Pulse Width Modulated (PWM) Controller for 12 Volt Motors

This electronic controller is designed to allow a user to vary the speed and power output of a typical 12 volt motor such as a fuel pump, water injection pump or cooling fan. It could also be used as a secondary injector controller. Other uses, robots and small electric scooters and carts. Anywhere a 12 volt DC motor needs to vary speed or power. This controller circuit allows setting a "Low speed" when full power is not needed and a "Hi speed" for use when full power is needed. An additional feature included is a "Progressive" feature that smoothly ramps speed up from Low speed to Hi speed based on an input signal of 0-5 volts. This circuit will be offered both in kit form and fully finished.

The inspiration was a request to control the speed of a large positive displacement fuel pump. The pump was sized to allow full power of a boosted engine in excess of 600 Hp. At idle or highway cruise, this same engine needs far less fuel yet the pump still normally supplies the same amount of fuel. As a result the fuel gets recycled back to the fuel tank, unnecessarily heating the fuel. This PWM controller circuit is intended to run the pump at a low speed setting during low power and allow full pump speed when needed at high engine power levels.

Motor Speed Control (Power Control)

Typically when most of us think about controlling the speed of a DC motor we think of varying the voltage to the motor. This is normally done with a variable resistor and provides a limited useful range of operation. The operational range is limited for most applications primarily because torque drops off faster than the voltage drops. Most DC motors cannot effectively operate with a very low voltage. This method also causes overheating of the coils and eventual failure of the motor if operated too slowly.

Of course, DC motors have had speed controllers based on varying voltage for years, but the range of low speed operation had to stay above the failure zone described above. Additionally, the controlling resistors are large and dissipate a large percentage of energy in the form of heat.

With the advent of solid state electronics in the 1950's and 1960's and this technology becoming very affordable in the 1970's & 80's the use of pulse width modulation (PWM) became much more practical. The basic concept is to keep the voltage at the full value (in this case 12 volts) and simply vary the amount of time the voltage is applied to the motor windings. Most PWM circuits use large transistors to simply allow power On & Off, like a very fast switch. This sends a steady frequency of pulses into the motor windings. When full power is needed one pulse ends just as the next pulse begins, 100% modulation. At lower power settings the pulses are of shorter duration. When the pulse is On as long as it is Off, the motor is operating at 50% modulation.

Several advantages of PWM are efficiency, wider operational range and longer lived motors. All of these advantages result from keeping the voltage at full scale resulting in current being limited to a safe limit for the windings. PWM allows a very linear response in motor torque even down to low PWM% without causing damage to the motor. Most motor manufacturers recommend PWM control rather than the older voltage control method.

PWM controllers can be operated at a wide range of frequencies. In theory very high frequencies (greater than 20 kHz) will be less efficient than lower frequencies (as low as 100 Hz) because of switching losses. The large transistors used for this On/Off activity have resistance when flowing current, a loss that exists at any frequency. These transistors also have a loss every time they "turn on" and every time they "turn off". So at very high frequencies, the "turn on/off" losses become much more significant. For our purposes the circuit as designed is running at 526 Hz. Somewhat of an arbitrary frequency, it works fine. Depending on the motor used, there can be a hum from the motor at lower PWM%. If objectionable the frequency can be changed to a much higher frequency above our normal hearing level (>20,000Hz) .

Note that I am using the terms "full power", instead of "full speed". Although we tend to think in terms of motor 'speed' both methods discussed are really varying the "power" available to the motor. The actual speed of the motor is the result of the load curve of the application. An axial fan has basically a linear load curve. As power goes up, speed will increase linearly. A centrifugal fan has a velocity squared load curve. To double the speed the power will have to be four times as great. The point is that we are not really controlling speed as much as power to the motor. So depending on the application, speed will not always be directly in relation to the PWM%.

<u>PWM Controller Features</u>

This controller offers a basic "Hi Speed" and "Low Speed" setting and has the option to use a "Progressive" increase between Low and Hi speed.

Low Speed is set with a trim pot inside the controller box. Normally when installing the controller, this speed will be set depending on the minimum speed/load needed for the motor. Normally the controller keeps the motor at this Lo Speed except when Progressive is used and when Hi Speed is commanded (see below). Low Speed can vary anywhere from 0% PWM to 100%.

Progressive control is commanded by a 0-5 volt input signal. This starts to increase PWM% from the low speed setting as the 0-5 volt signal climbs. This signal can be generated from a throttle position sensor, a Mass Air Flow sensor, a Manifold Absolute Pressure sensor or any other way the user wants to create a 0-5 volt signal. This function could be set to increase fuel pump power as turbo boost starts to climb (MAP sensor). Or, if controlling a water injection pump, Low Speed could be set at zero PWM% and as the TPS signal climbs it could increase PWM%, effectively increasing water flow to the engine as engine load increases. This controller could even be used as a secondary injector driver (several injectors could be driven in a batch mode, hi impedance only), with Progressive control (0-100%) you could control their output for fuel or water with the 0-5 volt signal. Progressive control adds enormous flexibility to the use of this controller.

