Towards Better Control of Small D.C. Motors

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The circuit was designed for controlling model locomotives but can be used in any application which requires that the speed of a small d.c. motor remains constant under varying loads. The supply to the motor is pulsed; the rate the pulses are applied is determined by comparing a potentiometer-set voltage specifying required speed with the motor's back e.m.f. The back e.m.f. is measured between pulses when there is no supply on the motor. The idea is based on a circuit which appeared in *Control* (Oct. 1967).

The use of electronics to improve the control of very small permanent-magnet motors has intrigued the model railway fraternity ever since transistors first became available to the hobbyist. As the scale of the models has diminished, so the scale of the problem has increased and called for greater ingenuity. The electronic regulator to be described was developed for an N-gauge model railway (scale-1:148), but the improvement in performance the circuit gives over conventional circuits has been so substantial that the idea is likely to be of value to all who need to control the speed of small d.c. motors under varying loads.

Earlier solutions

Rheostat control: The classical method of controlling a small motor is to wire a variable resistance in series with the supply. This allows continuous control of the armature current, and hence of torque. Trouble occurs at low speeds as the torque is substantially independent of back e.m.f. (whose mean value is proportional to motor-speed) and the speed therefore becomes very dependent on load.

Pulse controllers: A popular and simple improvement over the variable resistance method consists of allowing unsmoothed pulses of mains ripple from a rectifier to reach the motor. This technique gives better low-speed performance because the alternating component, rich in harmonics, contributes greatly towards overcoming the high 'stiction' of small motors. The model can consequently be run at a lower speed without stalling than is possible if a smooth voltage were applied. Pulses can be generated by more sophisticated means than this, and a great deal has been written about the best shape and p.r.f. for the job. However, this system does not provide any improvement in load regulation.

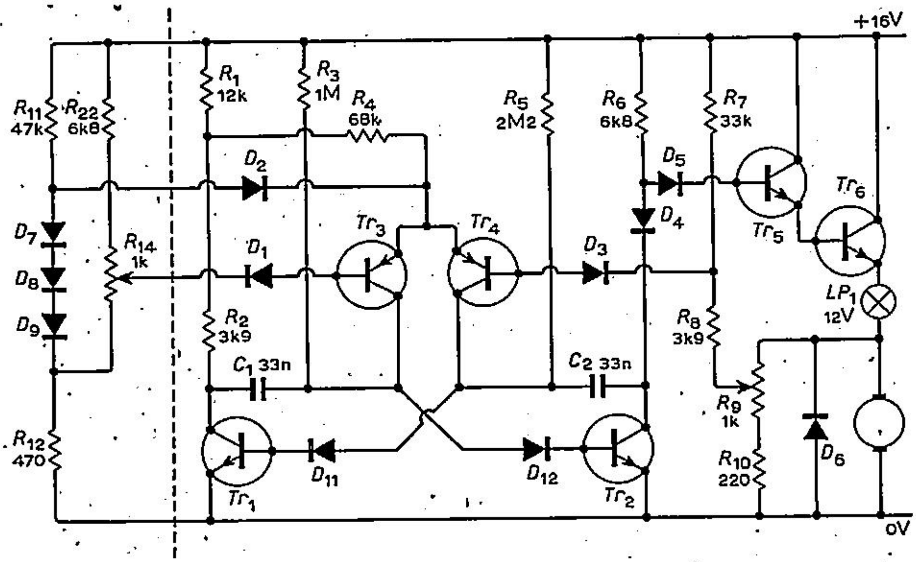


Fig. 1. Circuit of the d.c. motor speed controller. Potentiometer R_{14} is the speed control.

Emitter follower: A different line of attack has been the use of Darlington or compound emitter followers to provide a low impedance variable-voltage source to power the motor. This is very effective for motors with low armature winding resistance, because when the back e.m.f. becomes less than the source voltage a large current will flow in such a direction as to tend to make the two voltages equal. Unfortunately the armatures of many small motors for models are deliberately wound with many turns of thin wire having a high resistance in an effort to cause them to run slowly, so that more than half the applied voltage is dropped across the armature resistance. The value of an emitter-follower controller is, in this instance, much reduced.

