Pulse Width Modulation for DC Motor Control Based on LM324

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ABSTRACT

The DC motor is an important part of an equipment in many industrial applications requiring variable speed and load characteristics due to its ease of controllability.

Nowadays, there are lots of good-quality motor speed controllers on the market. However, their costs are relatively high. A speed controller with both low cost and good performance will be highly marketable, especially for small mobility applications.

The current work allows controlling the speed of a DC motor in both forward and reversing direction, from fully off to fully on. It runs in switch mode so it is quite efficient. In this work, designing motor bi-directional DC control circuit using Pulse Width Modulation (PWM) based on an operational amplifier model LM324 is implemented.

The proposed system offers many advantages such as simple structure, low cost, accurate, quite efficient, lightweight nature, small volume, and bi-directional speed control.

Keywords: PWM, H-Bridge, Speed Control, DC Motor

السيطرة على سرعة محرك التيار المستمر بأستخدام تقنية تضمين عرض النبضة معتمداً المشغل الوظيفي LM324

الخلاصة

محرك التيار المستمر يمثل أداة مهمة تدخل في العديد من التطبيقات الصناعية التي تتطلب خصائص سرعة وحمل متغيرة بسبب سهولة قابلية التحكم بسرعتها.

في الوقت الحاضر يوجد في الاسواق الكثير من المسيطرات على سرعة المحرك ذات النوعية الجيدة, مع ذلك تبقى كلفها عالية نسبياً. وبذلك سيكون مسيطر السرعة ذات الكلفة المنخفضة والاداء الجيد رائج جداً وخصوصاً للتطبيقات ذات قابلية الحركة الصغيرة.

العمل الحالي يسمح بالسيطرة على سرعة المحرك ذو التيار المستمر في كلا الاتجاهين الامامي والعكسي من الأطفاء التام الى التشغيل الكامل. المسيطر الحالي يعمل في نمط التشغيل مما يجعله كفوءًا

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جداً. في البحث الحالي تمّ انجاز تصميم دائرة سيطرة على محرك التيار المستمر وبالاتجاهين باعتماد تقنية تضمين عرض النبضة وباستخدام المشغل الوظيفي LM324.
المسيطر المقترح يُبدي عدة ميزات كبساطة التركيب والكلفة المنخفضة والدقة والكفاءة العالية وخفة الوزن وصغر الحجم والسيطرة على سرعة المحرك وبالاتجاهين.

INTRODUCTION

Often, people attempt to control DC motors with a variable resistor or variable resistor connected to a transistor. While the latter approach works well, it generates heat and hence wastes power. The simple Pulse Width Modulation PWM DC motor control eliminates these problems. It controls the motor speed by driving the motor with short pulses. These pulses vary in duration to change the speed of the motor. The longer the pulses, the faster the motor turns, and vice versa [1].

Many works had been published a very popular switch mode speed control circuits, but they works in only one direction. To change direction, a double-pole changeover switch or relay is needed to change the polarity of the applied voltage and the motor spins the other way. However, this has the disadvantage that they then a Double-pole/Double-throw DPDT switch has to be added to change the polarity of the applied voltage.

Therefore, there are two ways to control the motor-a direction switch as well as the speed control. Also, it is not a good idea to suddenly reverse the voltage on a DC motor while it is spinning. It can cause a big current surge that could burn out the speed controller, as well as causing big electrical and mechanical stresses on the motor itself [1].

The current designed circuit overcomes both these problems. The direction and speed is controlled using a single potentiometer. Turning the pot in one direction causes the motor to start spinning. Turning the pot in the other direction causes the motor to spin in the opposite direction. The center position on the pot is off, forcing the motor to slow and stop before changing direction.

