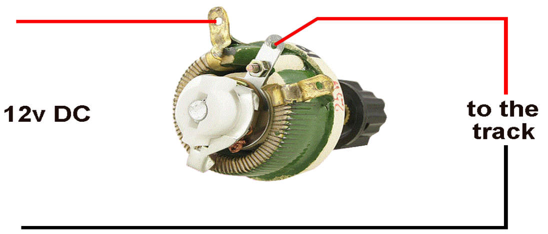
Note:
With no brushes, these motors produce no radiated interference to other modules.
Brushed motors create commutation pulses at a high frequency and a small suppression capacitor (around 100nF) is usually fitted directly across the motor's terminals.
Do not do this with DCC as it will degrade the DCC signal. The loco will still receive power but the control message to the decoder will be affected.

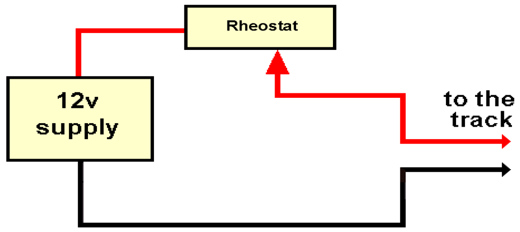
Loco controllers

As you have probably found out, loco controllers are available in all shapes, sizes, prices, with different facilities, accessories and so on.
But let's start at the beginning.

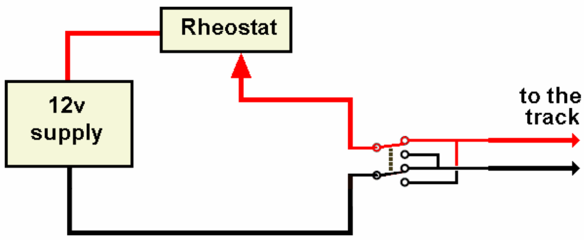
The simplest controller

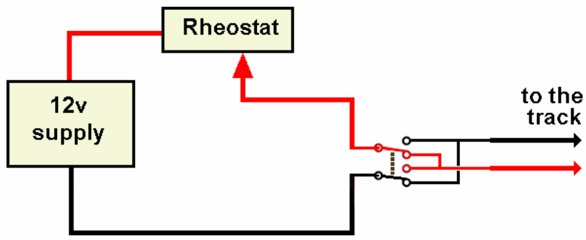
Here is the simplest DC speed controller – one that was used extensively in early model railway controllers. It uses a *'rheostat'* (a large wirewound variable resistor capable of handling large currents). As the knob is turned, the wiper rubs across the windings, varying the resistance placed in series with the locomotive's electric motor.
Turning the knob clockwise decreased the added resistance, increasing the voltage across the motor, thus increasing the current flow and the motor speed.





This works well on a basic level but it only allows the loco to travel in one direction – there is no facility to change loco direction.
Reversals are achieved by adding a DPDT (double-pole, double-throw) switch to the circuit.





Overload protection

No matter how well you build and run a layout, there are always unexpected derailments with wheels shorting across points or the track.
Our circuit above would not be able to cope with short circuits. If the rheostat was turned to minimum or no resistance, then there is almost no resistance across the power supply. Unless the power supply had its own protection, there would a huge amount of current (limited only by the current rating of the transformer). The wire windings of the rheostat would then act more like the bar of an electric fire – unless the diodes blew in the supply.
You could fit a simple fuse between the power supply and the rheostat but that would be a bad idea, as it would need to be replaced regularly.
It is best to fit a circuit breaker. The one on the left is a thermal breaker (it breaks and resets itself when the short is gone). The one on the right needs to be manually reset, like in your domestic fusebox.

If you want, go to eBay or an electronic supplier, buy a rheostat, a DPDT switch and a circuit breaker – and you can build your own basic DC loco controller!
Rheostats are expensive so many circuits replace them with power transistors which are cheaper and smaller. Apart from that, they function in the same way – reducing or increasing the resistance between the supply voltage and the loco's motor.
Of course, you will not have the most refined controller like those that are now available.