Negative resistance: An ingenious and moderately successful attempt to deal with the armature resistance was described by H. M. Butterworth[1], who arranged to balance it out in a Wheatstone bridge circuit and was able to isolate the back e.m.f., compare it with an e.m.f. proportional to the desired speed, and amplify the difference to drive the motor in such a direction as to make the two e.m.fs. equal. This was equivalent to connecting an equal negative resistance in series with the armature resistance. The circuit has therefore to be matched to a particular motor, and on small two-rail systems where electrical pick-up is made from the running-wheels its performance is reduced by the extra resistance due to dirt and corrosion on the rails. It is also surprisingly difficult to measure the effective armature resistance by a direct method because in the normal type of 3-pole motor the commutator segments are arranged to switch in alternately two coils in parallel, followed by two in series with each other and in parallel with the third, as the rotor rotates.

A solution

The circuit of Fig. 1 takes advantage of the best aspects of earlier work in this field and overcomes all the problems which have been mentioned above. Drive to the motor is by voltage pulses from a free-running multivibrator, and during each pulse the full voltage of the supply is switched across the motor. In the interval between each pulse and the next, the back e.m.f. is monitored and compared with a reference; the result of the comparison determines whether the subsequent pulse is accelerated or retarded, thereby tending to correct any error in the motor speed.

K. C. Johnson[2] has described a similar method for controlling an electric drill but using unsmoothed a.c. and a thyristor. In this application the multivibrator was preferred because of its greater flexibility in respect of p.r.f. and duty cycle. Because the back e.m.f. is measured when no current is flowing, the regulator will accommodate wide variations in circuit resistance, without requiring to be matched to the load.

In operation the circuit has added strikingly to the realism of a model railway, allowing trains to be accelerated and decelerated as smoothly and gradually as any operator could wish. Because of the closed-loop nature of the circuit, models exhibit no tendency to stall or race on gradients, and when left running trains maintain a steady speed regardless of track conditions and load (this feature may not appeal, of course, to those enthusiasts who favour realistic prototype steam locomotive behaviour!). Although one preset is provided the circuit is not at all critical and once set up will certainly accommodate any model of the same gauge without adjustment.

In Fig. 1, Tr_1 and Tr_2 are the multivibrator transistors. Capacitor C_1 determines the duration of the pulse and C_2 the interval between pulses. During the interval between pulses Tr_3 and Tr_4 form a long-tailed pair differential comparator, comparing the reference voltage set on the potential divider R_{12}, R_{14} and R_{22} (R_{14} is the speed control) with the back e.m.f. of the motor (now acting as a tachometer generator). The back e.m.f. appears at the cathode of D_3 after being attenuated by R_9 and R_{10}, and level-shifted by R_7 and R_8. During the interval Tr_2 is conducting and Tr_1 is cut off, C_2 is discharging through R_5 and Tr_4; if the back e.m.f. is too low Tr_4 takes most of the tail current and discharges C_2 quickly, thereby increasing the mark-space ratio. If the back e.m.f. is too great, the reverse happens, Tr_4 takes little of the tail current and C_2 discharges slowly through R_5.

During the pulse the voltage across the motor is greater than the back e.m.f. and so D_3 and Tr_4 are non-conducting and all the tail current passes through Tr_3, discharging C_1. However, since the tail (R_4) is not taken to 16V, but to the junction of R_1 and R_2, the voltage across it during the pulse is much less than during the interval, and is dependent to a much greater extent on the reference voltage set on R_{14}. Resistors R_1 and R_2 are chosen so that at the maximum setting of R_{14}, no current flows in R_4, and C_1 discharges slowly through R_3. At low settings of R_{14}, C_1 discharges about twice as quickly, partly through R_3 and partly through Tr_3; consequently the pulse duration is varied directly by the speed setting in anticipation of a greater mark-space ratio, preventing excessively wide variations in p.r.f. over the operating range.

When R_{14} is set to minimum D_2 conducts, causing enough current to pass through Tr_3 to discharge C_1 very quickly, generating very short pulses. The object of this is to prevent the locomotive from inching forward when the speed is set to zero. The short pulses may just be heard as a low buzz from the motor. Resistors R_7 and R_8 have been chosen so that at this setting Tr_4 does not conduct, and the p.r.f. is minimum.