R. Karthick [2] designed a circuit allowed controlling the speed of a DC motor (in eight levels) from PC's parallel port. The PC used a software program to control the speed of the motor. MilošHujdič and P. Záskalický [3] designed a Brushless Permanent Magnet BLPM motor drive might serve as a potential alternative to existing servo industrial AC motor, especially in a small frame size, for variable speed drives. This work deals with a topology of the converter for small three phase brushless DC motor. M. Rylee [4] discussed how to use the Enhanced, Capture, Compare, and PWM (ECCP) on the PIC16F684 for bi-directional brushed DC (BDC) motor control. M. George [5] proposed the speed controller of a separately excited DC motor with varying armature voltage. Speed controller system based on NARMA-L2 controller had been successfully developed and it was found able to regulate the speed well above the rated values. K.-H.Kim et.al [6] presented a robust speed control scheme for a Brushless DC (BLDC) motor using an adaptive input-output linearization technique. This work acts as a simple, high reliability and comparatively low cost bi-directional BLDC motor control. The application note in [7] demonstrated the use of NXP Semiconductors LPC2101 microcontroller for bi-directional brushed DC motor control. A. S. Zein El Din [8] presented a simplified approach for speed control of a separately excited DC motor using Programmable Logic Controller PLC. Yu Qiao and Jing Y. Guo [9] designed a high-performance low-cost low-loss wireless DC motor speed control unit. The principles of PWM and Hall sensor have been introduced by W. Wang [10]. He proposed the designing strategy of DC motor speed control system based on single chip microcontroller with integrated circuits. A. K. Dewangan [11] investigated an implementation of the ATmega8L microcontroller for PWM speed control of Permanent Magnet DC motor fed by a DC chopper with speed feedback through a tachogenerator. Gregor T. George [12] designed circuit for controlling the voltage across the DC motor by varying the duty cycle with PWM scheme. A PWM scheme would allow for simple interfacing with the DAC. The variable DAC output voltage is integrated as an input to the operational amplifier which acts as a comparator circuit. As a result, varying user inputs in LabVIEW would be used to drive the motor at different speeds. R. K. Kumordzi [13] provided efficient and simple method for control speed of DC motor using PWM technique based on dual timer IC-NE555.

The works [4,10] above depend upon microcontroller chips technology and other advanced power electronic technologies, and therefore with these techniques, the DC motor speed technology is gradually turning from analogue to digital. The microcontroller receives (programmed) software commands from PC though interface devices. Therefore, these techniques will be more complex and higher cast with respect to analogue one.

Compared with all previous drives, the current work proposed a very low cast PWM drive scheme. This drive is chosen to vary the voltage applied across the motor terminals. The PWM generator design is based on a single low cast operational amplifier (LM324) model. The duty cycles of the output waveform could be varied from 0% to 100% using this design.

The proposed drive has additional advantages such as lightweight nature, small volume, accurate, low cost, and high efficiency as well as it allows controlling the speed of a DC motor in both the forward and reverse direction. The range of control is from fully off to fully on in both directions. It can be used for motors running at 12V or 24V and drawing up to about 5A. It runs in switch mode so it is quite efficient.

SPEED CONTROL OF DC MOTORS

In essence, there are four ways to vary the speed of DC motors:

1. By using mechanical gears to achieve the desired speed. This method is generally beyond the capability of most home workshops.
2. Reducing the motor voltage with a series resistor. However, this is inefficient (energy wasted in resistor) and reduces torque. As the current drawn by the motor increases, the motor load increases too. More current means a larger voltage drop across the series resistor and therefore less voltage to the motor. The motor now tries to draw even more current, resulting in the motor “stalling”.
3. Using a transistor to continuously vary the voltage to the motor. This works well but a substantial amount of heat is dissipated in the power transistor.

4. By applying the full supply voltage to the motor in bursts or pulses, eliminating the voltage losses in the series resistor or transistor. This is called Pulse Width Modulation PWM and it is the method used in the current proposed circuit. It is a very efficient way of providing intermediate amounts of electrical power between fully on and fully off. Short pulses means the motor runs slowly; longer pulses make the motor run faster [13, 14].

The main advantage of a PWM circuit over a resistive power controller is the efficiency. One additional advantage of PWM is that the pulses reach the full supply voltage and will produce more torque in a motor by being able to overcome the internal motor resistances more easily. Finally, in a PWM circuit, common small potentiometers may be used to control wide varieties of the loads whereas large and expensive high power variable resistors are needed for resistive controllers [13].

SPEED CONTROL WITH PWM

One essential aspect of controlling motors is the ability to change the speed of rotation and the amount of torque produced. One simple but usually impractical means of achieving this is to adjust the supply voltage up and down as required. However, it is more effective and common to use the PWM concept. By adjusting the duty cycle of the signal (modulating the width of the pulse, hence the “PWM”) i.e, the time fraction it is "on", the average power can be varied, and hence the motor speed.