Hi Speed is that same as hard wiring the motor to a steady 12 volt DC source. The controller is providing 100% PWM, steady 12 volt DC power. Hi Speed is selected three different ways on this controller: 1) Hi Speed is automatically selected for about one second when power goes on. This gives the motor full torque at the start. If needed this time can be increased (the value of C1 would need to be increased). 2) High Speed can also be selected by applying 12 volts to the High Speed signal wire. This gives Hi Speed regardless of the Progressive signal. 3) When the Progressive signal gets to approximately 4.5 volts, the circuit achieves 100% PWM – Hi Speed.

Circuit Specifications

This circuit is intended for use on a typical 12 volt automotive electrical system. Most of these systems actually run at 13-14 volts. Some race cars use an extra cell in their battery to achieve a higher voltage. If this will be in excess of 16 volts, we would need to use a different diode in the power supply portion of the circuit (contact the MYO-P for this change).

The prototype circuit is intended to run loads that draw up to 20 amps continuously. Although the main mosfet transistor used is rated at 50 amps, under load, at working temperature, don't expect more than 20 amps. The wires leading to the mosfet are rated to 26 amps so there is some margin but please respect the design. The "production" circuit will have provision for at least a second main transistor and possibly a third transistor. In this case the load could be 20 amps per transistor or a total of 60 amps.

The PWM controller should be mounted fairly close to the motor to be controlled. Temperature can be an issue. The die cast aluminum housing that is suggested for use IS the heat sink for the large mosfet transistor and the voltage regulator. The transistor will operate up to 150 C internally but most other components on the circuit board are only good to 70 C (180 F). For use in a very warm environment, specific selection of components could get the heat tolerance up to about 100 C. Contact the designer if this is needed. So a cooler location is better, in the fender well rather than on the firewall above the motor of a car.

Normal water spray found under hood during rain should not be a problem IF die cast enclosure is properly sealed at final installation. Again, less water is better. Obviously water cannot be allowed into the enclosure.

Installation Schematic and Operational Considerations

Figure #1 shows the connection schematic for the typical use. Please note that the schematic shown is for the original prototype, wire colors could change for the "production" kits. If you save this information from the website and then later assemble a kit or install a controller, make sure you have the current schematic, wire colors and sizes could change. Every attempt to keep the web site up to date will be made but please double check to avoid confusion.

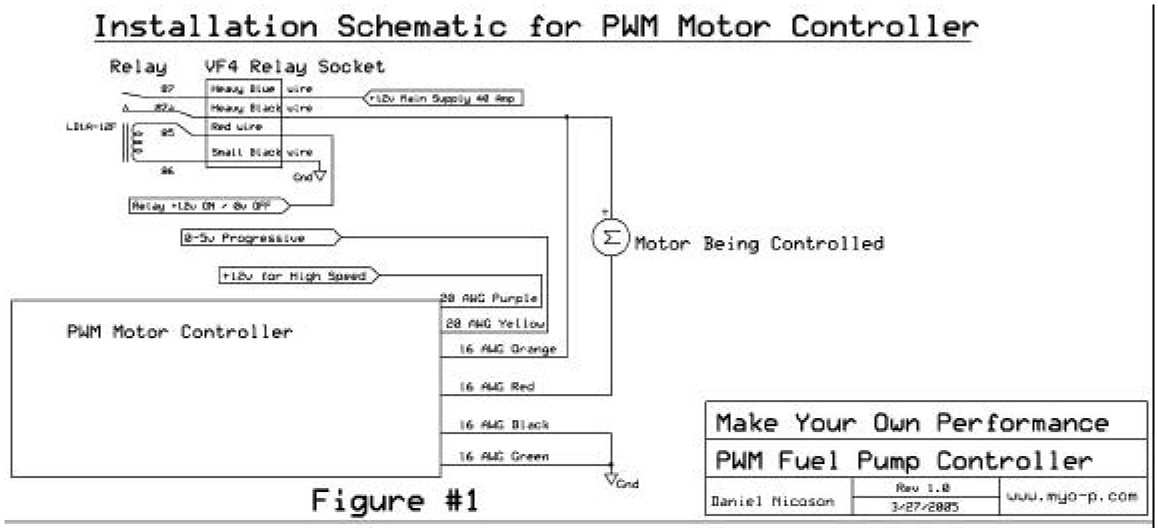

Figure #1

In the descriptions below I keep mentioning "the transistor". This is the large 50 amp transistor used like a ON/OFF switch to give us the modulated power for the motor.

Wire Functions on PWM Controller:

16 AWG Green wire – provides ground for the controlling circuit, actually does not carry even one amp of current. Shown here on the prototype as a 16 AWG, should/could easily be a 22 or 20 AWG wire on the "production" kits. This ground wire should be attached to the common ground outside the PWM controller case. Do NOT simply "jumper" this wire inside the case to PCB connection #6 (16 AWG Black wire connection).