The diode D_4 is needed to prevent the multivibrator from synchronizing with the mains ripple on the supply or switching off prematurely owing to the effect on the supply of the sudden load following the onset of a pulse. In the absence of this diode any fall in voltage at either end of R_6 during the pulse would be transferred through C_2 to the base of Tr_1, switching the latter off and causing the pulse to disappear. If other circuits are to be fed from the same rectified supply, a second diode should be similarly located in the Tr_1 collector circuit.

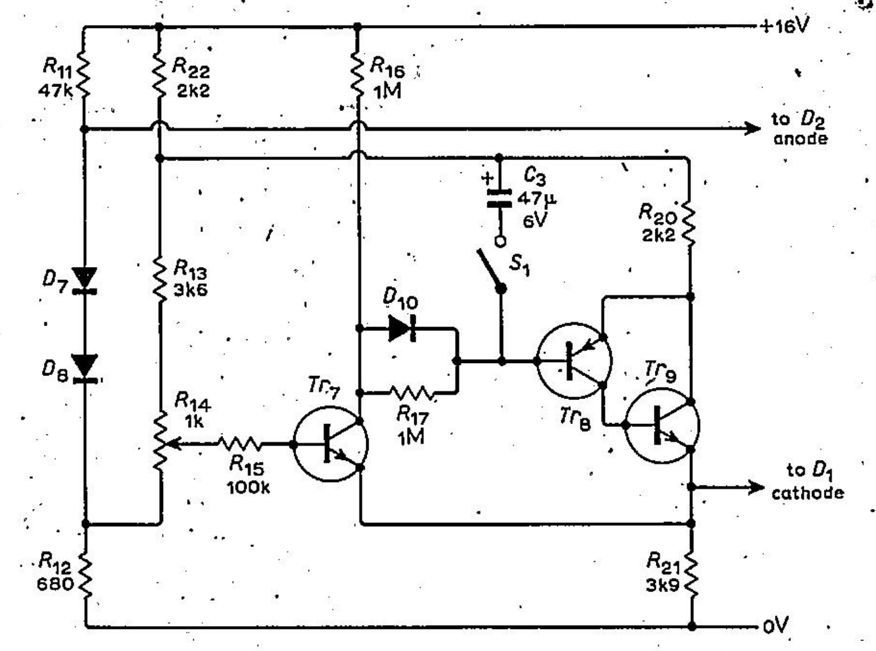


Fig. 2. Add-on circuit which gives a motor a controlled rate of acceleration and deceleration.

The pulse is coupled to the load via the Darlington emitter follower Tr_5, Tr_6, and the lamp LP_1, which provides both overload protection and indication. An incandescent lamp filament does not obey Ohm's Law, but conforms approximately to a square law, and so at half its rated current drops only one-quarter of its rated voltage, leaving the remainder to power the locomotive.

The quenching-diode D_6 is provided to 'catch' the negative-going spike at the end of each pulse caused by the inductance of the armature winding, which tries to maintain the current set up during the pulse.

Acceleration and deceleration control

It will not be denied that the circuit, Fig. 1, is a good deal more complicated than most model train controllers, but its performance really does justify the extra expense. In any case the cost of the circuit in Fig. 1 is still unlikely to be much more than that of the mains transformer needed for any such unit. However, for those with a positive passion for realism an auxiliary circuit is described (Fig. 2) which will control the rate of acceleration and braking to simulate the inertia of the more massive, under-powered real thing. A simple resistor and capacitor will not do this because of the exponential characteristic, but by amplifying the curve and using a small part of it, such a network may be used to effect nearly uniform acceleration and deceleration. Much satisfaction is to be derived from setting up the speed on the controller and watching the train slowly accelerate away as if under its own volition.

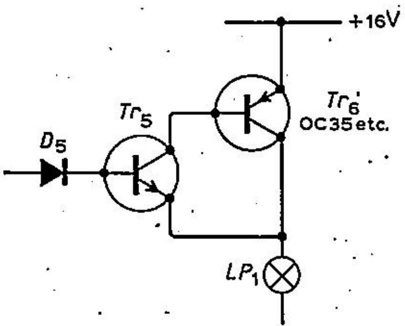


Fig. 3. If wished the n-p-n output transistor of Fig. 1 can be replaced with a p-n-p type.