This is a control technique where power to the motor is switched on and off rapidly, at rates high enough that the effects of the switching can be negligible (The output transistor is either on or off, not partly on as with normal regulation, so less power is wasted as heat and smaller heat-sinks can be used). The resulting effective voltage is then the average fraction of the time the power is on. This technique is also used in many other applications.

Figure (1) illustrates the PWM concept. The drive signal is switched on and off with a given period and is in the “on” state at voltage V_{ON} for a fixed fraction of the period. This “on” time is referred to as the “duty cycle” and is stated as a percentage, calculated as:

$$Duty\,Cycle\,(\%) = \frac{On\ Time}{Period} \times 100 \qquad \dots (1)$$

Figure (1) shows a duty cycle of 50%, with the resulting average *perceived* voltage of this PWM signal equal to 50% of the maximum voltage. The frequency of the PWM drive signal is calculated by taking the reciprocal of the period [15]:

$$PWM\ Frequency = \frac{1}{Period} \qquad \dots (2)$$

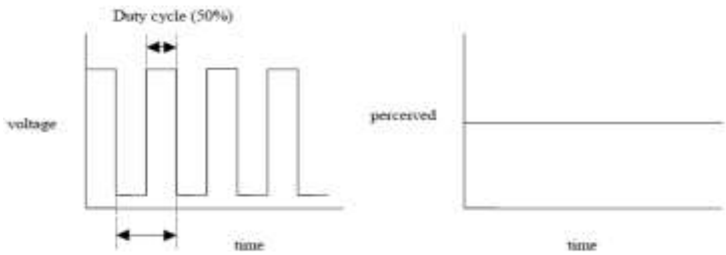


Figure (1) Pulse Width Modulation with 50% Duty Cycle.

Changing the duty cycle of a PWM signal changes the average, or perceived voltage level. For instance, adjusting the duty cycle shown in Figure (2) so that, it is in the “on” state for 80% of the period, the situation will change to that shown in Figure (2).

By increasing the duty cycle to 80%, the perceived voltage increases to 80% of V_{ON}.

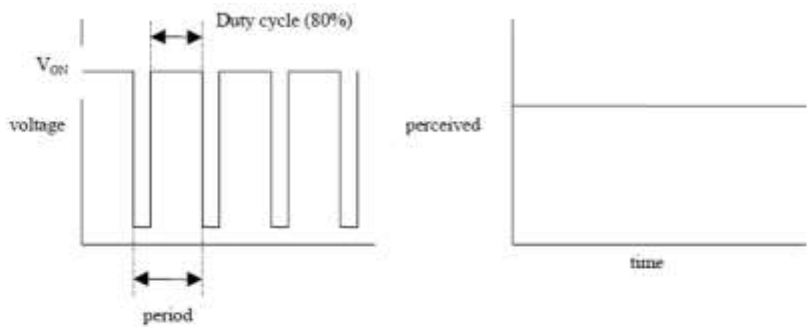


Figure (2) Pulse Width Modulation with 80% Duty Cycle.

If PWM is implemented at a frequency that is too low, the result will be a jerky, stop-start response.

Instead, the desired result is to approximate the “perceived voltage” as closely as possible with a minimum of perceptible ripple. When driving a permanent magnet brushed DC motor with PWM, the smoothing or filtering is very effectively performed by the physical inertia of the mechanical system. When done properly, the switching occurs too rapidly for the mechanical system to follow. For applications other than controlling the speed of a DC, filtering circuits may be used to perform the required smoothing of the PWM output.

In the extreme case where a very long period is chosen-much longer than the mechanical time constant, the motor will very obviously start and stop. Consider the case of PWM period of 2sec (which is a 0.5 Hz PWM frequency): the motor will almost certainly accelerate and decelerate noticeably during each period.
This is the undesirable “torque ripple” that will become much less noticeable if higher PWM frequencies are used. Usually, PWM frequencies in the range of 100Hz to

1,000Hz will give good results. Regardless of the PWM frequency, torque ripple (and, by extension, current ripple) will occur to some degree. Higher PWM frequencies result in less ripple, but since current flow in the inductive motor coils is never able to follow the crisp edges of the PWM drive signal, ripple is unavoidable.