What are problems with a basic controller?

Jerky starts

This is an all too familiar problem. The loco is stationary and you increasingly turn up the speed knob to find nothing happens – until the loco suddenly speeds away (a condition sometimes called *'jump starting'*). The effect is unrealistic and unsatisfactory.
The sources of the problem can be both mechanical and electrical.

Static friction

The motor and its gears have their maximum friction when they are stationary, a phenomenon unsurprisingly called *'static friction'* or *'stiction'* As the loco's speed control is turned up, the increasing current through the motor has no effect – until it is sufficient to overcome the static friction. By this time, the speed setting is well advanced and the loco flies off.

Cogging

See earlier section of this chapter for a full explanation.

Motor resistance

This is the main cause of jerky starts.
Its cause, back-emf, was covered earlier.

Loco slows or stalls

When an electric motor is presented with a greater load, its speed will slow. This reduces the back emf and results in it drawing a higher current and effectively lowering its resistance. Since this current flows through the controller as well as the motor, the voltage available to the motor is actually *reduced*, as the controller takes a greater proportion of the available voltage.
This explains why your loco slows on gradients, with heavy loads, or the friction of going round tight bends in the track. In the worst case, the motor voltage will drop to a level that prevents it from turning – a stall situation.

Jerky slow running

Some of the problems might simply be caused by dirt on the track, or the wheels or the power pickups. It might also be caused by poor mechanical transmission (motor gears, valve gear, coupling rods, etc.).
Otherwise, it is similar to the above problem. At slow speeds, most of the circuit resistance is in the controller and current changes affect the motor voltage less than the controller's resistance. There is insufficient torque (i.e. turning force) being created to maintain a smooth smooth rotation of the rotor.

Racing downhill

This is the opposite effect to slowing on inclines. When going down a gradient, the motor draws less current due to increased back EMF. The voltage across the motor increases and the loco speeds up.

Unrealistic performance

Unless you are very careful, it is difficult to achieve the realistic simulation of train inertia and momentum. It would be much better if the controller could simulate acceleration and deceleration effects.
So, if you suddenly turn the speed knob fully up you don't jerk away; you gradually build to maximum speed. Similarly, a quick turn of the knob fully down gradually slows the loco to a stop. In fact any speed changes should reflect the authentic performance of the loco.

Approaches to solving these problems

We can easily tackle mechanical issues with some cleaning, adjustments and lubricant.
The electronic problems mostly concern achieving and maintaining sufficient torque (i.e. turning force) in the motor.
If we can achieve sufficient instantaneous torque from the motor, we can overcome the retarding effects of friction and cogging – achieving smoother starts.
If we can maintain torque levels throughout the twists, turns, gradients and declines in the track, we minimize stalling and jerky slow running.

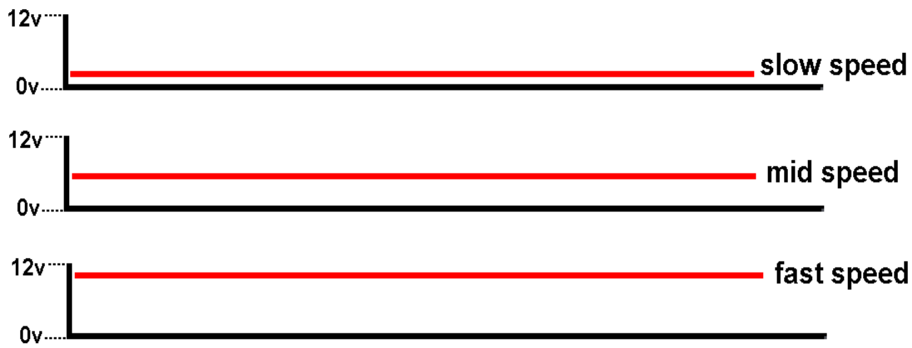
The two main ways that controllers tackle this is by:

- PWM – Pulse Width Modulation
- Back-EMF Feedback

PWM

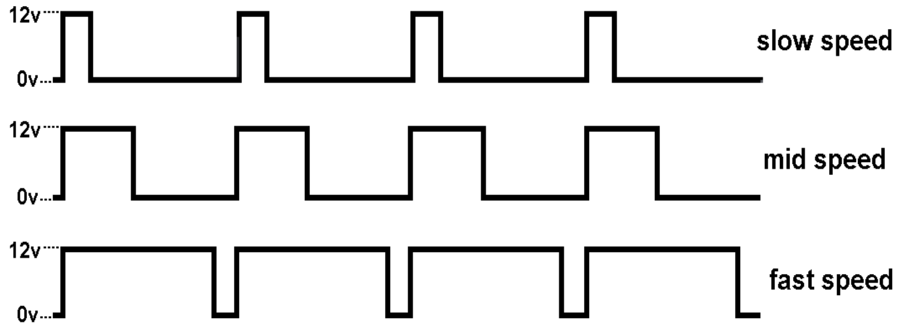
In most of the above situations, we wish we could just give the motor a bit of a 'kick' to get it started or to avoid jerking or stalling – and that's just what PWM aims to do. In fact, Pulse Width Modulation (PWM) is nothing other than giving the motor continual 'kicks'.
With normal DC, we change the voltage from 0V (stop) to maybe 12V (full speed), with every voltage in between.
At high voltages, we avoid some of the problems of stiction and cogging, due to the momentum of a high spinning motor.
It is at low motor voltages that the problems are mostly evident.

If you could look at the voltage across a motor when using ordinary DC, it would like these three charts which show the voltage at different speeds.



You can see how difficult it is to maintain torque at the slower speeds, with such small voltage levels.

A PWM signal, on the other hand, looks like this for the same three speeds.



At the faster speeds, the output looks similar to a normal DC voltage. In fact, at the very fastest speed, it would be a continual 12V just like normal DC.
It is the slow speed on that chart that is of the greatest interest. Instead of sending a small voltage (say 2V) to the motor, a succession of 12V pulses are sent to the motor. Over a period of time, its effective voltage is the same as the small DC voltage. If you tried to measure the signal with a meter, it would look like a low voltage, as the meter would average out the pulses.
However – and this is the big advantage – the 12V kicks provide the instantaneous torque that tackles stiction and cogging. Its increased torque also minimises problems with stalling and jerky slow running.

The PWM signal has two factors:

- How often the 'kick' happen – known as the *'clock cycle'*.
- How long the pulse lasts – known as the *'duty cycle'*.

The clock cycle is measured in Hz and the duty cycle is measured as a percentage of the available time.
In the example, the duty cycle's slow speed is running at 10%, the mid speed at about 40% and the fast speed at around 90%.

Clock cycle

The clock cycle cannot be too long, as the pulses would appear too infrequently to be effective. If the clock cycle is too short, the pulses would be arriving at a much faster rate. At excessively high frequencies, the coil in the motor behaves more like an inductor and its impedance (resistance to current changes) inhibits the passage of high frequency pulses and reduces the current flow through the motor.

There is no one frequency that can be applied to all motors. ZTC Controls produces a useful chart (see next page) that shows the best PWM frequencies to use for different motor types; it varies from 31Hz to 32kHz.

As a general rule, the older 3-pole open frame motors, with straight slotted poles, benefit most from running at lower frequencies.
Modern, 5 or 7-pole can motors, with skew wound poles, use mid frequencies.
Coreless motors can be run happily at higher frequencies, although slow speed running might not be enhanced.

