Drive Electronics for Moving Magnet Type Linear Motor Compressor

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ABSTRACT

An inexpensive drive circuit to operate a moving magnet type linear motor compressor up to 100 W power is described. It is a Pulse-Width Modulated (PWM-based) circuit with provisions to adjust the frequency, modulation index of the sine wave, frequency of the carrier wave, etc. It is a simple circuit without any need for software development, as discrete electronic components are used in the circuit, and no microcontroller is used. Power MOSFETs are used in the H bridge circuit for driving the linear motor with opto-coupler isolation to eliminate any EMI interference from the motor to the gate circuit. The required logic states are generated using a toggle circuit and the PWM wave form is generated using off-the-shelf operational amplifiers. The circuit is designed to operate with D.C. power supplies of ±5V and +12V. Hence, it can be conveniently operated from the power supply of a Pentium IV computer. This way, the need for developing a specialized D.C. power supply for the electronics is avoided. The developed circuit is capable of providing up to 100 watts of power to drive a single compressor. With suitable modifications, it can be adapted to operate dual opposing compressors of each 100 W. The circuit design, schematic, working principle of the circuit, and the performance are discussed.

INTRODUCTION

Pulse-width modulation (PWM) is a very efficient way of controlling the voltage of a power supply for AC loads that do not draw constant power during their operation. This method eliminates the use of a rheostat, a conventional method of controlling the power to a variable load. A PWM circuit provides a digital means of controlling power in which the width of the voltage pulses is varied in accordance with the difference in the amplitude of the modulating and carrier waves. Variable frequency power supplies based on PWMs can be inexpensive, light weight, and compact.

In this paper a very inexpensive way of generating the PWM signal is described, which, with the use of simple analog devices, eliminates the use of digital processors. A combination of power MOSFETs is used in the H-bridge configuration for driving the linear motor compressor. The gate logic pulses are generated using a toggle circuit, where as the PWM gate pulses are generated using operational amplifiers. Opto-couplers are used to eliminate any motor-caused EMI interference between the gate terminal and gate drive circuit. The complete circuit including the motor drive is energized by a 450-watt power supply (SMPS) meant for the CPU of a Pentium IV computer.

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CIRCUIT DESCRIPTION

The drive circuit includes a PWM wave generator, sine wave generator, H-bridge and other signal conditioners viz. a toggle circuit, phase shifter, comparator, etc. In addition, there are power supply filter circuits for operating the drive from a Pentium IV's SMPS. The design and operation of the individual modules are discussed in this section.

SMPS Power Supply for Drive Circuit

A commercially available 450 W capacity SMPS is used to provide the power supply for the circuit. Unfortunately, the ripple of the SMPS's DC outputs is too high for our application, as the sine and triangular waves are distorted, which in turn affects the PWM wave. To solve this problem, second- and third-order network filters were used for the +5V & -5V circuits to reduce the magnitude of ripple from 42 mV to 8 mV and from 55 mV to 13 mV, respectively. The schematic block diagram of the filters and regulated supplies is given in Fig. 1. The +12 V output of the SMPS is used as the input for the regulated +5 V supply, and the -12V output is used for the -5 V supply.

Filter & Regulator Circuits. The second- and third-order filters shown in Fig. 1 consist of a zener diode and capacitor parallel network as shown Figs. 2(a) and 2(b), respectively. The output of the filters is then fed to a voltage regulator to maintain +5v & -5v. At the output of the regulator, a low pass filter is used to further reduce the noise. In both configurations, the diodes are connected in forward biased mode in parallel with the capacitors. For the +5V DC regulated output, a second-order filter is used, where as for the -5V DC regulated output, the filter is of third order. This is because the ripple generated in the -12 V DC output of the SMPS is much higher in comparison to that of the +12 V DC, and they are of different frequencies.

