AN843

Speed Control of 3-Phase Induction Motor Using PIC18 Microcontrollers

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INTRODUCTION

Induction motors are the most widely used motors for appliances, industrial control, and automation; hence, they are often called the workhorse of the motion industry. They are robust, reliable, and durable. When power is supplied to an induction motor at the recommended specifications, it runs at its rated speed. However, many applications need variable speed operations. For example, a washing machine may use different speeds for each wash cycle. Historically, mechanical gear systems were used to obtain variable speed. Recently, electronic power and control systems have matured to allow these components to be used for motor control in place of mechanical gears. These electronics not only control the motor's speed, but can improve the motor's dynamic and steady state characteristics. In addition, electronics can reduce the system's average power consumption and noise generation of the motor.

Induction motor control is complex due to its nonlinear characteristics. While there are different methods for control, Variable Voltage Variable Frequency (VVVF) or V/*f* is the most common method of speed control in open loop. This method is most suitable for applications without position control requirements or the need for high accuracy of speed control. Examples of these applications include heating, air conditioning, fans and blowers. V/*f* control can be implemented by using low cost PICmicro® microcontrollers, rather than using costly digital signal processors (DSPs).

Many PICmicro microcontrollers have two hardware PWMs, one less than the three required to control a 3-phase induction motor. In this application note, we will generate a third PWM in software, using a general purpose timer and an I/O pin resource that are readily available on the PICmicro microcontroller. This application note also covers the basics of induction motors and different types of induction motors.

Note:	Refer to Appendix C for glossary of technical terms.

Induction Motor Basics

NAMEPLATE PARAMETERS

A typical nameplate of an induction motor lists the following parameters:

- Rated terminal supply voltage in Volts
- Rated frequency of the supply in Hz
- Rated current in Amps
- Base speed in RPM
- Power rating in Watts or Horsepower (HP)
- Rated torque in Newton Meters or Pound-Inches
- Slip speed in RPM, or slip frequency in Hz
- Winding insulation type - Class A, B, F or H
- Type of stator connection (for 3-phase only), star (Y) or delta (Δ)

When the rated voltage and frequency are applied to the terminals of an induction motor, it draws the rated current (or corresponding power) and runs at base speed and can deliver the rated torque.

MOTOR ROTATION

When the rated AC supply is applied to the stator windings, it generates a magnetic flux of constant magnitude, rotating at synchronous speed. The flux passes through the air gap, sweeps past the rotor surface and through the stationary rotor conductors. An electromotive force (EMF) is induced in the rotor conductors due to the relative speed differences between the rotating flux and stationary conductors.

The frequency of the induced EMF is the same as the supply frequency. Its magnitude is proportional to the relative velocity between the flux and the conductors. Since the rotor bars are shorted at the ends, the EMF induced produces a current in the rotor conductors. The direction of the rotor current opposes the relative velocity between rotating flux produced by stator and stationary rotor conductors (per Lenz's law).

To reduce the relative speed, the rotor starts rotating in the same direction as that of flux and tries to catch up with the rotating flux. But in practice, the rotor never succeeds in 'catching up' to the stator field. So, the rotor runs slower than the speed of the stator field. This difference in speed is called slip speed. This slip speed depends upon the mechanical load on the motor shaft.

The frequency and speed of the motor, with respect to the input supply, is called the synchronous frequency and synchronous speed. Synchronous speed is directly proportional to the ratio of supply frequency and number of poles in the motor. Synchronous speed of an induction motor is shown in Equation 1.

EQUATION 1:

$$\text{Synchronous Speed (Ns)} = 120 \times F/P$$

where:

F = rated frequency of the motor

P = number of poles in the motor

> **Note 1:** The number of poles is the number of parallel paths for current flow in the stator.
>
> **2:** The number of poles is always an even number to balance the current flow.
>
> **3:** 4-pole motors are the most widely used motors.

Synchronous speed is the speed at which the stator flux rotates. Rotor flux rotates slower than synchronous speed by the slip speed. This speed is called the base speed. The speed listed on the motor nameplate is the base speed. Some manufacturers also provide the slip as a percentage of synchronous speed as shown in Equation 2.

