Journal of Energy and Power Engineering 6 (2012) 656-662

Microcontroller-Based Variable Speed Drive for Three-Phase Induction Motor in Cooling Applications

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Received: February 25, 2011 / Accepted: July 29, 2011 / Published: April 30, 2012

Abstract: This paper presents an electronic VSD (variable speed drive) for three-phase IM (induction motor) using a microcontroller. The VSD is designed for cooling applications where the IM is coupled to a cooling fan. The drive receives temperature feedback from objects to be cooled and output a corresponding frequency to the IM. A prototype of the VSD is constructed to control a 175 W, four pole, squirrel cage three-phase IM. The heart of the control circuit is a low-cost microchip's PIC16F777 microcontroller which is programmed using C language to generate variable frequency SPWM (sinusoidal pulse width modulation) switching signals. These switching signals are fed to an IGBT inverter. The VSD constructed can be switched between two modes of speed control: automatic temperature-controlled mode and manual user-controlled mode. Cost savings using the prototype are demonstrated.

Key words: IGBT inverter, PIC microcontroller, SPWM, three-phase induction motor, variable speed drive.

1. Introduction

A major concern of the power industry is to use cost effective conservation technologies as the electric motors consume around 70% of electricity [1]. Therefore, a small gain in energy savings and lower operating costs is highly significant especially when energy conservation and green technology have become the world's agenda. In most cases the electric motors consume more electricity than required ones [2]. Many applications use induction motor drives without a speed controller which runs very close to full speed. Besides wasting more power, the motor keeps running at nominal speed that is faster than the requirement. Furthermore, it is a common practice for engineers to oversize the motor to cater for future expansion which wastes unnecessary energy. Over sizing also occurs because motors are available only at certain rating of speed and engineers normally opt for the next bigger size relative to the process requirement [3]. Besides energy wastage, motor running that is higher than the required speed leads to premature wearing-off, increase in maintenance costs and reduction of motor lifespan.

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One way of reducing motor power consumption is to control the motor speed and to ensure that the motor does not run faster than the required speed. Also it is possible to achieve energy efficiency by introducing an electronics VSD (variable speed drive) which controls the frequency of AC supply to the motor. An energy-efficient drive can be cost-effective with simple paybacks on investment within a few years.

A discussion on energy savings by VSDs and theoretical calculation methods for selecting variable frequency drives is reported in Ref. [4]. A detailed approach for practical applications of VSDs in process control of materials handling, fundamental understanding of operation and control of VSDs is presented in Ref. [5]. According to Ref. [6] performance tests for VSDs for variable torque loads to measure the efficiency of VSD unit and the efficiency of the involved three-phase IM are suggested. It is reported that the savings possible by using VSD systems overshadow the energy savings of motors which have higher efficiencies. A study on V/f control and vector control of three-phase IMs and future trends in VSDs is outlined in Ref. [7]. A low cost solution by implementing PIC microcontrollers to control the speed of a three-phase induction motor in open-loop is reported in Ref. [8]. However, in this case three PWM controllers are needed for the operation of three-phase bridge inverter which controls the motor. A low-cost VF solution using the PIC16F7X7 family of devices is introduced in Ref. [9] by implementing three dedicated PWM modules in hardware to control a three-phase induction motor. A set of defined routines and parameters for V/f control are developed in firmware by using assembly language. A single-phase induction motor drive scheme using a pulse width modulation SG3525A IC and H-bridge MOSFET inverter is proposed in Ref. [10]. However, the developed VSD module and the experimental tests are valid only for a single-phase fractional horsepower motor. The main focus of this paper is to develop cooling applications of a prototype of low-cost energy-efficient VSD for a three-phase IM by using microchip's PIC16F777 microcontroller which is programmed by using C language [11]. A control circuit is developed to sense the temperature and user setting before generating variable frequency three-phase SPWM signals which result in variable frequency AC output voltage.