16 AWG Black wire – provides the "ground" connection for the motor circuit. This wire will carry the full amp load of its respective transistor. It should connect to the common ground outside the case. With our example of an automotive application, ensure there is a sufficient ground path back to the battery.

16 AWG Red wire – connects the output of the motor (motor's negative connection) to the input of the large transistor in the controller. This wire carry's the full amp load of the motor. Good connections are important.

16 AWG Orange wire – This wire carries the 12 volt power to the control circuit. It will actually carry less than one amp. In the "production" kits this will likely be a 22 or 20 AWG wire. Ensure if the relay is not used that this wire gets power any time the motor is given power, tie it to the "positive" terminal of the motor.

20 AWG Yellow wire – This wire is used to provide the 0-5 volt Progressive signal. If you are just using the two speed feature, connect this wire to ground. If using the Progressive feature there is a buffer in the control circuit for this wire so it should not actually draw any current and upset the "providing" circuit. For example if this controller uses the Throttle Position Switch (TPS) on a fuel injected engine to provide a 0 – 5 volt signal, you wouldn't want this PWM circuit to add a load to the output of the

TPS switch and cause an erroneous voltage signal to go to the engine computer. The buffer built in to this circuit will ensure no current is drawn, ensuring no change to the TPS signal to the engine computer.

20 AWG Purple wire – This is the "High Speed" control wire. If using either the two speed function or progressive function, connecting this wire to +12 volts will cause the controller to go to 100% PWM, running the motor at full power. This function is available at any time regardless of the status of the Progressive function or the "Low Speed" setting. Again, this wire will draw virtually no amperage (.000375 amps) so most any source will do the job.

Fuse, Reverse Voltage and Voltage Spike Protection

There is protection for reverse polarity and keeping any voltage spikes from leaving the circuit. The PCB has a 3 amp replaceable fuse mounted on it inside the PWM controller case. If you test the reverse polarity feature you will most likely blow the fuse. That is the real purpose of the fuse. Remember, this control circuit uses much less than one amp for operation. Any voltage spike generated within the control circuit is clipped at 16 volts per normal automotive practice. Any spike trying to enter the circuit from outside will also be clipped. This 16 volt spike protection is why use with a 14-16 volt battery will require a different diode (D2).

Use of the standard 40 amp automotive relay is not essential but useful in this case. If you don't use the relay, ensure that the PWM controller gets 12 volts of power anytime the motor is supplied with power, tie them together. Figure #1 shows how to use the relay.

How To Set Low Speed

Once the PWM controller is connected per the Installation Schematic (Figure #1), you can set the slow speed. For the initial design the potentiometer (pot) controlling the slow speed setting is mounted on the PCB. You will need to take off the enclosure top to have access.

The pot is a high quality Bourns Inc. cermet potentiometer, 25 turns for full range. Basically this pot forms a voltage divider, the output is the movable wiper that provides a variable voltage to the control circuit. If you turn the screw counter-clockwise (CC) it will increase the PWM%. If you turn the screw clockwise (CW) it will decrease the PWM%. 100% PWM% is full speed/power. If you turn the screw to one extreme or the other you will hear the pot "clicking" each turn of the screw (it's a fairly quite click sound). I wouldn't spend endless hours making this thing click, 'not sure how much it will take.

To set the "Slow Speed" I would turn the pot full CC so you have 100% PWM. Then start your pump and start turning the screw CC until you achieve the slow speed you need. As the user you will have to determine what constitutes a useful low speed for your application. Keep in mind that just because you have a perfectly linear PWM controller now you won't necessarily be able to run your huge fuel pump at 40% PWM. Your fuel pump may stall at just 80% PWM, whereas your buddy can take his radiator cooling fan all the way down to 35% PWM for slow air movement through his radiator in between rounds at the drag strip. Every application will have a different “ideal” slow speed setting.

<u>Using Progressive Control</u>

Progressive control was incorporated to give this circuit great flexibility and increase its usefulness. Progressive allows the user to increase PWM% (power) from the slow speed setting to hi speed in a linear manner based on the 0-5volt input signal (20 AWG Yellow wire). This 0-5 volt signal can be supplied any way the user wants. It can come from a TPS, MAF, BAP sensor, a PIC microcontroller, any source you want.

I have listed a simple circuit below that will give a manual control of the Progressive function (Figure #2). As noted earlier there is a unity buffer in the main circuit to ensure the 20 AWG Yellow wire does not draw any appreciable current from the reference circuit. This ensures the PWM controller will not affect the reference circuit.