CV9 Value	PWM Frequency(Hz)	Notes	CV9 Value	PWM Frequency(Hz)	Notes
255	31	Large	143	327	Low
251	33	Motors	139	357	Power
247	35	only	135	393	Precision
243	38		131	437	Motors
239	41		127	490	Only
235	41		123	523	
231	49		119	561	
227	55		115	604	
223	61		111	654	
219	65		107	714	
216	69	DEFAULT	103	786	
215	70		99	874	
211	75		95	980	
207	82		91	1046	
203	89		83	1208	USE
199	98		79	1309	EXTERNAL
195	109		75	1429	FILTER
191	123		71	1572	WITH
187	131	MOST	67	1748	SMALL
183	140	SMALL	63	1961	MOTORS
179	151	MOTORS	59	2092	ZTC150
175	164		55	2242	ZTC151
171	179		51	2415	&
167	197		47	2618	ZTC156
163	219		43	2857	
159	245		39	3145	
155	262		35	3497	
151	290		31	3922	
147	302		27	4184	
			23	4484	
			19	4831	
			15	5236	
			11	5714	
			7	6289	
			3	6993	
			1	16Khz	
			0	32Khz	Whisper drive, Coreless Motors RG4, RG7 etc Mini Motors, etc

Buzzing

The average human ear, depending on your age, can hear frequencies between 20Hz and 20kHz, with maximum sensitivity between 1Khz and 4kHz (your landline telephone only uses a band from 300Hz to around 3kHz).
With exception of the very highest frequencies in the ZTC list, all are within the human hearing range.
Feeding a motor with pulses in the audible range usually results in an distinct buzzing or humming sound from the motor. This is not normally harmful to the motor but some find it annoying.

To counteract buzzing, a loco controller can increase the frequency of its clock cycle, to take it beyond the range of human hearing. 16kHz usually is beyond the hearing of a middle-aged male, with frequencies up to 32kHz being beyond everyone's hearing ability.
The downside to a higher frequency is often poorer performance at slower speeds.

> **Note**
> If you are already using DCC, then your decoders are using PWM to control motor speed, set by the values in CV9 to match your individual loco's motors (see the chapter on DCC). This CV is sometimes referred to as the *'repeat rate'*. The value entered into CV9 is the period (the reciprocal of the frequency). So, higher values result in lower frequencies and vice versa. Decoder manufacturers like to promote their decoders' by describing their abilities to produce high frequency PWM. So, we have Silent Running(from NCE and Zimo), Supersonic (from Digitrax) and Quiet Drive (from TCS).

Duty cycle

The duty cycle decides the effective running speed of the motor. It is a ratio of the voltage's 'on' time to its 'off' time. A 0% ratio means the pulse has no width, hence zero volts, while 100% means the pulse has no 'off' time, resulting in the full supply voltage across the motor. While the clock cycle is a fixed value, the duty cycle will vary as the operator speeds and slows the loco.

If you go back a page and look again at the PWM waveforms, you can make the following observations. In the first chart, the 'on' time was 10% leaving an 'off' time of 90%. This would be known as 1:9 mark-space ratio and would be the equivalent of 1.2V DC for a 12V supply. The second chart would equate to 4.8V DC and the bottom chart would equate to 10.8V DC. If the operator tuned the control to full speed, there would be no 'off' period and the voltage on the motor would a continuous 12VDC (just like a straight DC controller).

While high mark-space ratios are broadly similar to normal DC working, the real benefits come at lower ratios. While a constant 1.2V DC supply exposes the motor to stalling, etc., the short bursts of full power produce greater torque and are much more likely to keep the motor turning.

Heat dissipation

In our earlier example rheostat controller, if we wanted to reduce a 12V supply to only 3V for the motor, we would have to drop the other 9V across the rheostat. If the loco consumed 1A, then the power developed in the rheostat would be a full 9W. The same power would be developed if we had instead used power transistors as the drive electronics. In both cases, the power would be dissipated as unwanted heat.

PWM working reduces the harmful overheating effects. With PWM, power is totally switched off during the 'off' times and the power developed during the 'on' times is nearly all used by the motor. There is very little wasted power in a PWM controller.

PWM is also very handy for the controllers built into DCC decoders, otherwise the excessive heat would melt the plastic bodies of the locos!

Lower clock cycles however, can have an effect on increasing the heating of the motor coil; this is usually worse for small motors with little metal to absorb the heat.

Conclusions on PWM

Despite the noise and heat problems, PWM offers a great step forward in obtaining much smoother running of locos, particularly at slow speeds.

Most DC controllers use PWM for that reason, and it is almost universally used as the motor control system built into DCC decoders.