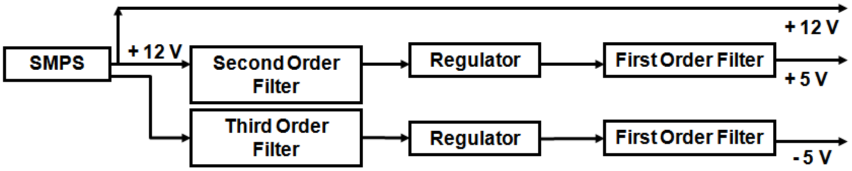
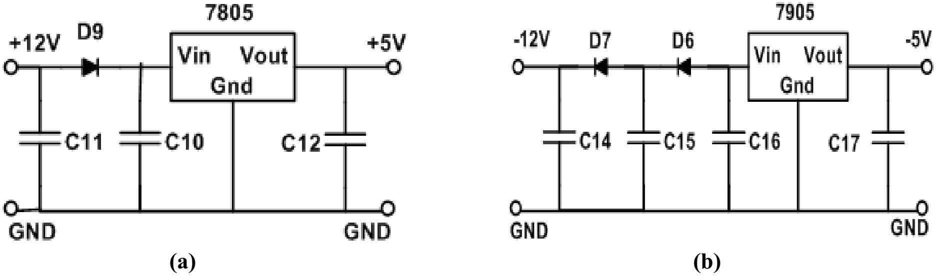


Figure 1. Block diagram of SMPS regulator and filter circuits.



(a) (b)

Figure 2. Filter and regulator circuit schematics of +5 V & -5 V power supplies.

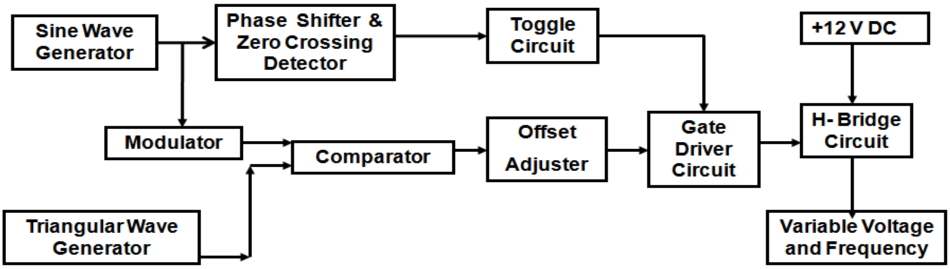


Figure 3. Complete block diagram of PWM generator.

PWM and Signal Conditioning Circuits

PWM modulation requires a stream of digital pulses to be generated, often using digital processor techniques. However, here an attempt is made to generate the PWM pulses using analog electronics components [1]. The benefit of using analog components is that they are lower cost as compared to digital processors. The drive circuit consists of the modules shown in Figure 3. Each module is described in this section. The schematic circuit diagram of the drive circuit for operating the linear motor compressor is shown in Figure 4.

Sine Wave Generator. The circuit is capable of varying the frequency and amplitude of the sine wave [2]. It is an op-amp based circuit as shown in Figure 4. The frequency of the sine wave is given by the following equation.

$$f = \frac{1}{2\pi C1\sqrt{\mathbf{R1R2}}}\ Hz \qquad (1)$$

where, C1, R1 and R2 are the capacitor and resistors referred in Figure 4.

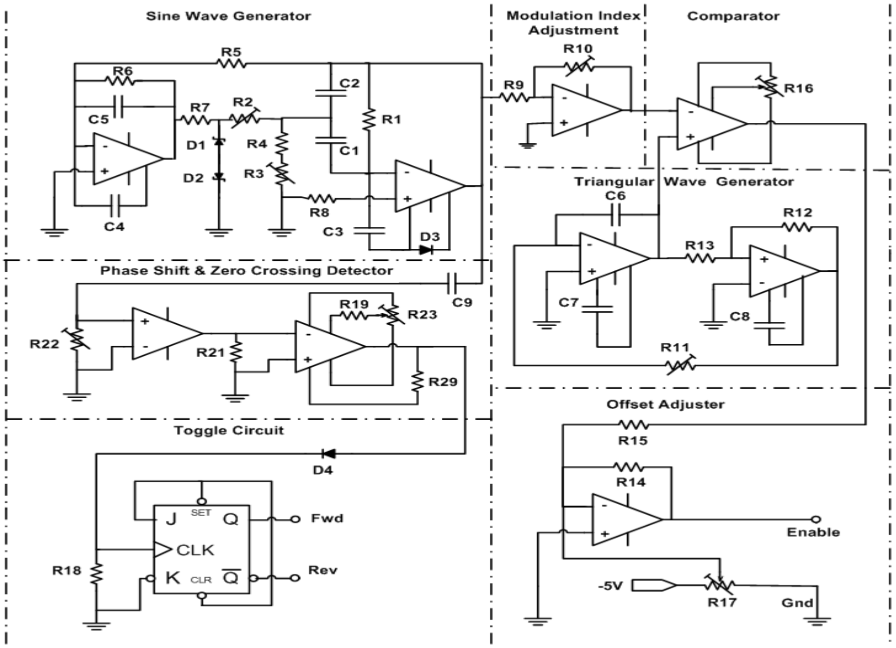


Figure 4. Schematic circuit diagram of the PWM wave generator and signal conditioning cirucits.