0-5 volt Progressive Controller

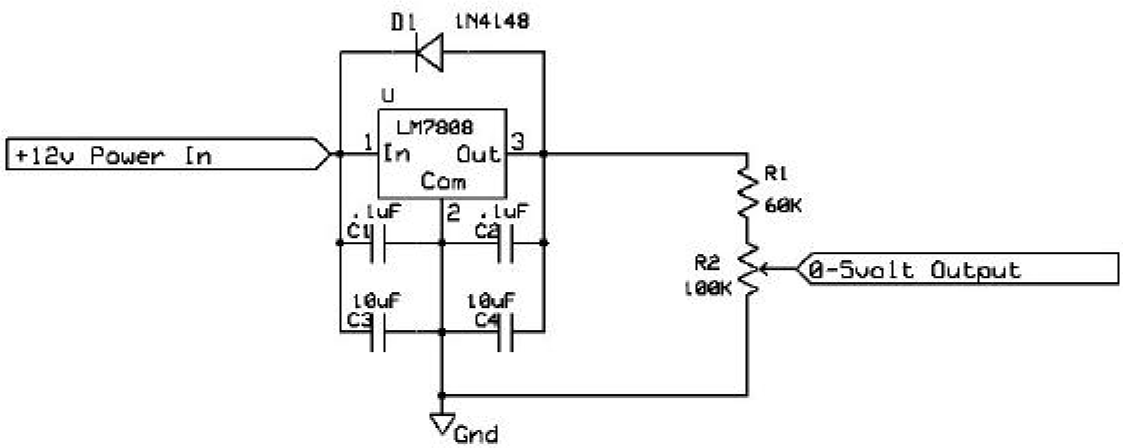

Figure #2

This simple circuit will give an accurate 0-5 volts using normal 12 volt automotive power. The LM7808 is a simple voltage regulator, the four capacitors and the diode simply smooth out the resulting 8 volts that goes to the resistors. R1 is a simple 60,000 ohm resistor. If you can’t get exactly 60,000 ohms go slightly lower, 59,000 or so. This way your 0-5 volts becomes 0-5.1 volts rather than not quite reaching 5.0 volts. R2 is a simple Radio Shack 100K ohm (100,000 ohms) potentiometer. Buy a knob, a small plastic enclosure and these components at Radio Shack and you will have less than $10.00 invested.

Pulse Width Modulated (PWM) Circuit Basics
The basic idea to Pulse Width Modulation is to provide full voltage for a specific percentage of time. 50% PWM means full power (voltage) is provided for only half the time. The way it is done in this circuit is best presented with the aid of Figure #3.

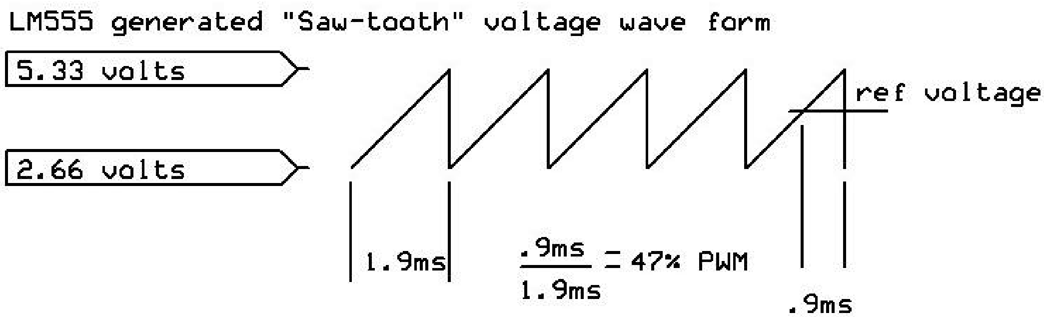

Figure #3

First a "saw-tooth" voltage signal is generated at a set frequency. Then a device called a "comparator" is used to compare a reference voltage to the changing saw-tooth signal. When the changing saw-tooth signal rises above the reference voltage the comparator's output goes "high" (comparator output is either low or high, Off or ON).

The example in Figure 3 shows the basic interval to be 1.9 micro seconds (ms). If the reference voltage depicted is set to 4.0 volts, anytime the voltage goes above 4.0 volts the comparator goes high (turns ON) for the remaining amount of time - in this example .9ms. Doing the math will show .9ms to be 47% PWM.

So, in Figure #3 an ON signal is generated 47% of the time. If the reference voltage were to be moved down to 3.0 volts, it would generate a larger PWM%. If the reference voltage is 2.66 volts or lower, the comparator will be ON all the time, 100% PWM. Conversely if the reference voltage is raised above 5.33 volts the PWM% =0, no power.

How does a PWM "ON" signal drive the motor? A circuit is set up so every time the comparator output goes high-ON, it turns on a large transistor. This large transistor is really an On-Off switch to the motor power circuit. This circuit is really turning the power on/off to the motor very quickly and precisely.

In the final circuit there is a "Hi speed" feature that applies full power (100% PWM) with the application of 12 volts. Referring to Figure 3, for 100% PWM the reference voltage either has to drop below 2.66 volts or the saw-tooth voltage can never come below 5.33 volts. This circuit actually uses a feature of the LM555 chip to drive the saw-tooth voltage above 5.33 volts by taking Pin #4 of the LM555 to ground. The "Lo speed" setting is a static reference voltage set by a potentiometer, anywhere between 5.33 and 2.66 volts. The "Progressive Function" smoothly moves the reference voltage from the "Lo speed" level to the "Hi speed" level in a linear relationship to a 0-5 volt signal.