BI-DIRECTIONAL CONTROL OF DC MOTOR

It would be more practical to design a control circuit capable of causing current to flow in either direction through a motor using only a single positive power supply. The most common way of accomplishing this is through the use of a network of transistors, arranged in what is known as an “H-bridge” configuration. The shape of the circuit resembles an “H”, which gives rise to the distinctive name. Figure (3) illustrates an H-bridge, which consists of four N-channel MOSFETs. For ‘forward’ rotation Q1 and Q4 are switched on while Q2 and Q3 are off. For ‘reverse’ rotation Q2 and Q3 are on while Q1 and Q4 are off.

If the upper two MOSFETs are turned off and the lower ones are turned on, the motor is ‘braking’. The motor will ‘coast’ (free running) if all four switches are turned off [7].

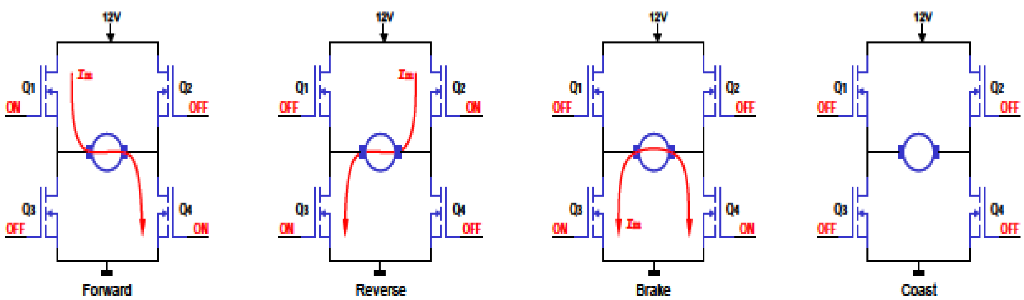


Figure (3) Bi-directional rotation using a full-bridge [7].

The no-load motor speed is proportional to the voltage applied across the motor. Thus, by simply varying the voltage across the motor, one can control the speed of the motor. PWM is used to implement this see Figure (4). It is based on a fixed frequency pulse waveform with a variable duty cycle. The average voltage applied to the motor is proportional to the PWM duty cycle.

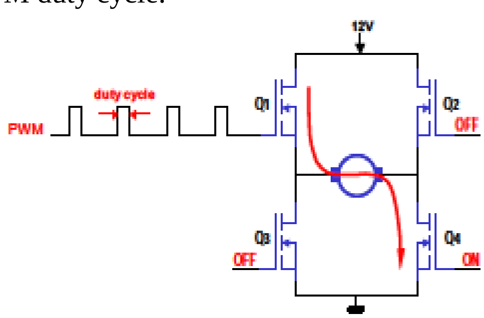


Figure (4) PWM speed control [7].

DC MOTOR DRIVE

A DC motor consists of stator and armature winding in the rotor as shown in Figure (5). The armature winding is supplied with a DC voltage that causes a DC current to flow in the winding. This kind of machines is preferred over AC machines in high power application, because of the ease control of the speed and the direction of rotation of large DC motor. The filed circuit of the motor is exciting by a constant source. The steady state speed of the motor can be described as [15]:

$$\omega = \frac{V_a - I_a R_a}{K_b} \qquad \dots (3)$$

Where K_b (is the back *emf* constant), R_a (armature resistance), I_a, and V_a (armature current and voltage, respectively), and ω (angular velocity).

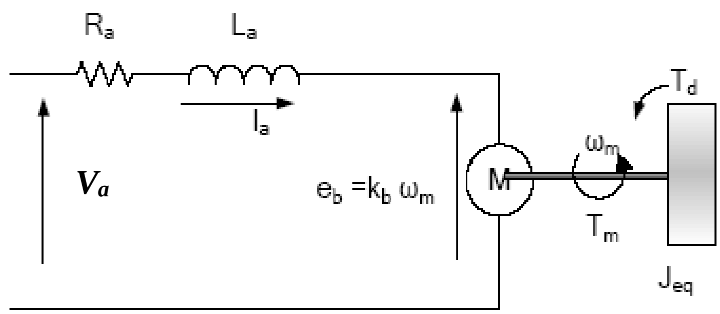


Figure (5) Permanent magnet DC motor.