2. System Overview

Fig. 1 shows the block diagram of an overall drive system consisting of a VSD and a three-phase IM coupled with a cooling fan. The VSD converts the incoming DC voltage to a variable frequency AC voltage based on the feedback temperature of object to be cooled. The relationship between frequency generated and temperature is linearly proportional with a frequency range from 15 Hz to 50 Hz while the temperature ranges from 0 ^{o}C to 100 ^{o}C. The control circuit can be re-programmed to cater for other ranges as long as the frequency does not exceed motor requirement. Based on the temperature, there are two

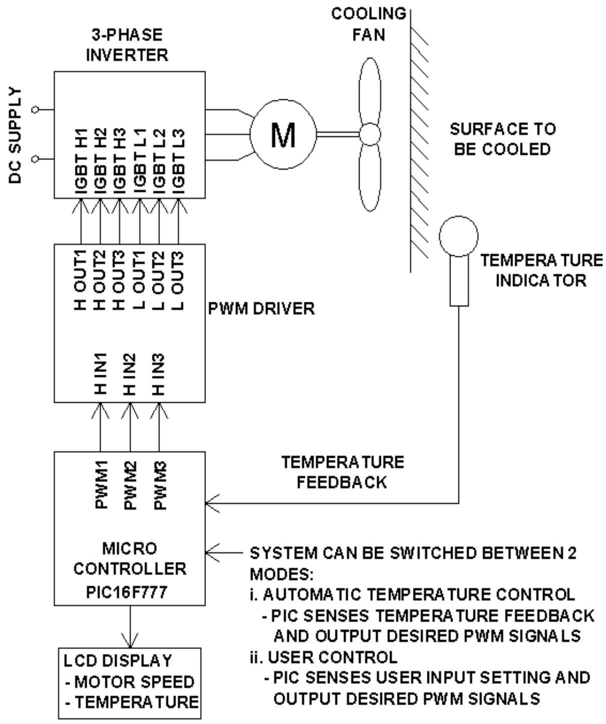

Fig. 1 System overview.

modes available for speed control of the motor: automatic temperature control mode and manual user control mode. Both the modes allow a better control on the motor speed.

Fig. 2 shows the main hardware components used for the experimental setup.

The VSD is designed and constructed to run a 175 W, four-pole, three-phase squirrel cage IM. The VSD includes a three-phase inverter and a frequency control circuit. The inverter used is of lab-volt's 8837—a three-phase IGBT inverter while the control circuit mainly consists of a PIC16F777 microcontroller, a PWM driver, and a 16-pin LCD display unit. The PWM driver is simply a DM74LS04N Not-gate.

2.1 The Inverter Drive

A three-phase IGBT inverter as shown in Fig. 3 receives SPWM signals from frequency control circuit to produce a variable frequency AC. Switches IGBTH1 through IGBTH3 are at the upper side of the inverter while switches IGBTL1 through IGBTL3 are at the lower side.

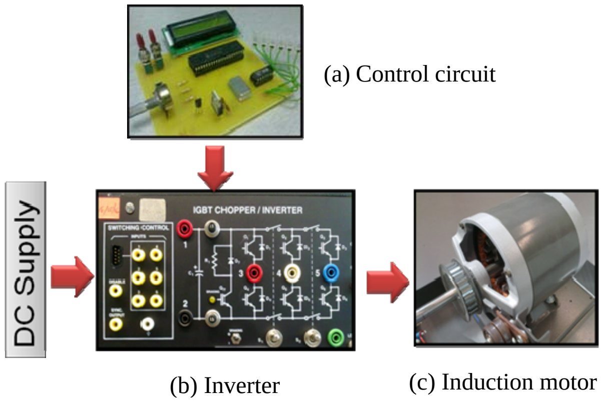

Fig. 2 Main hardware components.

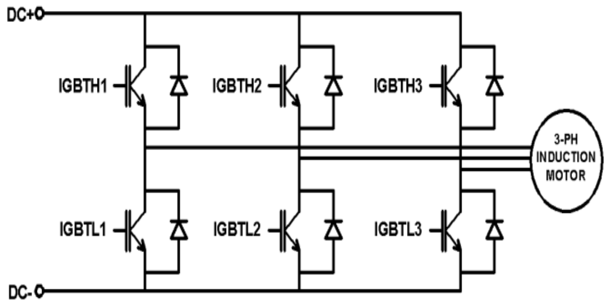

Fig. 3 Three-phase IGBT inverter and IM.