Actual Circuit Schematic and Function

For the remainder of the discussion the actual circuit schematic will be built, component by component. The component numbers will be the actual numbers used in the design, so they won't necessarily be in order of introduction. The function of various components will be discussed with regard to this PWM Controller circuit. Much more detail of "How and Why" for a specific component can be found in data sheets from the manufacturer. Generic component names are used in this discussion, checking the component list for this circuit posted elsewhere on this web site will allow one to retrieve the actual data sheet from the manufacturer. Other source for data sheets are www.digi-key.com or www.mouser.com.

The regulated control voltage chosen was 8 volts. A LM7808 linear voltage regulator is used to provide this from the automotive 12 volt power supply. This regulator is important because the 12 volt supply actually ranges in voltage from below 12 volts to almost 15 volts depending on the automotive phase of operation. The opamps, timer and voltage references used in this circuit are powered by this 8 volt regulator. The comparator and large transistor are powered by the automotive 12 volt supply (reasons why explained later).

To generate the saw-tooth signal the LM555 timer was used. This is an industry standard timer that can generate a very precision length pulse, once (monostable mode); or it can be used to generate a stable frequency of pulses of a specific length (astable mode). In this circuit we are using the astable mode of operation.

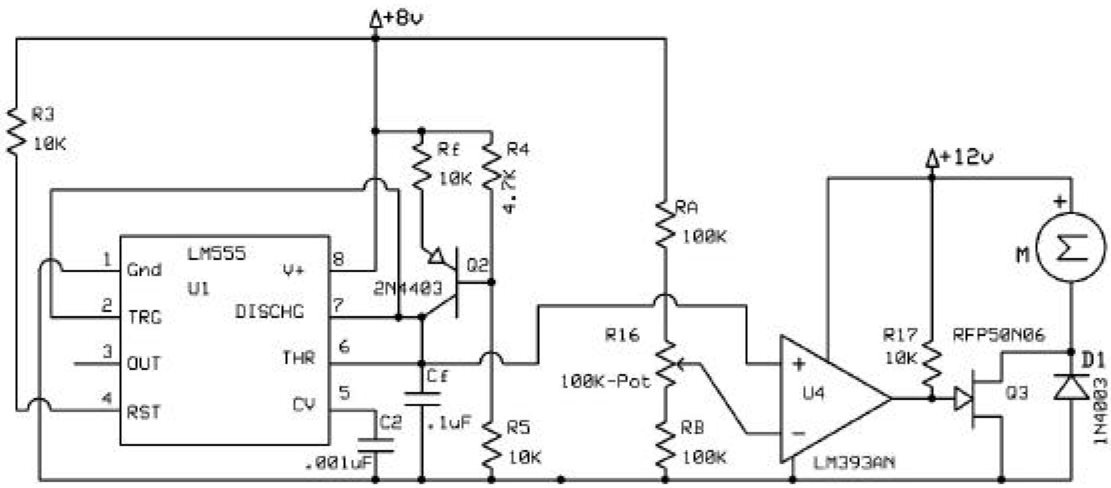

Figure #4

Figure 4 is a watered down version of the real schematic for discussion of how the PWM shown in Figure 3 actually works. All components depicted here are on the final circuit excepting RA and RB. They are there to make this a complete example circuit.

The LM555 works by charging a capacitor, Cf, with a current from transistor Q2. The IC monitors that charging process noting the voltage at pin #6. When the capacitor has reached 2/3 of the full voltage, the IC takes pin #7 to ground, discharging the capacitor.

That discharge instant is the vertical part of our saw-tooth in Figure 3. As the capacitor discharges the IC monitors Pin #6, when the voltage drops below 1/3 of full voltage, the IC re-starts the charging process.

The charging time is determined by the value of Cf and Rf . This charging time correlates to the frequency of the output wave form. Raise the value of either Cf or Rf and the frequency goes lower. If changing the frequency, Rf should not go much below 5k (5,000 ohms). Cf can vary easily from .001uF to above 10F. If you want to change the frequency, check the data sheet for the 555 timer you are using. For our basic circuit we use the values shown to achieve 526 Hz.

Think of Q2 as a "throttle". Normally a 555 circuit doesn't use a transistor here. The saw-tooth waveform would have a curve in place of the angled straight line. A straight line is desired here to ensure the PWM response is linear. That is the point of Q2.

R4 & R5 simply set up a voltage divider to provide 5.33 volts to the base of Q2. This voltage turns Q2 "ON". The fact that 5.33 volts is used has no relation to the function of the 555 circuit, simply a coincidence.

RA, R16 & RB form another voltage divider. Note that they are all 100K. This arrangement ensures the top of R16 is 5.33 volts, the bottom is 2.66 volts. So as the wiper on R16 (it is a potentiometer, variable resistor) moves from top to bottom it changes the reference voltage that feeds the non-inverting input (-) to U4, the comparator. With this arrangement the reference voltage can be varied between 2.66 volts and 5.33 volts. Setting the position of R16 actually sets the Low Speed in the finished circuit.