The speed of a DC motor can be controlled by varying the voltage applied to the terminal. These can be done by using a PWM technique as shown in Figure (6), where T is the signal period, t_d is the pulse-width, and V_m is the signal amplitude. A filed voltage signal with varying pulse-width is applied to the motor terminal. The average voltage is calculated from:

$$V_{ag} = \frac{1}{T}\int_0^T V_a(t)\,dt = \frac{t_d}{T}V_m = KV_m \qquad \dots (4)$$

Where K is the duty cycle, it can be mentioned from these equation that the average DC component of the voltage signal is linearly related to the pulse-width of the signal, or the duty cycle of the signal, since the period is fixed. The motor current is either continuous or discontinuous depending on the duty cycle K and inductance of the armature circuit [1].

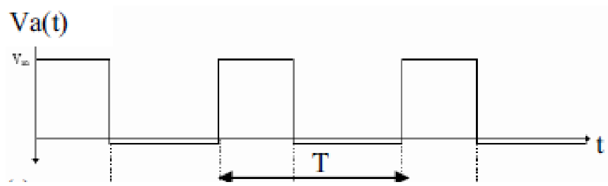


Figure (6) Pulse width modulation technique.

DRIVE CIRCUIT DESIGN:

The proposed control circuit can be broken down in four parts:

1. Motor control: ICa
2. Triangle wave generator: ICb
3. Voltage comparators: ICc and ICd
4. Motor drive: Q3-6.

The schematic of the PWM speed controller circuit is shown in Figure (7) and essentially consists of an LM324 quad op amp and four MOSFETs in a bridge configuration to drive the motor.

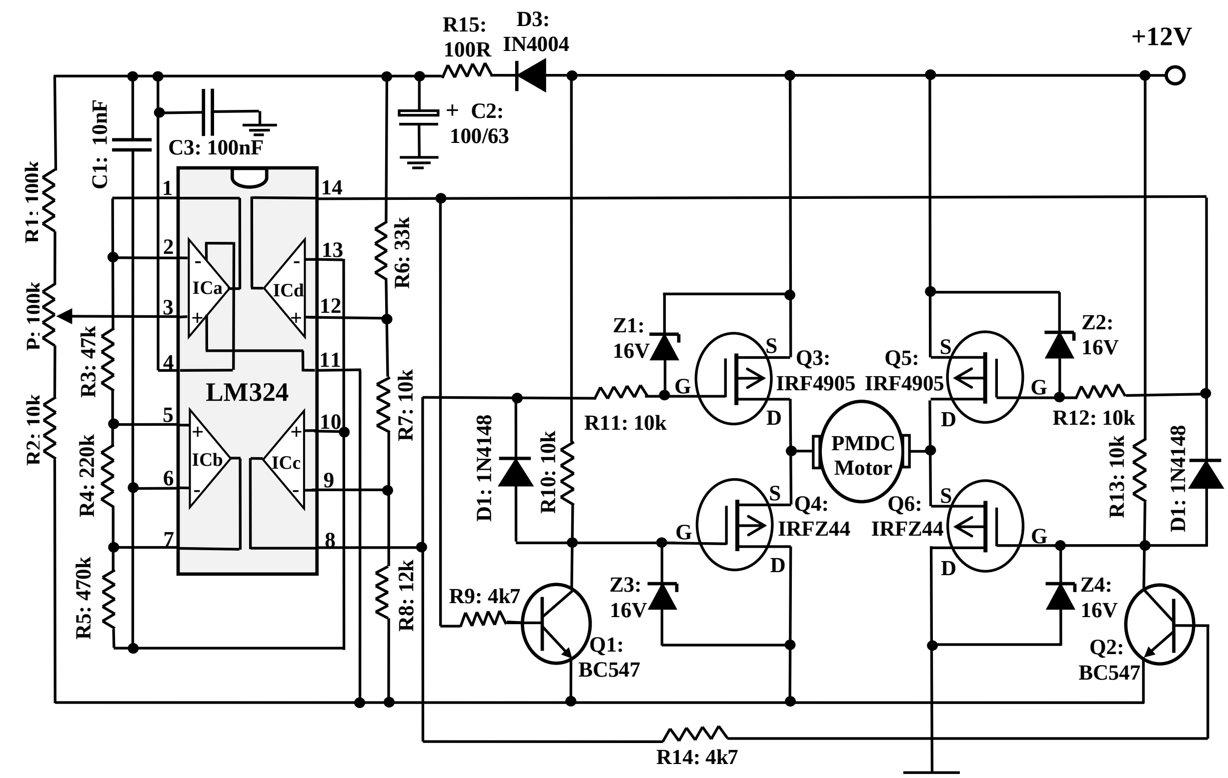


Figure (7) Schematic shows the PWM speed controller, power and PMDC motor.