EQUATION 2:

$$\text{Base Speed N} = \text{Synchronous Speed} - \text{Slip Speed}$$

$$\text{Percent Slip} = \frac{(\text{Synchronous Speed} - \text{Base Speed}) \times 100}{\text{Synchronous Speed}}$$

> **Note 1:** Percentage of slip varies with load on the motor shaft.
>
> **2:** As the load increases, the slip also increases.

INDUCTION MOTOR TYPES

Based on the construction of the rotor, induction motors are broadly classified in two categories: squirrel cage motors and slip ring motors. The stator construction is the same in both motors.

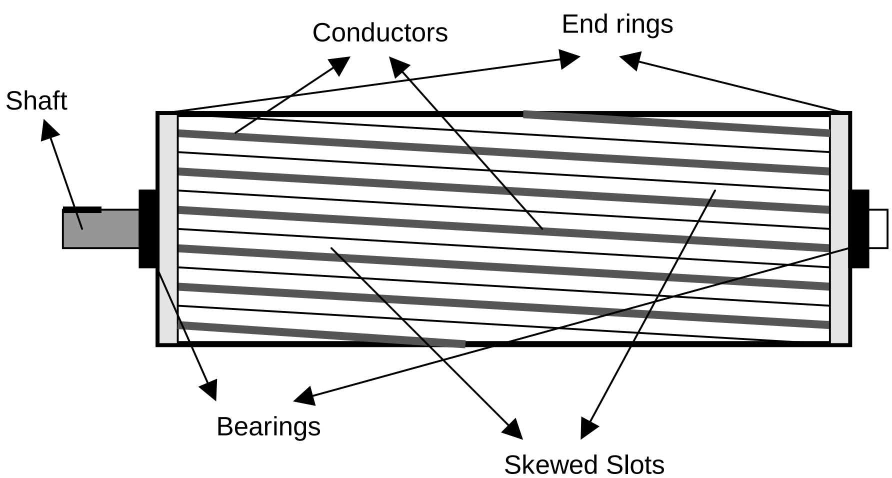
Squirrel Cage Motor

Almost 90% of induction motors are squirrel cage motors. This is because the squirrel cage motor has a simple and rugged construction. The rotor consists of a cylindrical laminated core with axially placed parallel slots for carrying the conductors. Each slot carries a copper, aluminum, or alloy bar. If the slots are semi-closed, then these bars are inserted from the ends. These rotor bars are permanently short-circuited at both ends by means of the end rings, as shown in Figure 1. This total assembly resembles the look of a squirrel cage, which gives the motor its name. The rotor slots are not exactly parallel to the shaft. Instead, they are given a skew for two main reasons:

a) To make the motor run quietly by reducing the magnetic hum.

b) To help reduce the locking tendency of the rotor. Rotor teeth tend to remain locked under the stator teeth due to direct magnetic attraction between the two. This happens if the number of stator teeth are equal to the number of rotor teeth.

FIGURE 1: TYPICAL SQUIRREL CAGE ROTOR



Slip Ring Motors

The windings on the rotor are terminated to three insulated slip rings mounted on the shaft with brushes resting on them. This allows an introduction of an external resistor to the rotor winding. The external resistor can be used to boost the starting torque of the motor and change the speed-torque characteristic. When running under normal conditions, the slip rings are short-circuited, using an external metal collar, which is pushed along the shaft to connect the rings. So, in normal conditions, the slip ring motor functions like a squirrel cage motor.

SPEED-TORQUE CHARACTERISTICS OF INDUCTION MOTORS

Figure 2 shows the typical speed-torque characteristics of an induction motor. The X axis shows speed and slip. The Y axis shows the torque and current. The characteristics are drawn with rated voltage and frequency supplied to the stator.

During start-up, the motor typically draws up to seven times the rated current. This high current is a result of stator and rotor flux, the losses in the stator and rotor windings, and losses in the bearings due to friction. This high starting current overcomes these components and produces the momentum to rotate the rotor.