<u>Commanding Hi Speed Operation - Full Power</u>

There are two ways to command 100% PWM (Full Power) – 1) Drive the reference voltage to the comparator (U4) below 2.33 volts so that the "saw-tooth" voltage is always higher allowing the comparator output to stay "hi" all the time. 2) Make the "saw-tooth" voltage higher than 5.33 volts all the time. This ensures the comparator (U4) output stays "hi" all the time.

Figure #5 (following page) shows that this circuit drives the "saw-tooth" voltage high by grounding Pin #4 on the LM555. This method was selected to allow a Full-Power startup feature and to keep the Full Power function separate from the Low Power setting and the Progressive functionality. Note that C1, R1, R2 & Q1 are added to the previous circuit. When Q1 is saturated, acting as a switch in the ON position, it takes Pin #4 of the LM555 to ground. Without getting into LM555 detail, grounding this pin forces continuous high voltage at pin #6, the resulting signal forces 100% PWM. Q1 is only turned on at startup or when 12 volts is applied between C1 & R1. At startup while C1 is charging, there is enough current to saturate Q1 causing a full power start. Removing this capacitor would take away the full power start.

When +12 volts is applied as shown in Figure 5, current will flow through R1 & R2 to ground. R1 & R2 act as a simple voltage divider to set the proper base current and voltage to saturate Q1. This takes Pin #4 to ground causing 100% PWM.

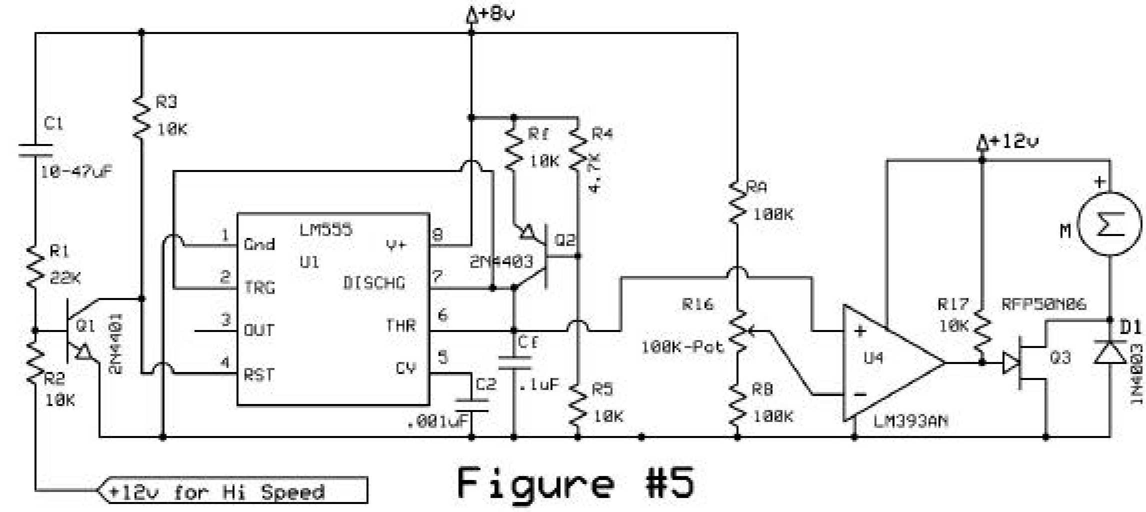

Figure #5

<u>Progressive Circuit Details</u>

The development of the Progressive feature was considered to be very important to give this circuit the most flexibility in application. Various configurations were investigated and the final choice was to simply have the Progressive signal manipulate the source voltage for the R16 potentiometer, effectively controlling the reference signal for the comparator (U4).