The three upper switches receive the original three-phase SPWM signals generated by the microcontroller while the three lower switches receive the complemented signals of the upper switches. The diodes protect the switches from feedback currents.

2.2 The Frequency Control Circuit

Fig. 4 shows the block diagram of the constructed control circuit. The 40-pin PIC16F777 is chosen as the controller because it is low-cost and it has three built-in PWM modules which are required for a three-phase application. The PIC is programmed by using C language [11]. A maximum clock speed of 20 MHz is used to minimize delay in executing the instructions. IC LM35 is used to sense the temperature in this prototype while a variable resistor is used as the speed controller. The temperature and frequency are displayed on the LCD display. The three-phase SPWM signals are generated from the microcontroller and are inverted by using a not-gate. The three original signals are fed to IGBTH1 through IGBTH3 while the complimented signals are fed to IGBTL1 through IGBTL3.

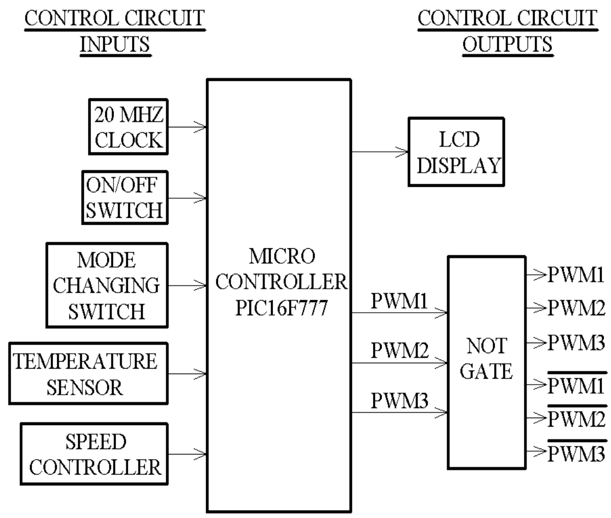

Fig. 4 Block diagram of control circuit indicating all inputs and outputs.

3. Generation of SPWM Using PIC16F777

Fig. 5 shows the basic pattern of a SPWM signal that needs to be generated and fed to the IGBT switches of the inverter to produce a complete sinusoidal cycle at the inverter output terminals. A full duty cycle PWM pulse gives positive peak voltage while a zero duty cycle PWM pulse gives negative peak voltage. Three signals of SPWM are required with each signal being 120° apart from each other.

Since voltage level depends on the duty cycle of PWM pulses, the strategy that has been used in this prototype is to divide a sinusoidal cycle into 36 steps of duty cycle. Five PWM pulses are repeated for each step of duty cycle. Thus, a total of 180 (36×5) pulses are available in a complete output AC cycle. The PIC16F777 [12] provides a built-in programming function for the setting of duty cycle of PWM pulses, as shown in Eq. (1):

set_pwm1_duty (CCPR1L:CCP1CON<5:4>) (1)

The memory storage, CCPR1L:CCP1CON<5:4> is of 10-bit and its value determines the duty cycle of PWM pulses generated [12]. Its maximum value is 1024 (2^{10}) which produces a full duty cycle while its minimum value is 0, producing zero duty cycle. The relationship between the angles of a sine wave, their corresponding duty cycles and value of memory CCPR1L:CCP1CON<5:4> is presented in Table 1.

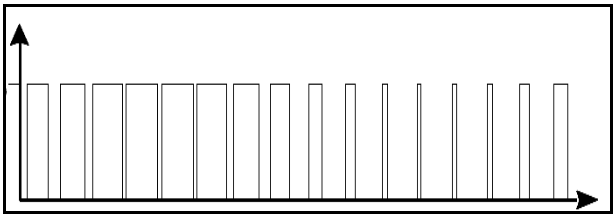

Fig. 5 Basic pattern of SPWM signal to produce a complete output cycle.