At start-up, the motor delivers 1.5 times the rated torque of the motor. This starting torque is also called locked rotor torque (LRT). As the speed increases, the current drawn by the motor reduces slightly (see Figure 2).

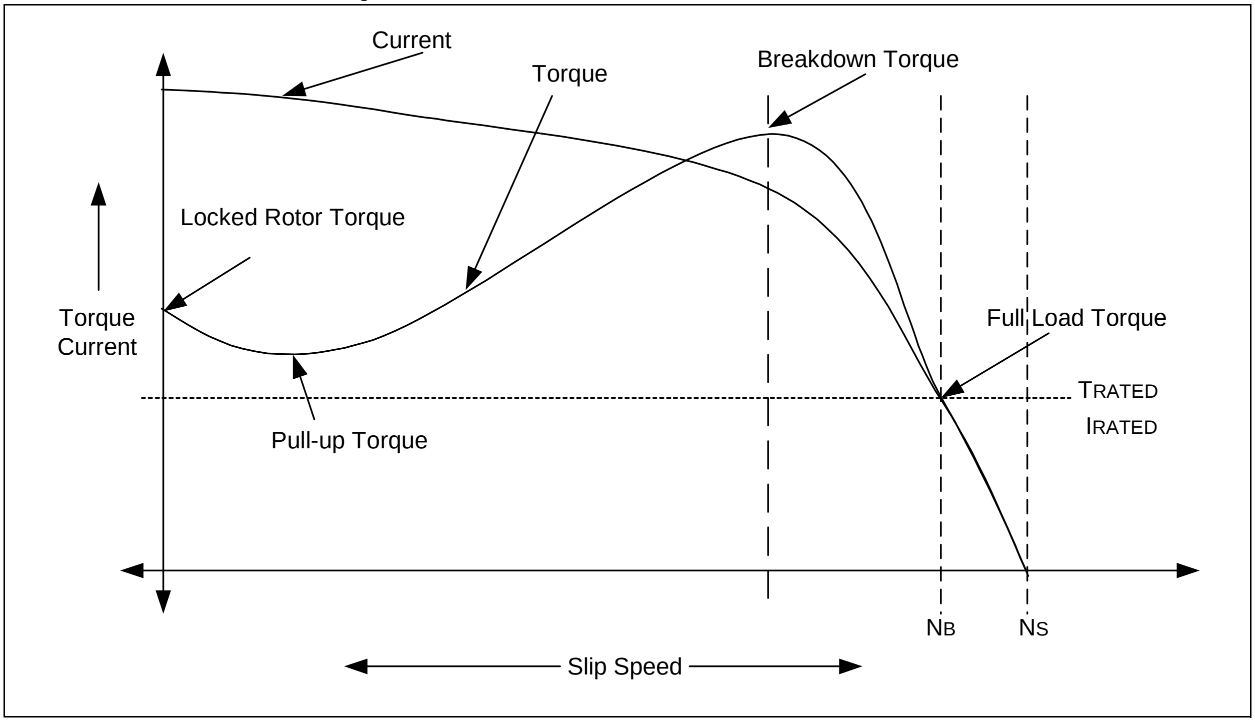
The current drops significantly when the motor speed approaches ~80% of the rated speed. At base speed, the motor draws the rated current and delivers the rated torque.

At base speed, if the load on the motor shaft is increased beyond its rated torque, the speed starts dropping and slip increases. When the motor is running at approximately 80% of the synchronous speed, the load can increase up to 2.5 times the rated torque. This torque is called breakdown torque. If the load on the motor is increased further, it will not be able to take any further load and the motor will stall.

In addition, when the load is increased beyond the rated load, the load current increases following the current characteristic path. Due to this higher current flow in the windings, inherent losses in the windings increase as well. This leads to a higher temperature in the motor windings. Motor windings can withstand different temperatures, based on the class of insulation used in the windings and cooling system used in the motor. Some motor manufacturers provide the data on overload capacity and load over duty cycle. If the motor is overloaded for longer than recommended, then the motor may burn out.