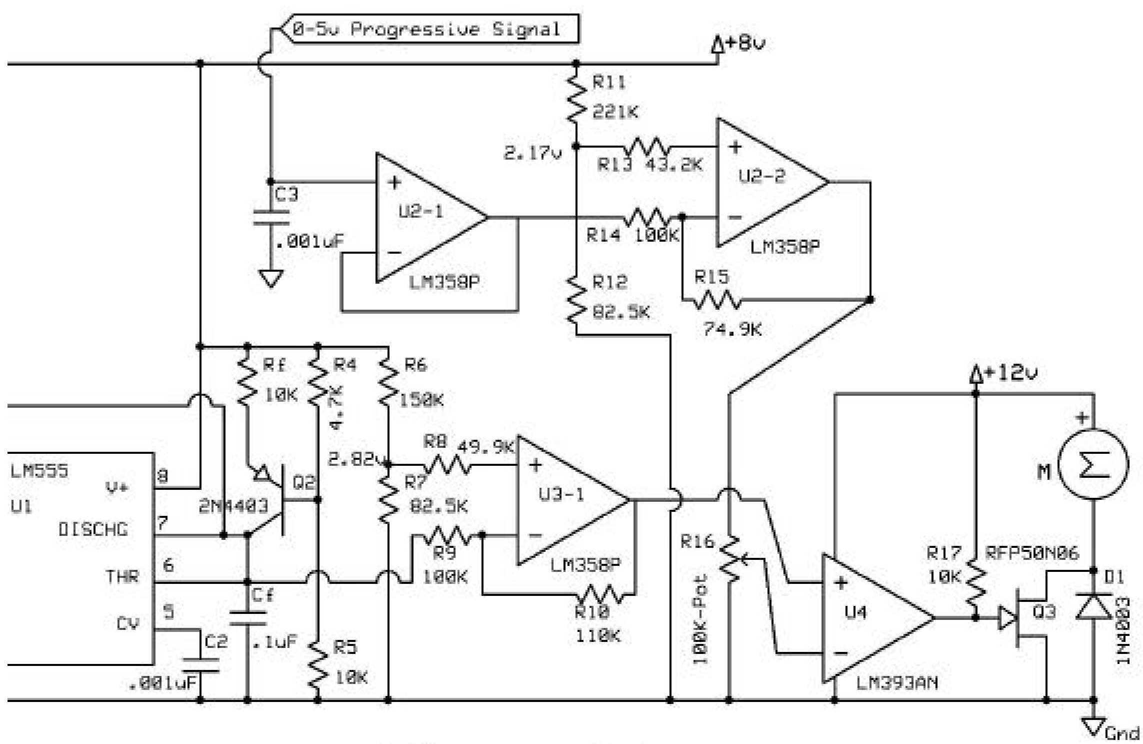

Figure #6

In the course of development the "saw-tooth" voltage depicted in Figure 3 was shifted down so that it varies between .15 volts (100% PWM) and 3.60 volts (0% PWM). This shift also expanded the Progressive range of operation from 2.67 volts to 3.51 volts. This expansion allows the setting of Low Speed and operation of the Progressive function to be less sensitive.

In Figure 6, U3-1 is an opamp configured as an inverted amplifier used to invert and expand the "saw-tooth" signal as needed. R9 & R10 actually control the amplification factor. R6 & R7 have very specific values forming a voltage divider that shifts the output of the opamp so that it achieves the voltage range of .15 – 3.60 volts. The value of R8 simply complements R9 & R10 in achieving the proper amplification

To manipulate the Progressive signal we first want to protect this circuit and ensure that it doesn't affect the circuit providing the 0-5 volt signal by pulling significant current. U2-1 is an opamp configured as a "unity buffer". This kind of buffer gives the same voltage out that came in but has very high resistance at the input ensuring no current flow into the device. So if the progressive signal comes from another sensitive circuit like the output of a Mass Air Flow sensor (MAF), this circuit will not introduce any errors to the MAF system.

Our objective for the Progressive signal is to have full voltage (greater than "saw-tooth's 3.60 volts) at the top of R16-Pot when the Progressive signal is 0 volts and as the Progressive signal approaches 5.0 volts we want the voltage at the top of R16-Pot to go near zero (less than "saw-tooth" .15 voltage) to ensure 100% PWM. U2-2 in an opamp configured as an inverted amplifier that will output a voltage ranging from 3.8 volts (0% PWM) down to .08 volts (100% PWM). This range is just slightly larger than the "saw-tooth" signal ensuring a full range of PWM from 0 to 100%. R11 & R12 are a voltage divider that shifts output of U2-2 precisely. R14 & R15 set the amplification level complemented by R13.

<u>Final Drive – Comparator and Large Transistors(Figure #6)</u>
The primary object of this circuit is to accurately switch the large transistor (Q3) on and off at the right frequency and for the precise amount of time desired. The comparator (U4) is the final component that makes this possible. The comparator "compares" the non-inverted (+) signal with the inverted (-) signal. If the (+) signal is greater than the (-) signal the comparator releases it's output from ground (output "hi"). In this case the "pull-up" transistor, R17, pulls the output up to 12 volts. This hi voltage takes the transistor gate to a high enough voltage to turn the transistor fully on. This is a "mosfet" transistor, they like a very high voltage at the gate in the "ON" condition. When the comparator output is "Lo" it actually takes the output to ground. This "lo" state turns off Q3.

Q3 is a very fast switching transistor that has very low resistance when carrying a large current. This particular transistor, RFP50N06, is rated to carry up to 50 amps. For purposes of this circuit the current load should be limited to 20 amps. D1 is a large diode intended to pass any inductive voltage spikes past Q3. Controlling motors and solenoids ensures there WILL be spikes on this part of the circuit. Operation without this diode will destroy Q3 in less than a second.

Power Supply and Circuit Protection (Figure #7)

Objectives for the power supply are to provide steady 8 volt power for the control circuit section, protect against reverse polarity and eliminate any voltage spikes greater than 16 volts that try to enter or leave the control circuit. Figure 7 shows the power supply section, circuit protection and an optional relay for circuit power.