Both the control circuit and the motor use the same power supply. And while the maximum operating voltage of the LM324 is 32V DC, it would be suggested that the maximum operating voltage of the circuit is 24V DC, as supplied by a 24V battery. In practice, this means that the supply could be almost 29V.

Any more than this means that; there is very little safety margin (i.e., below the maximum of 32V). The IRFZ44 MOSFET can handle 49A and the IRF4905 can handle 74A.

Let's start with the motor drive section, based around MOSFETs Q3-6. Only two of these MOSFETs are on at any one time. When Q3 and Q6 are on then current flows through the motor and it spins in one direction. When Q4 and Q5 are on the current flow is reversed and the motor spins in the opposite direction. ICc and ICd control which MOSFETs are turned on.

Zener diodes Z1-4 limit the gate-source voltage of the MOSFETs to 16 volts. This protects the MOSFETs when powering the control circuit from higher voltages i.e. 24V battery.

Opamps ICc and ICd are configured as voltage comparators. The reference voltage that each triggers at is derived from the resistor voltage divider of R6, R7 and R8. Note that the reference voltage for ICd is connected to the '+' input but for ICc it is connected to the '-' input. Therefore, ICd is triggered by a voltage greater than its reference whereas ICc is triggered by a voltage less than its reference.

Opamp ICb is set up as a triangle wave generator and provides the trigger signal for the voltage comparators. The frequency is approximately the inverse of the time constant of R5 and C1-270Hz for the values used. Reducing R5 or C1 will increase the frequency; increasing either will decrease the frequency.

The peak-to-peak output level of the triangle wave is less than the difference between the two voltage references. Therefore, it is impossible for both comparators to be triggered simultaneously. Otherwise all four MOSFETs would conduct, causing a short circuit that would destroy them.

The triangle waveform is centered on a DC offset voltage. Raising or lowering the offset voltage changes the DC position of the triangle wave accordingly. Shifting the triangle wave up cause's comparator ICd to trigger; lowering it causes comparator ICc to trigger. When the voltage level of the triangle wave is between the two voltage references then neither comparator is triggered.

Instead of using a variable DAC used in [12] to vary the motor speed, a potentiometer is used as; an input to the operational amplifier LM324 which acts as a comparator circuit. The DC offset voltage is controlled by the potentiometer P via ICa, which is configured as a voltage follower. This provides a low output impedance voltage source, making the DC offset voltage less susceptible to the loading effect of ICb. As the 'pot' is turned the DC offset voltage changes, either up or down depending on the direction the pot is turned.

Winding the pot up increases the DC bias on the triangle wave and pushes the peaks further above the DC reference, resulting in the motor being powered for a greater portion of each cycle.

Note that an unavoidable side effect of decreasing DC bias is a decrease in the oscillation frequency of the triangle generator. With the pot set for minimum DC bias (full speed); the frequency will be about 150Hz.

Diode D3 provides reverse polarity protection for the controller. Resistor R15 and capacitor C2 are a simple low pass filter. This is designed to filter out any voltage spikes caused by the MOSFETs as they switch to supply power to the motor.

RESULTS AND DISCUSSION

The circuit of the speed controller was shown in Figure (7) and essentially consists of an LM324 quad op amp and four Mosfets in a bridge configuration to drive the motor. The prototype for this circuit is constructed on a PC board as shown in Figure (8) has experimentally validated the proposed PWM speed control DC motor drive circuit.