The operating frequency of the drive circuit is half of the generated sine wave frequency. This is because one full wave is used for moving the piston in one direction. Tantalum capacitors were used in the circuit to maintain the frequency stable without any drift.

Modulation Index Adjustment. As shown in Figure 4, the output of the sine wave is fed to an amplifier to adjust its magnitude to vary the modulation index. The modulation index plays a crucial role in deciding the degree of change of the pulse width of the PWM waves. An excessively high or low modulation index will result in malfunction of the compressor.

Triangular Wave Generator. The triangular wave generator generates input for the carrier wave and the frequency range varies from 1 kHz to 14 kHz. The carrier frequency decides the train of PWM pulses in a cycle, and the ON time of the PWM pulses will depend on the difference of magnitude of the sine wave and triangular wave. The frequency of the triangular wave is adjusted by the variable resistor R11 as shown in Figure 4.

Comparator. The comparator compares the amplitudes of the sine and triangular waves. This determines the width of each pulse. The pulse width will vary as a function of sine wave amplitude.

Offset Adjuster. As only positive pulses are required to drive the gate circuit, it is necessary to maintain the pulses between +Vcc and 0V. This offset adjuster is a simple summing amplifier with dc voltage to the output; it is designed so that the negative part of the PWM wave is eliminated.

Phase Shifter. This is used to shift the phase by 90^0 so that the direction change of the compressor piston occurs at the lowest amplitude of the sine wave instead of at the zero point. The phase shifted wave is used as a zero crossing detector and the input to the phase shifter is used in the PWM circuit to ensure the direction change of the compressor piston takes place at the right point. The zero crossing detector output is coupled to the flip-flop clock input point through a diode to ensure that the negative part of the signal is filtered out.

Toggle Circuit. A J-K flip flop is used in the circuit. The Q and $\overline{Q}$ outputs of the IC are used as Forward (Fwd) and Reverse (Rev) inputs for the gate circuit. Both the output pulses are compliments to each other and the output frequencies are half of the input clock frequency. The output of the zero crossing detector acts as a clock pulse for the toggle circuit.

Gate Drive Circuit. The outputs of the PWM circuit namely, Forward (Fwd), Reverse (Rev), and Enable ($\overline{E}$) are fed to opto-couplers as shown in Fig. 5. The opto-couplers isolate the gate terminals of the MOSFETs from the PWM circuit [3]. This helps to eliminate EMI inference of the motor on the PWM circuit. The opto-couplers have a high switching frequency with a very short rise time and off time which makes them suitable for high frequency applications.

H – Bridge Circuit. The H - Bridge circuit is a combination of P and N-type MOSFETs as shown in Fig. 5. The unregulated +12 V output of the SMPS is used as the power supply to the H – Bridge circuit. The linear motor is connected across the drain terminals of the MOSFETs as shown in Fig. 5. The maximum output voltage of the inverter is 8 Vrms.

