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Controlling DC Power with Pulse-Width Modulation

IF YOU NEED to control the speed of a small dc motor, the brightness of a lamp, or otherwise drop a dc voltage, consider using pulse-width modulation (PWM). Ordinarily, dc power is controlled by dropping a portion of the available voltage across a variable resistor or a potentiometer-governed pass transistor. This method, although it is inexpensive, has two major drawbacks. It is inefficient in that much of the energy potentially available to the load is dissipated as heat by the transistor or resistor. Also, in the case of a motor, start-up is awkward because torque decreases with motor speed. Here we will describe how PWM can be employed and will present a working PWM control circuit you can assemble from inexpensive readily available parts.

PWM (and Motor) Basics. Shown in Fig. 1 is a circuit which demonstrates the operating principle of a PWM power controller. It consists of a power supply represented as a battery, a switch *S* and a dc motor. During the interval T_{OFF}, switch *S* is open and the motor receives no voltage (or current) from the supply. During the interval T_{ON}, the switch is closed and the motor receives the full supply voltage and draws the maximum amount of current from the supply (assuming there is no load on the motor). Over the long term, the average voltage applied across the motor is determined by the ratio $T_{ON}/(T_{OFF} + T_{ON})$.

The speed of a dc motor is primarily determined by the average voltage across the rotor coil (or the average current flowing through it) and the strength of the magnetic field surrounding the armature and rotor coil. An increase in applied voltage or the surrounding magnetic field (or both) will cause an increase in rotor speed. In most small motors, the magnetic field is generated by a permanent magnet and is therefore fixed.

The amount of torque (torsion or twisting force) a motor generates, as well as its power, which relates torque to time, are also affected by the applied voltage and surrounding magnetic field. An increase in either or both will result in an increase in torque and power. Torque is important if the motor is to be smoothly brought up to speed from a dead stop—an almost impossible feat using variable-voltage techniques, but a simple task for a PWM controller.

The relationship between motor torque and rotor current and the effects of a motor's *time constants* make PWM an effective way to control motor speed. A motor's mechanical time constant is that interval required for the motor to accelerate from 0 rpm to 63 percent of its maximum rotational velocity. This time constant typically varies from 5 to 200 milliseconds and depends on the size and design of the motor. The inductive time constant is the period required for the rotor current to increase from zero to 63 percent of its ultimate value, about 0.2 times the mechanical time constant.

If the T_{ON} interval of the control switch is shorter than the motor's mechanical time constant, the inertia of the motor will act as an averaging device and the motor will rotate at a speed that is less than the maximum the motor can deliver. Also, keep in mind that the torque a motor can generate is proportional to the applied voltage and the amount of current flowing through the rotor coil. It is therefore possible to obtain a large amount of torque, even at slow speeds, by applying constant-amplitude voltage pulses to the motor. The pulses should be long enough to allow rotor current to increase to a substantial value but short enough (or spaced far enough apart) so that either the motor cannot achieve its full speed or the average voltage is low.

This allows very smooth start-up of a dc motor, something that is rarely achieved using variable-voltage control. What usually happens in a variable-voltage system is that the motor speed control must be advanced to the point when there is enough rotor current flowing (and enough torque generated) to allow the motor to "break loose." When the motor finally does start turning, its speed quickly becomes so great that the operator must dramatically back off the control to slow the motor down. If he reduces the control setting too much, the motor will stall. Model railroaders, boaters, and others who use variable-voltage control of small dc motors are painfully aware of awkward, unrealistic start-up and the difficulties of maintaining slow-speed control. For them, PWM is an ideal solution. What follows is a description of a working PWM controller that can be used with loads drawing as much as several amperes of dc.

The PWM Controller The controller (Fig. 2) employs the familiar 555 timer IC operating in the astable mode, but there is a twist—the multivibrator produces square waves of a constant frequency but variable duty cycle. The addition of silicon switching diodes *D1* and *D2* (1N914 or similar) makes this possible. Here's how.

Assuming *C1* is initially discharged, the output of the IC (pin 3) remains low as the capacitor starts to charge up toward the positive supply voltage. The capacitor receives charge via *R1* and the wiper, which we will refer to as *R2A*. Diode *D1* is forward-biased and effectively connects the positive plate of the capacitor to the wiper of the potentiometer. Diode *D2*, on the other hand, is reverse-biased and isolates the capacitor's positive plate from *R3* and the other portion of the potentiometer, which we will call R2B.

When *C1* charges up to two-thirds of the positive supply voltage, a flip-flop inside the IC toggles and simultaneously forces pin 3 high and pin 7 low. The capacitor then starts to discharge through

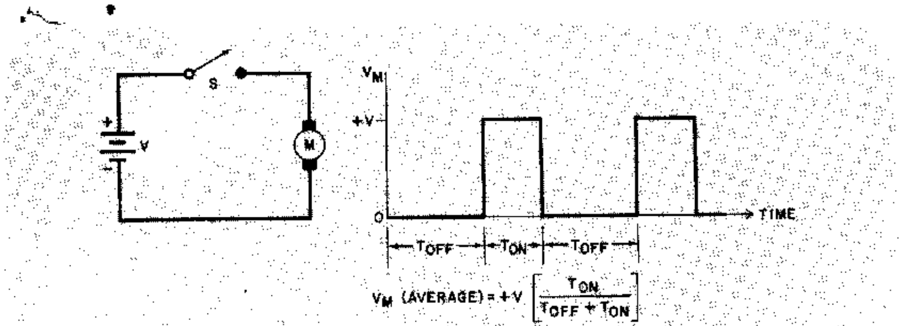

Fig. 1. In basic PWM, switch S is toggled to create dc pulse train across the motor. The longer time T_{ON} is, the higher the average voltage across the motor and the faster the motor turns.