As seen in the speed-torque characteristics, torque is highly nonlinear as the speed varies. In many applications, the speed needs to be varied, which makes the torque vary. We will discuss a simple open loop method of speed control called, Variable Voltage Variable Frequency (VVVF or V/*f*) in this application note.

FIGURE 2: SPEED-TORQUE CHARACTERISTICS OF INDUCTION MOTORS



V/*f* CONTROL THEORY

As we can see in the speed-torque characteristics, the induction motor draws the rated current and delivers the rated torque at the base speed. When the load is increased (over-rated load), while running at base speed, the speed drops and the slip increases. As we have seen in the earlier section, the motor can take up to 2.5 times the rated torque with around 20% drop in the speed. Any further increase of load on the shaft can stall the motor.

The torque developed by the motor is directly proportional to the magnetic field produced by the stator. So, the voltage applied to the stator is directly proportional to the product of stator flux and angular velocity. This makes the flux produced by the stator proportional to the ratio of applied voltage and frequency of supply.

By varying the frequency, the speed of the motor can be varied. Therefore, by varying the voltage and frequency by the same ratio, flux and hence, the torque can be kept constant throughout the speed range.

EQUATION 3:

$$\text{Stator Voltage (V)} \propto [\text{Stator Flux}(\phi)] \text{ x } [\text{Angular Velocity } (\omega)]$$

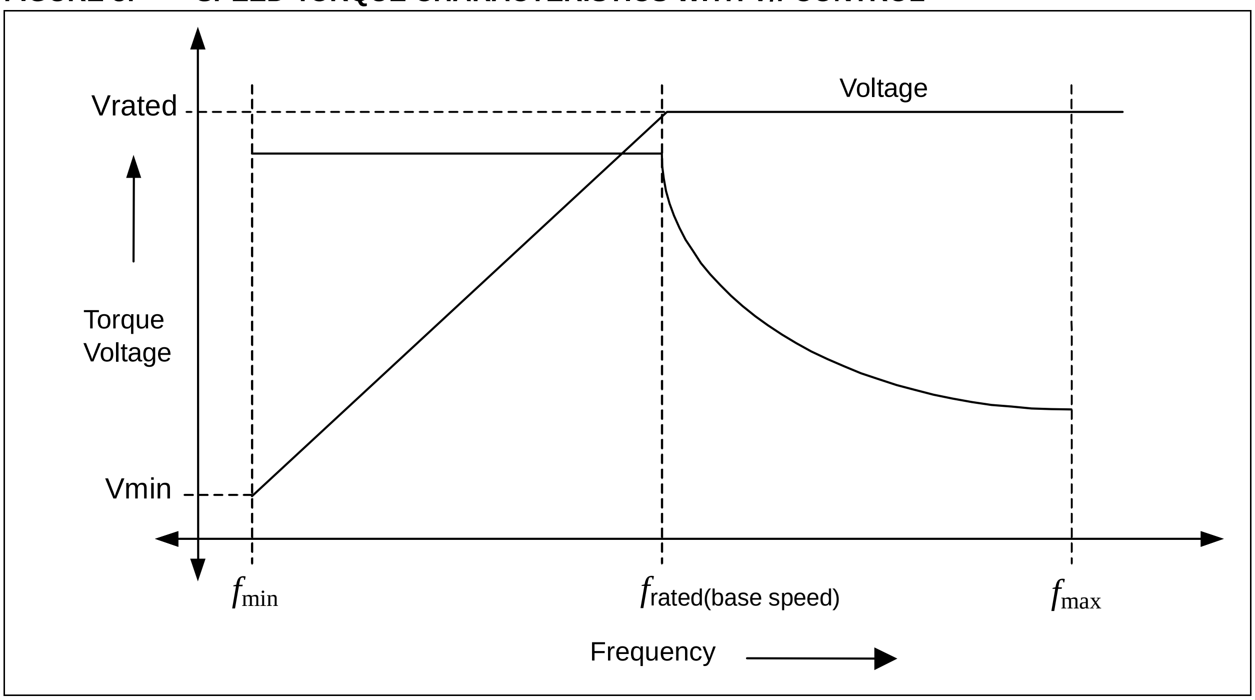
$$V \propto \phi \text{ x } 2\pi f$$

$$\phi \propto V/f$$

This makes constant V/*f* the most common speed control of an induction motor.