The circuit uses a composite transistor, Tr_8, Tr_9, to avoid loading the relatively small timing-capacitor C_3. Any change in the setting of R_{14} causes Tr either to bottom or to turn off, and C_3 then discharges or charges very slowly through R_{17} or R_{16} and D_{10}. The slowly changing voltage appears on the emitter of Tr_8, and a similar voltage changing slowly in the opposite direction is present at the emitter of Tr_9 because nearly identical currents flow in R_{20} and R_{21}. When the voltage on R_{21} reaches about 600mV, below that set on R_{14}, Tr_7 resumes its initial state of conduction. If switch S_1 is left open, the speed will respond immediately to the setting of R_{14}.

Practical points

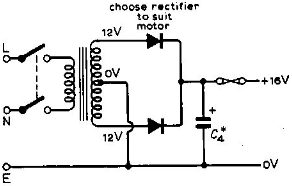
Transistors Tr_1, Tr_2, Tr_5 and Tr_9 must be very high gain silicon transistors having an h_{fe} of not less than 200 (BC109 or 2N930); Tr_3, Tr_4, Tr_7 and Tr_8 should all be silicon, but no other special characteristics are required.

The choice of Tr_6 and the lamp are closely linked with the maximum load intended. The lamp should be for 12V operation and the range of motor car lamps available give one a wide choice. For small models taking about 250mA when running uphill with a train, use a 2N1613 or one of the ZTX300 series (or any 500mA transistor) with a 5 or 6W lamp (BFS254, BFS980, side-lamp bulbs). For locomotives requiring 500mA the BFY50 series of transistors (rated 1A) is available, and a 12W lamp is called for (which might be difficult to obtain). If this is the case use a 21W lamp (BFS380, BFS382) and a power transistor although, because it is either off or dropping only a volt or two, no heat-sink will be required. For those wishing to use a p-n-p transistor such as OC35, a compound emitter follower circuit is given in Fig. 3. Few trains will require as much as 1A even with double-heading, but it is as well to bear in mind that as motors age and lose their magnetism they consume more current.

The diodes should all be silicon small-signal devices, such as 1N914.

Resistors R_7, R_8, R_{12}, R_{13}, and R_{22} must be 5% tolerance or better, but the remaining resistors may be 20%; R_9 and R_{14} should be linear, and preferably wirewound.

A suitable power supply circuit is given in Fig. 4; C_4 should be rated at least 20V and have a value not less than that given in the table.



max mean motor current Amps	Tr_6 I_{CM} rating Amps	lamp rating Watts	C_4^* μF
0·25	0·5	5 or 6	500
0·5	1·0	12	1,000
1·0	2·0	21	2,000

Fig. 4. Circuit of a suitable power supply.

The use of the preset R_9 will become obvious when the unit is tried out, and no instrument is needed to set it up. It merely allows the working range of the speed control R_{14} to be adjusted to suit the user and the general characteristics of the gauge of model in use. Larger gauges, though still nominally 12V, will tend to produce larger back e.m.fs than smaller ones. Some operators, too, are known to run their models at a maximum speed which would put the advanced passenger train to shame; but most will want to restrict maximum speed to safe limits and R_9 allows both to have their way.

The value of C_3, which determines acceleration and braking rates, is a compromise between pedantic realism and what is practical on a small layout. To obtain differing rates of acceleration and braking, vary R_{17} or R_{16}.

Specification

Dynamic pulse duration: variable between 10 and 20ms
Idling pulse duration: 1.0ms
Minimum pulse interval: 2.5ms
Maximum pulse interval: 50ms
Maximum back e.m.f. accommodated: variable between 1.5 and 12V
Acceleration and braking (Fig. 2 only): start to maximum and maximum to stop in 12s
Nominal operating voltage: 12V

REFERENCES

1. H. M. Butterworth, "Speed Control for D.C. Model Motors", *Wireless World*, September 1967, p.440.
2. K. C. Johnson, "Thyristor Speed Control for Electric Drill Motors", *Wireless World*, July 1967, p.328.