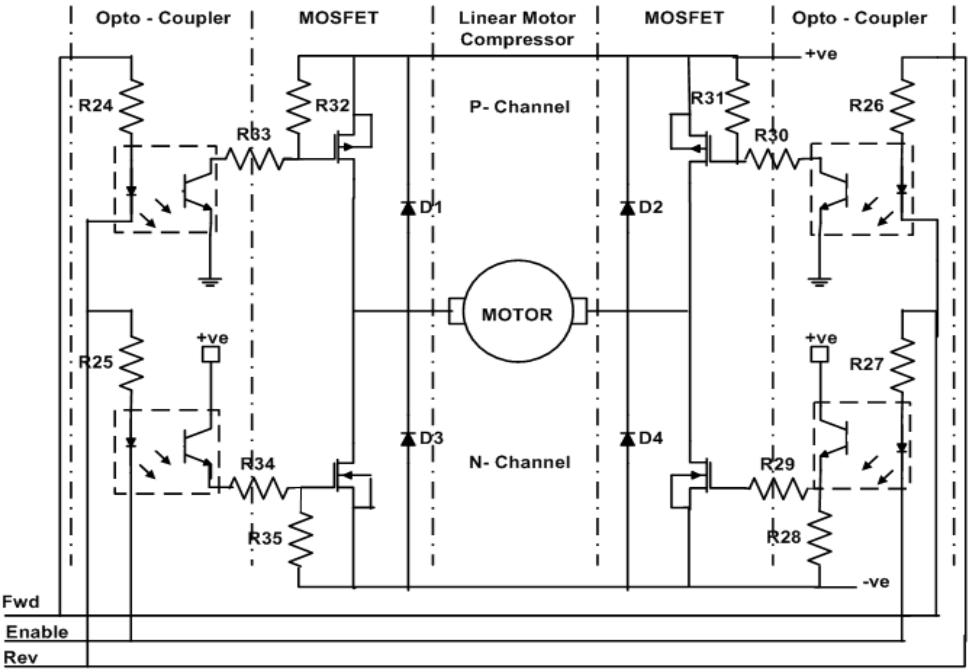


Figure 5. Schematic of gate driver circuit and H-bridge drive.

TEST DESCRIPTION

The designed analog PWM board has been tested for different frequencies, modulation index, carrier frequency, and voltages by connecting it to a TWINBIRD Free Piston Stirling Cooler (FPSC) module (SC-UA04) [4]. The test setup is shown in Fig. 6, and the current and PWM wave forms across and through the motor respectively are shown in Fig. 7. It can be noted that the current wave form is mainly a sine wave, even though the PWM wave is supplied to the motor. This is due to the filtering effect of the mechanical system. The main objective of testing was to investigate any drift in the output of any of the PWM analog circuit components due to changes in their characteristics as a result of heating or extended operation at full load.

In this setup, a constant load (TWINBIRD FPSC 40W motor) was connected with the output of the H-bridge inverter board. The load voltage was kept constant and the frequency was varied in the range of 66 Hz to 80 Hz. It was observed that the load current waveform is sinusoidal and the operating frequency can be varied smoothly by adjusting the trim pots. During operation, frequency drift was observed. On investigation, it was found that a change in the ESR values of ceramic capacitors was the cause. This was eliminated by replacing them with tantalum capacitors. The data were collected for a fixed voltage and load and with a variable frequency supply to identify the resonance of the FPSC. An RTD was mounted on the cold tip to monitor the decrease in the temperature of the cold tip when exposed to ambient temperature (31°C). The frequency versus current and frequency versus temperature plots for constant load and load voltage are shown in Figs. 8 and 9. As per the instruction manual of the TWINBIRD, 79.1 Hz is the resonance frequency of the FPSC motor.

Further, the effects of varying the modulation index and carrier frequency were also studied. When the modulation index is too high, the PWM pulses become unreliable causing discontinuous flow of power, where as if the modulation index is too low, then the output PWM pulses have very little variation in the pulse width, resulting in harmonics in the drive's output current causing excessive vibration and waste of input power. Similarly, if the carrier frequency is too high, the output waveform distorts, resulting in spikes. However, a smooth sine wave is observed for the carrier frequency in the range of 2.5 kHz and 5 kHz.

Figure 6. Photograph of the working TWINBIRD FPSC motor with analog PWM H-bridge inverter board. The ice formation can also be observed at the top most point of cold end. The setup was tested for continuous run of 8 hours. With a minimum temperature recorded during the test is -30° C.