Table 1 Relationship between angle, duty cycle and CCPR1L:CCP1CON <5:4>.

Angle	Duty cycle	*CCPR1L:CCP1CON <5:4>
0	0.500	512
10	0.587	601
20	0.671	687
30	0.750	768
40	0.821	841
50	0.883	904
60	0.933	955
70	0.970	993
80	0.992	1,016
90	1.000	1,024
190	0.413	423
200	0.329	337
210	0.250	256
220	0.179	183
230	0.117	120
240	0.067	69
250	0.030	31
260	0.008	8
270	0	0

*CCPR1L:CCP1CON <5:4> = [sin(angle) +1] × 1024/2.

A sine look-up table is based on the values of memory CCPR1L:CCP1CON<5:4> and it is used as part of the program in generating sine waves. As for the realization of variable frequency AC output, the strategy used here is to control the period of each PWM pulse and at the same time to maintain a total of 180 pulses in a complete cycle. When the period of each PWM pulse is reduced, the total time taken to generate 180 pulses is also reduced. Thus the period of one cycle of AC output is reduced and hence a higher output frequency is realized. In contrast, when the period of each pulse is increased, a lower output frequency is generated.

The PIC16F777 provides a built-in function that allows setting of period of PWM pulses, as shown in Eq. (2):

setup_timer_2 (TMR2_prescaler_value, PR2,1) (2)

The PWM period, T_{PWM}, is calculated as shown in Eq. (3):

$$T_{PWM} = (PR2 + 1) \times 4 \times T_{OSC} \times TMR2\_prescaler\_valu \quad (3)$$

The period of oscillator, T_{OSC}, is fixed at 1/(20 MHz) while the timer two pre-scale value is limited to 1, 2, 4, or 16 [12]. Thus the period of PWM pulses depends very much on the value of register PR2. It is an eight-bit register and can be set from 0 to 255. Increasing the value of PR2 results in reduction of AC output frequency, and vice versa.

Fig. 6 shows the flowchart of the control circuit. After initializing the PIC, the PWM modules are configured for operation. The sine look-up table is defined in the beginning. Then PIC reads the mode selection input. For temperature control mode, temperature is sensed and value of PR2 register is calculated based on the temperature. Period of each PWM pulse is then determined using calculated PR2 value. Similarly for user control mode, period of PWM pulses depend on the rheostat value. This is followed by the generation of three-phase SPWM signals from the PIC using the sine look-up table based on the PWM period determined earlier. At this point, the PIC continuously produces the same SPWM signals until there is any change in any inputs, i.e., mode select switch, temperature sensed, etc.. This allows the PIC to bypass complicated arithmetic instructions which result in a more stable output.

4. Results

As shown in Fig. 2, the IGBT inverter receives DC supply and its output terminals are connected to a three-phase IM. The control circuit is connected to the inverter to send the switching signals to the IGBTs' gates. Temperature sensed is displayed on a LCD while motor speed is captured by a tachometer. A three-phase, four-pole, 50 Hz, 175 W, 1360 RPM, 380 V, 0.52 A induction motor is used in the experimental set-up. The motor operates under no-load condition. Figs. 7a-7d