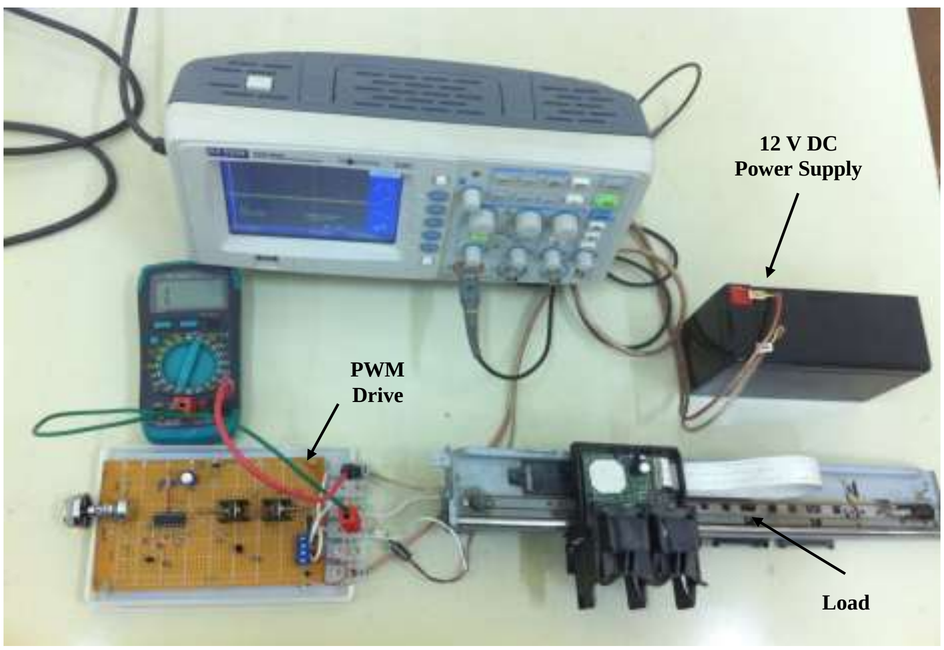
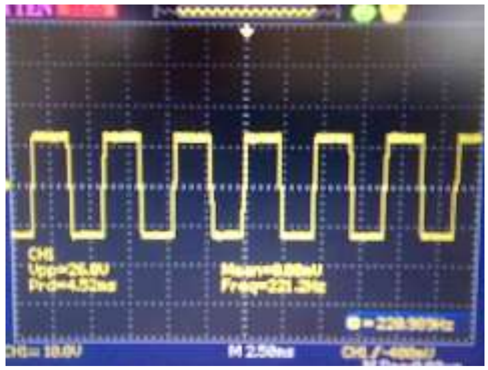


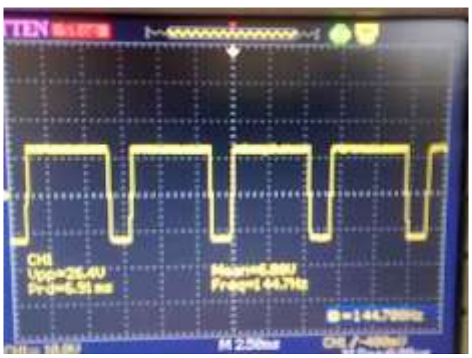
Figure (8) Experimental setup showing overall layout of all equipment used.

The experimental results for the prototype are shown as in Figures. (9-11).
Winding the pot on the PC board up, resulting in the motor being powered for a greater portion of each cycle. Figure (9) shows the no load voltage waveform on the output terminals with 0%, 50% and 80% PWM in the forward and backward direction, respectively. The drive circuit can be operated in bi-directional mode where the input is responsible for both direction and speed selection. In bi-directional mode 0V (or 0 pulses) will give 0% PWM duty. Increasing voltage from 0V to 12V will increase the

PWM duty from 0-100% and turn the motor in one direction. Decreasing the voltage from 0V to -12V will increase the PWM duty from 0-100% and turn the motor in the other direction.



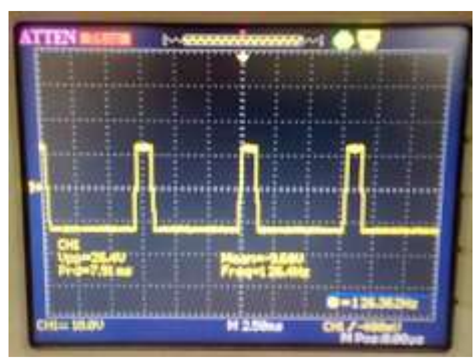
(a) 0% PWM



(b) 50 % PWM forward

(c) 50 % PWM backward

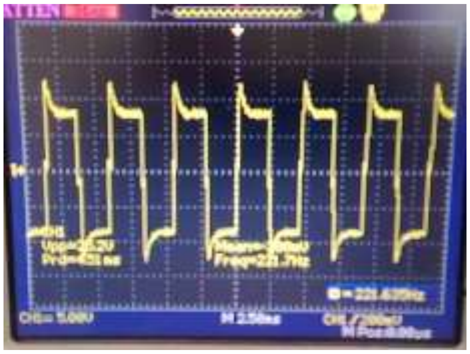
(d) 80 % PWM forward



(e) 80 % PWM backward

Figure (9) (a-e): the no load voltage waveform on the output terminals with 0%, 50% and 80% PWM in the forward and backward direction, respectively.