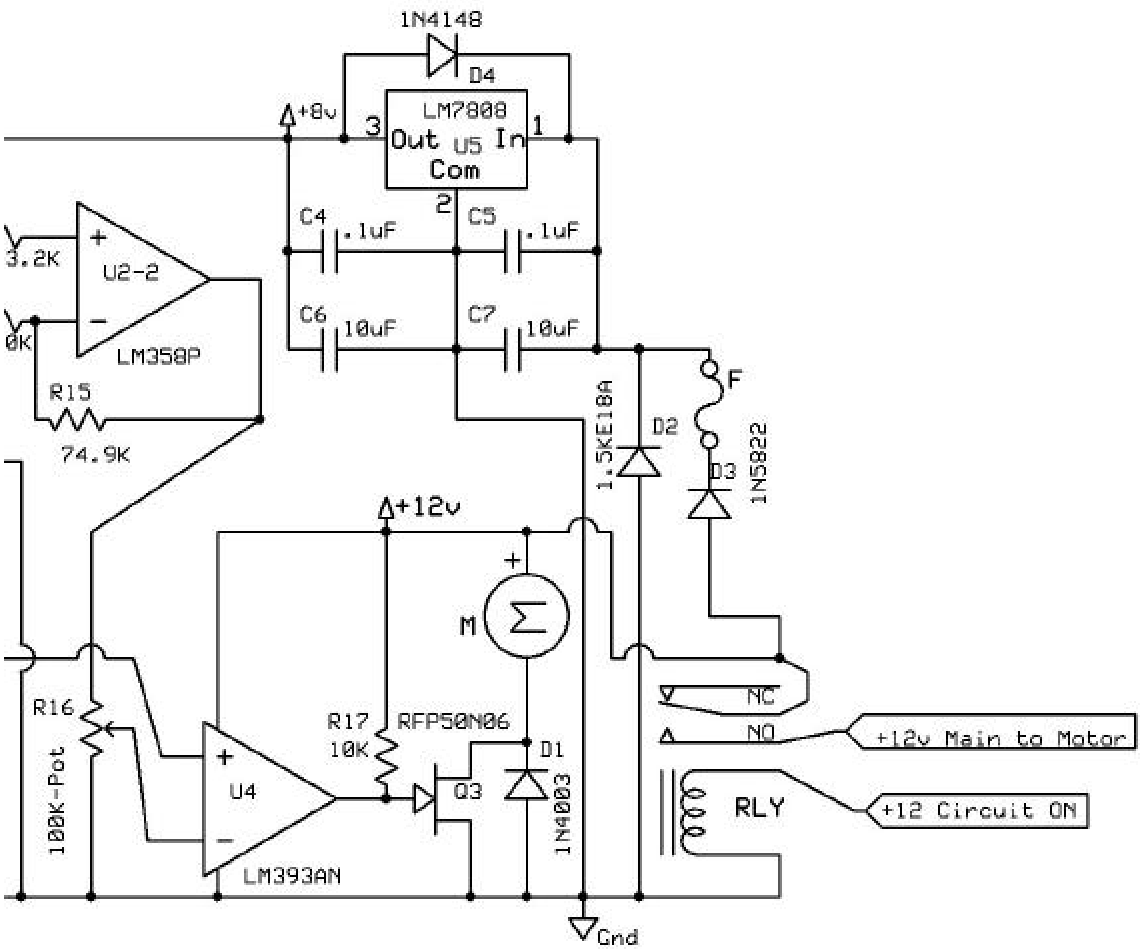

Figure #7

A quick note about fuses. Their normal purpose is to protect the circuit that follows AFTER the fuse. To protect the main wire feeding Figure 7 (not shown) you should place an appropriate sized fuse where that supply wire starts, say at the battery. This way if the wire gets damaged and shorts out, the fuse will blow protecting from fire etc. The fuse in Figure 7 has no protection for on any supply wires.

Reverse voltage protection is provided by D3, a Schottky barrier diode. This device acts like a one-way check valve. Current can flow one direction but not the other. Best advise is to check twice when connecting, then check connections a third time.

The fuse in Figure 7 will trip if there is any kind of a short circuit in circuit AFTER the fuse, basically the whole control circuit. If any component fails or any other short circuit develops and draws more than 3 amps, this fuse will blow. The actual control circuit uses well under one amp.

D3 is a Transient Voltage Suppression (TVS) Zener diode that is designed to "clip" any voltage spike at 18 volts. This covers for any spike entering from out side and any that originates inside the circuit. Any voltage over 18 volts is dumped to ground.

The LM7808 is an 8 volt linear regulator to provide steady, clean 8 volt DC power to the control circuit. C5 & C7 help to clean up the raw inbound 12 volt power. C4 & C6 help ensure the output is smooth by providing instantaneous extra current at 8 volts if any peak demands arise. In reality, this circuit is very simple and would probably work just fine without the capacitors. They have been used because the data sheets suggest them and testing has gone well with the capacitors. D4 is a simple diode that exists to allow any voltage spikes above 8 volts from within the circuit to bypass the LM7808 and be dealt with by D2.

You will note that the power lead going from the relay to the motor and U4 has no protection. In the "production" version of the board there will be a second TVS diode and a capacitor across the power leads of U4 to protect the IC from transient voltage peaks and to smooth the power into the IC.