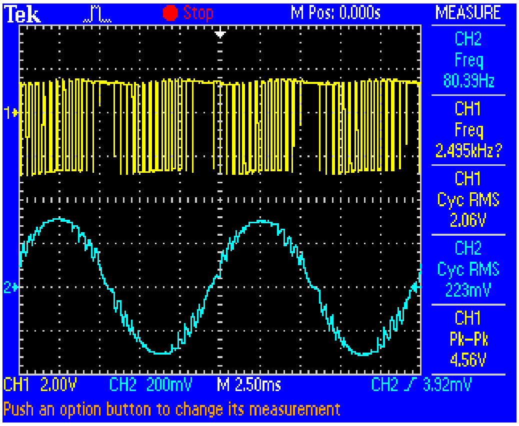


Figure 7. PWM wave (top curve) with carrier frequency at 2.5 kHz. This is the differential voltage across the two terminals of the motor. The bottom curve is the current waveform through the load (motor) at 80.39 Hz. It can be observed that the higher harmonics are filtered out of the current waveform by the mechanical system, and that it is mainly sinusoidal.

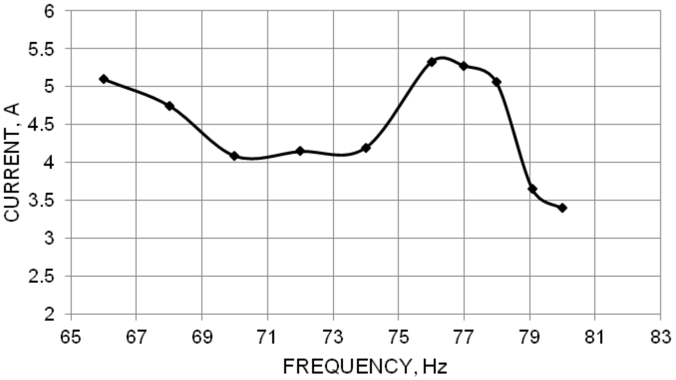


Figure 8. The change in load current for different frequencies. A sudden drop in current is observed at 79.1 Hz, which represents the resonance condition of the load.

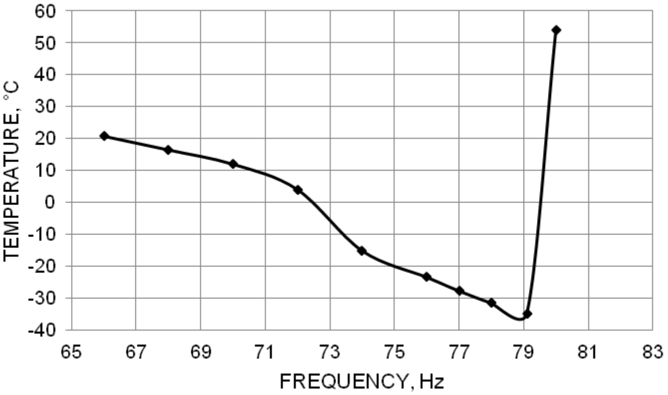


Figure 9. The variation in temperature at cold end of the FPSC motor for different frequencies for constant load and load voltage. The minimum temperature is -34.8°C when the cold tip is exposed to ambient conditions.

EXPERIMENTAL RESULTS

Tests were carried out on the analog PWM board using a constant load (TWINBIRD FPSC motor) and with constant load voltage for variable frequencies. The graph shown in Fig. 8, reveals a sudden drop in current from 5.06 A to 3.56 A, for the change in frequency from 78 Hz to 79.1 Hz. This indicates the resonance of the system is at 79.1 Hz, which matches the motor specifications provided by TWINBIRD. Moreover, the minimum temperature of -30°C is obtained at 79.1 Hz as shown in Fig. 9. Testing beyond 80 Hz was restricted due to a large vibration and tremendous rise of temperature at the cold tip. Please note that the cold tip was not isolated from ambient temperature during these measurements.

The testing of the analog PWM board was carried out with another linear motor where the maximum tested load current frequency was 178 Hz. The maximum frequency range of output current can be varied by changing capacitor C1 and resistors R1 and R2 values, which can be calculated using Equation (1).

CONCLUSIONS

The analog PWM wave generating board along with the gate circuit and H-bridge board is inexpensive, compact and easy to fabricate as compared to digital processors. It does not require programming skills for generation of PWM waves. The best feature of this is all the components used in the board are readily available at low cost which can be easily replaced and the complete system is being driven by just one SMPS from a Pentium IV computer, which makes it light weight. Another feature of the circuit is the ease of adjusting the carrier frequency, modulating signal frequency, modulation index etc. using trim pots. This board is capable of driving linear motor compressors up to 100 W with provision to vary the frequency in the range of 40 – 180 Hz and provides reliable continuous operation.

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