D2, which becomes forward-biased, through *R3*, and through *R2B*. Diode *D1* is reverse-biased and acts like an open circuit. Discharge continues until the voltage across the capacitor decreases to one-third of the supply voltage, at which time the internal flip-flop toggles again and causes pin 3 to go low and pin 7 to go high. Capacitor *C1* then starts to charge up again toward two-thirds of the positive supply voltage, and the cycle repeats itself endlessly.

A train of pulses much like the waveform shown in Fig. 1 appears at the output of the timer IC. The T_{OFF} interval corresponds to the time that pin 3 is low, and the T_{ON} interval corresponds to the period that pin 3 is high. Substituting our component labels for those found on manufacturer's 555 data sheets, we find that:

$T_{ON} - 0.7 (R1 + R2A) C1$,
$T_{OFF} = 0.7 (R3 + R2B) C1$, and
$T = 0.7(C1)(R1 + R2A + R3 + R2B)$
$= 0.7(C1)(R1 + R2 + R3)$

where T is the total period of the output waveform, the reciprocal of the output frequency. It can be seen upon inspection of these equations that T_{ON} and T_{OFF} vary with the setting of *R2*, but the total period of the waveform, and hence its frequency, do not.

For the component values given, the duty cycle of the waveform (the ratio of T_{ON} to T_{ON} plus T_{OFF}) varies from approximately 5 to 95 percent of the total period of the waveform, depending on the setting of *R2*. The total period should be about twice the motor's mechanical time constant, which you probably won't know if you've paid less than $10 for the motor. If that is the case, simply experiment with the value of *C1* until you achieve the desired result. As a general rule, the smaller the motor, the smaller the capacitance required.

The schematic suggests a capacitance of from 0.1 to 10 µF for *C1*. Neglecting tolerances, the period of the output waveform will be 0.0038 second and its frequency 263 Hz if a 0.1-µF capacitor is used. The period will be 0.38 second and the frequency 2.63 Hz if the value of *C1* is 10 µF. Substitutions can be made for *R1*, *R2* and *R3*, but the two fixed resistors should not be less than 1000 ohms.

A 555 timer can sink or source up to 200 mA of current. That's more than enough for some small motors, but to increase the circuit's flexibility, a high-power driver transistor has been included. Designated *Q1*, the transistor receives base drive from the timer IC via *R4*. The transistor alternately conducts and turns off in step with the output of *IC1*, acting like a switch to govern the operation of the motor. Diode *D3* has a dual function. It not only protects *Q1* against the inductive spikes generated across the rotor coil but acts as a "free-wheeling" diode. That is, it shunts the motor during the T_{OFF} interval, during which the motor acts as a generator. The diode employed as *D3* should be capable of handling one-half the current drawn by the motor and have a suitable PIV rating.

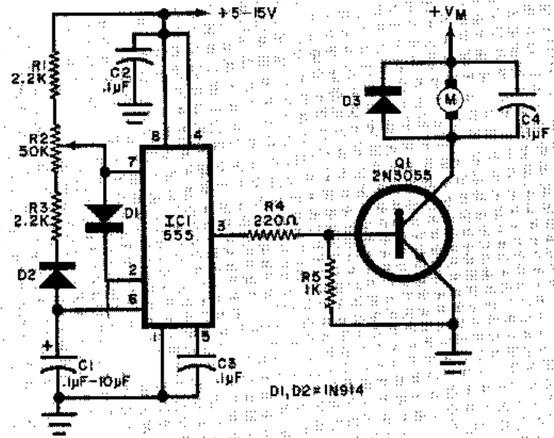

Fig. 2. A PWM controller for dc-powered loads. Timer IC1 generates a pulse train of constant period but variable duty cycle.

Other Approaches. There are many ways to obtain a pulse train with a variable duty cycle, the 555 circuit just presented being only one method. For example, an astable multivibrator triggering a monostable multivibrator with a variable-output pulse width could be used. The variable resistance in the one-shot circuit could be programmed using a rotary switch or a BCD thumbwheel switch teamed up with a BCD-to-decimal decoder chip and a group of fixed resistors. This would allow selection of one of several discrete motor speeds instead of continuously variable control.

A microprocessor could be programmed to provide a pulse train with a variable duty cycle. (It's always nice to find another use for that micro!) However, the limited current-sourcing abilities of microprocessors make it advisable either to connect a small npn transistor (2N2222 or similar) to *Q1* in Darlington or replace *Q1* with a commercial power Darlington device.

Pulse-width modulation can be used to control loads other than motors. For example, a lamp can be substituted for the motor in Fig. 2 and the "free-wheeling" diode removed. The circuit is now an efficient dc lamp dimmer. (The familiar ac lamp dimmers operate on this principle, employing thyristors as power switches.) Voltage dropping can also be accomplished using PWM, especially if the dropped voltage need not be very "clean" dc. Simply replace the lamp with the load you want to power and adjust *R2* until the required voltage drop exists across the load. Connecting a good filter capacitor across the load will smooth out the dc. Also, the higher the frequency of the pulse train driving the transistor, the easier it is to smooth the dc into an acceptable supply voltage. ◇