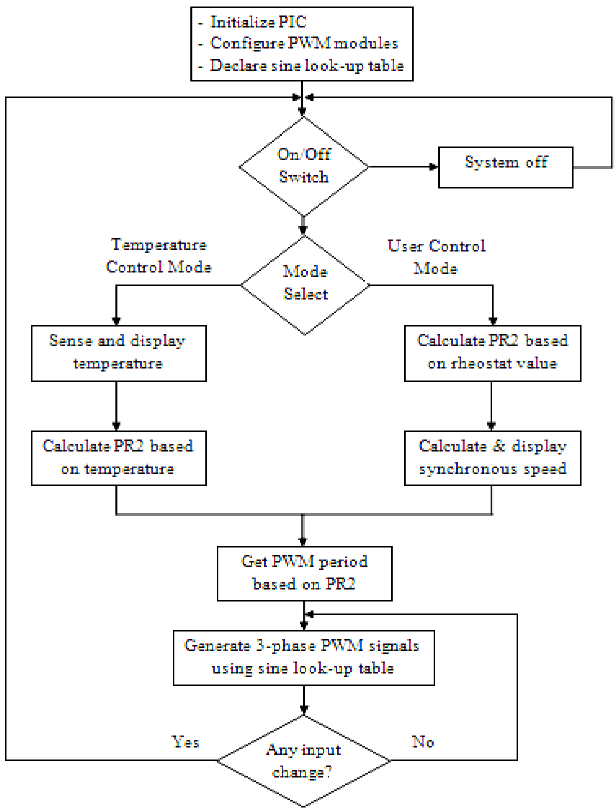

Fig. 6 Flow chart of control circuit.

show the results as compared between two different temperatures: 28.33 °C and 85.12°C under automatic temperature control mode.

Fig. 7a shows the results of two temperatures displayed on the LCD while their corresponding speeds of the motor are recorded using a tachometer. The motor line current waveforms of phases A, B and C and voltage waveform of phase A, corresponding to the recorded temperatures are shown in Fig. 7b. It can be clearly seen that the SPWM signals are more compact (period of each PWM pulse is smaller) for higher temperature (high frequency) as shown in Figs. 7c and 7d. Fig. 7b indicates that the motor line current waveforms are smooth and 120 apart. This is desirable as the motor produces low noise and losses. The frequency of the voltage produced corresponds to the temperature sensed. Figs. 7c and 7d show the SPWM signals generated by the control circuit which are displayed on a Tektronix digital oscilloscope. It is observed that the frequency of SPWM signals for higher temperature is higher comparatively.