For best results, the PWM clock cycle should be matched to the motors in use.

Feedback

Earlier, we looked at how a motor produces a back emf.

If we could detect these back emf changes, we would know if our loco was running slower or faster than the speed set by the operator. The controller's circuitry could then take steps to automatically adjust the loco's speed back to where it should be.

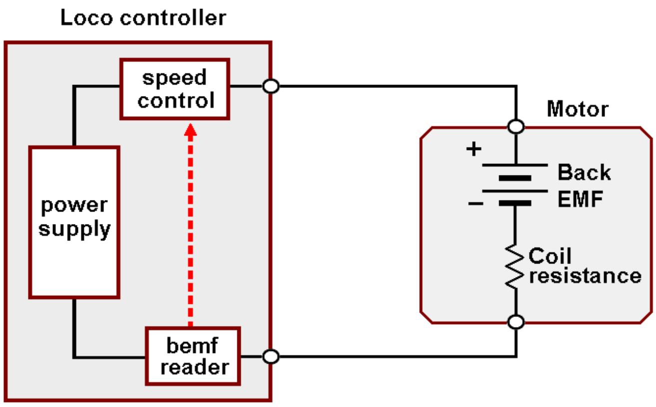
This approach is known as *'feedback'*, as the changes inside the motor are fed back to the circuit in the controller.

Of course, it is not possible to read this feedback at the same time as powering the loco.

So, the steps are:

- Power the loco.
- For a very short time, cut off the power.
- Read the feedback (the unpowered motor is still spinning due to momentum).
- Restore the traction power.

The illustration shows the principle of how it works.



The voltage from the controller is taken to the motor via the tracks.

When the feedback is to be measured, this voltage is cut off.

The back-EMF generated by the freewheeling motor is now on the tracks and fed back to the controller, but in the *opposite* polarity.

The detector circuitry measures the amount of back-EMF and compares it with previous readings.

If the readings are identical, no adjustments are made.

If the back-EMF reading has altered, either greater or smaller, this difference is used to alter the speed control's output (see the red dotted link) to compensate.

Three different control systems use feedback techniques.

- In a normal DC feedback controller, the circuit has to make periodic power breaks to allow the bemf to be measured. These breaks may only last less than a millisecond and need only occur infrequently (maybe every second or less).
- In a PWM-based controller, the power is being switched on and off continuously anyway, so it is easy to read the feedback during some of the 'off' periods of the duty cycle.
- In a DCC system, the bemf is read within the decoders, with no involvement on the part of the controller.

Controllers which combine PWM and back-EMF feedback, and also DCC decoders, provide much more consistent running than normal DC controllers.

You can expect:

- Elimination, or a huge reduction, of jerky starting.
- Improved slow running.
- Reduction in stalling.
- Consistent speeds up and down gradients and on track curves.
- Speed calibration on DCC, so that all locos run at the same speed on the same controller setting.

However, a balance has to be struck between improved running and having a train that runs at the same speed under all conditions (like a car's cruise control). After all, you would expect a train to slow somewhat on an incline.

The benefits of bemf may vary with older motors benefiting more then efficient modern motors.

Note

Coreless motors are problematic with bemf controllers. With no heavy metal core to maintain momentum, the rotor decelerates rapidly and does not produce much bemf. This, plus the lower inductance of the coils means that any bemf value does not accurately reflect the actual speed of the loco.
The PICtroller claims to automatically senses the motor type and adjust the operating parameters to suit cored or coreless motors, although this has been reported not be a complete solution.
In most cases, it is best to operate coreless motor with feedback switch off. For DCC, use a decoder with a high frequency PWM

Other features

Other useful features for a loco controller are the ability to introduce acceleration and deceleration. The controller converts an operator's sudden large speed change into a gradual increase or decrease in speed.
No more jerking away from a standstill, or screeching to a sudden halt, or lurches as the speed is altered by substantial amounts.
The controller's circuitry ensures gradual pulling away and slowing to a halt.
In DCC systems, this facility is saved as user-defined values inside in the DCC decoders.