When the motor is loaded with DC motor, the output voltage waveforms across the motor terminals in the forward and opposite direction are filtered to remove motor hash as shown in Figure (10).



(a) 0 % PWM

(b) 50 % PWM forward

(c) 50 % PWM Backward

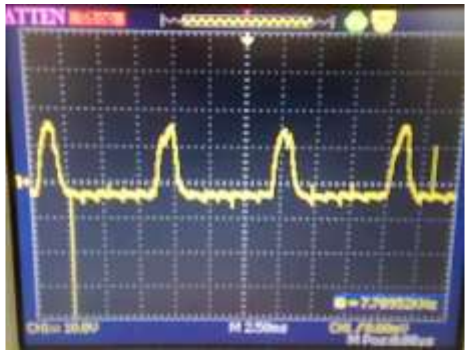
(d) 80 % PWM forward

(e) 80 % PWM Backward

Figure (10) (a-e) the input voltage waveforms across the motor terminals with 0%, 50% and 80% PWM in the forward and backward direction.

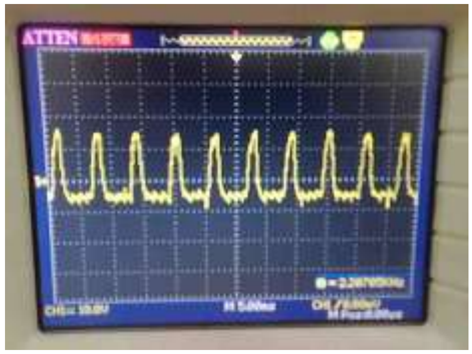
Figure (11) shows the drawn current of the motor operated for about 50% and 80% of the time, respectively.

(a) 50 % PWM forward



(b) 50 % PWM backward

(c) 80 % PWM forward



(d) 80 % PWM backward

Figure (11) (a-d) the motor current waveforms with 0%, 50% and 80% PWM in the forward and opposite direction, respectively.

By adjusting the potentiometer, the duty cycle (or input voltage) across the motor and thus its speed also varied.

Figure (12) shows how the input voltage affects motor speed and direction in bi-directional mode. Motor direction can only be changed when the analog input is close to 0V because reversing motor direction while the motor is turning could have damaging effects on the motor and drive circuit.

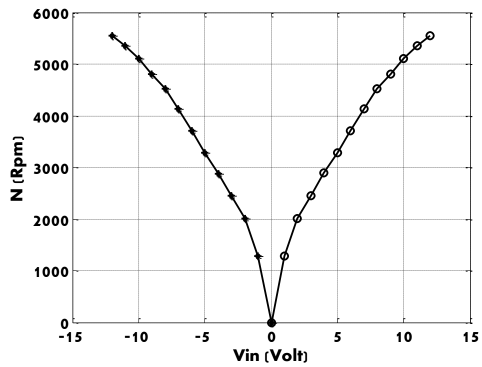


Figure (12) Motor bi-directional speed as a function of input voltage.

CONCLUSIONS

The proposed circuit acts as a simple, low-cost, light weight, efficient, and accurate design for PWM controlling the speed of a DC motor in both forward and reverse direction, from fully off to fully on.

Speed control of a DC motor via pulse width modulation of a fixed-voltage power supply is introduced.

The PWM waveform is created using an operational amplifier (op-amp) circuit. A quad op-amp integrated circuit (IC), an LM324 is used.

The output transistor is either on or off, not partly on as with normal regulation, so less power is wasted as heat and smaller heat-sinks can be used.

The proposed circuit is used for motor running at 12V or 24V and dawning up to about 5A. It runs in switch mode so it quite efficient.

This simple circuit can run a DC motor in clockwise or anti-clockwise direction and stop it using a single potentiometer.

The voltage on a DC motor can be suddenly reversed while it is spinning. This circuit overcomes both the big current surge that could burn out controller and big electrical and mechanical stresses on the motor.

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