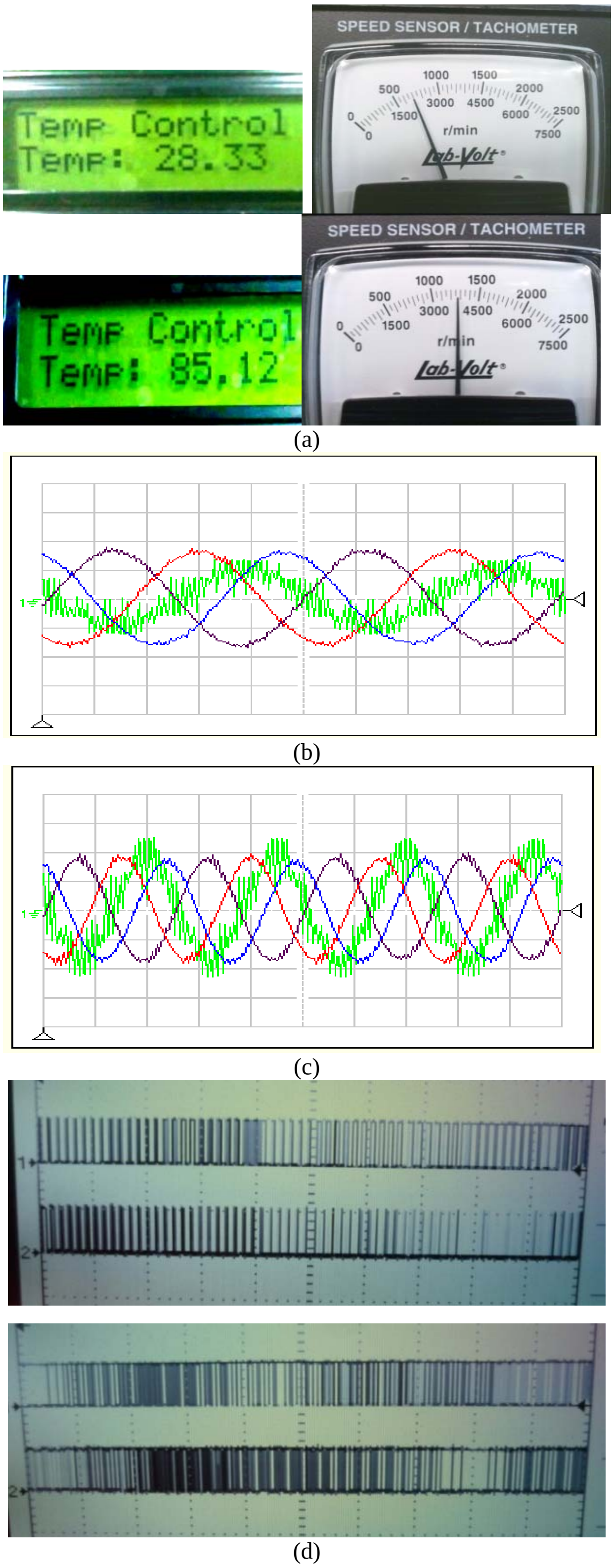

Fig. 7 (a) Temperature on LCD and the corresponding speed by tachometer; (b) Motor line current of phases A, B, C and voltage of phase A; (c) SPWM signals of phases A and B for 28.33 °C; (d) SPWM signals of phases A and B for 85.12 °C.

Table 2 Experimental results on automatic control mode.

Temp. sensed (Celsius)	Calculated		Measured			
	Frequence (Hz)	Synchronous speed (RPM)	Motor speed (RPM)	Speed regulation (%)	Line voltage (V)	Line current (A)
0	15.0	450	425	-5.56	114.0	0.09
10	18.5	555	530	-4.50	140.6	0.1
20	22.0	660	640	-3.03	167.2	0.1
30	25.5	765	725	-5.23	193.8	0.1
40	29.0	870	850	-2.30	220.4	0.1
50	32.5	975	940	-3.59	247.0	0.1
60	36.0	1,080	1,050	-2.78	273.6	0.1
70	39.5	1,185	1,125	-5.06	300.2	0.1
80	43.0	1,290	1,250	-3.10	326.8	0.1
90	46.5	1,395	1,350	-3.23	353.4	0.1
100	50.0	1,500	1,450	-3.33	380.0	0.1

Table 2 shows that as temperature increases, the frequency and synchronous speed increase. The motor actual speed follows the generated synchronous speed with average speed regulation of around -3% which is believed to be the slip of the IM. The line current remains at around 20% of rated current throughout the speed range as the motor is operating at no-load. The line voltage is increased to maintain the *V/f* ratio for an increase in frequency.

5. Cost Savings

Table 2 shows that the line voltage is lower at lower frequency or speed while current does not change. Thus power consumption of the motor reduces linearly with decreasing speed. The developed VSD prototype is tested by using an inverter with rated current of 1.5 A and it can support a three-phase IM up to 500 W rating (150% over current tolerance). Considering apply the VSD to a 500 W IM as the following assumptions:

(1) Motor operates at 85% efficiency and for 6,000 hrs per annum;

(2) Average speed is reduced by 20%;

(3) Tariff rate is 0.378 RM/kWh;

(4) VSD's initial cost is around RM 700.

The savings in cost and payback period are computed as follows:

(1) Annual savings

= Input power × speed reduction factor × running hours × tariff rate

= (500W/0.85) × 0.2 × 6000 hrs × 0.378 RM/kWh

= RM 267

(2) Payback period

= RM 700/RM 267

= 2.62 years

6. Conclusions

A modular design and prototype of the VSD is successfully demonstrated with proven experimental results and cost savings. The VSD uses mainly a 3-phase IGBT inverter and a low-cost frequency control circuit which includes the PIC16F777 microcontroller to drive a three-phase induction motor.

The control circuit is capable of sensing temperature and user setting before generating variable frequency 3-phase SPWM signals which results in variable frequency AC output voltage. A pre-defined look-up table is used to come out with sine waveforms while variable output frequency is realized through varying the period of each PWM pulse. With payback period of less than three years, the prototype is believed to be marketable as the industry is focusing on sustainability.

Acknowledgments

The authors gratefully acknowledge the support provided by Universiti Teknologi PETRONAS, Malaysia.

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