Figure 3 shows the relation between the voltage and torque versus frequency. Figure 3 demonstrates voltage and frequency being increased up to the base speed. At base speed, the voltage and frequency reach the rated values as listed in the nameplate. We can drive the motor beyond base speed by increasing the frequency further. However, the voltage applied cannot be increased beyond the rated voltage. Therefore, only the frequency can be increased, which results in the field weakening and the torque available being reduced. Above base speed, the factors governing torque become complex, since friction and windage losses increase significantly at higher speeds. Hence, the torque curve becomes nonlinear with respect to speed or frequency.

FIGURE 3: SPEED-TORQUE CHARACTERISTICS WITH V/*f* CONTROL



IMPLEMENTATION

Power

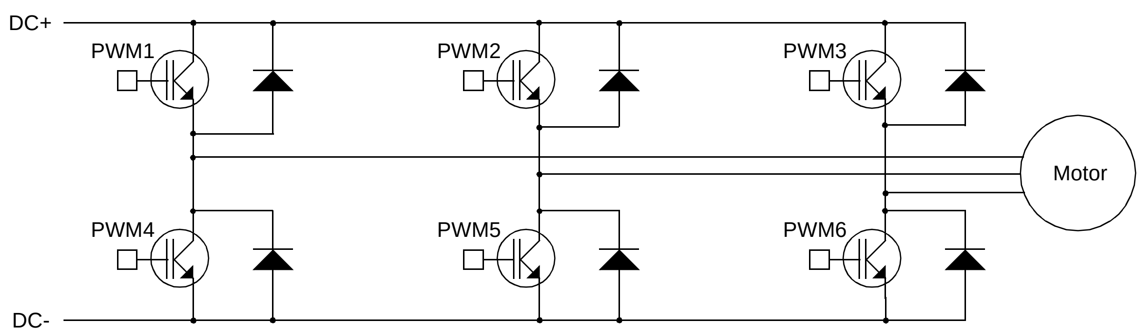
Standard AC supply is converted to a DC voltage by using a 3-phase diode bridge rectifier. A capacitor filters the ripple in the DC bus. This DC bus is used to generate a variable voltage and variable frequency power supply. A voltage source power inverter is used to convert the DC bus to the required AC voltage and frequency. In summary, the power section consists of a power rectifier, filter capacitor, and power inverter.

The motor is connected to the inverter as shown in Figure 4. The power inverter has 6 switches that are controlled in order to generate an AC output from the DC input. PWM signals generated from the microcontroller control these 6 switches. The phase voltage is determined by the duty cycle of the PWM signals. In time, a maximum of three switches will be on, either one upper and two lower switches, or two upper and one lower switch.

When the switches are on, current flows from the DC bus to the motor winding. Because the motor windings are highly inductive in nature, they hold electric energy in the form of current. This current needs to be dissipated while switches are off. Diodes connected across the switches give a path for the current to dissipate when the switches are off. These diodes are also called freewheeling diodes.

Upper and lower switches of the same limb should not be switched on at the same time. This will prevent the DC bus supply from being shorted. A dead time is given between switching off the upper switch and switching on the lower switch and vice versa. This ensures that both switches are not conductive when they change states from on to off, or vice versa.

FIGURE 4: 3-PHASE INVERTER BRIDGE



Control

To derive a varying AC voltage from the power inverter, pulse width modulation (PWM) is required to control the duration of the switches' ON and OFF times. Three PWMs are required to control the upper three switches of the power inverter. The lower switches are controlled by the inverted PWM signals of the corresponding upper switch. A dead time is given between switching off the upper switch and switching on the lower switch and vice versa, to avoid shorting the DC bus.

PIC18XXX2 has two 10-bit PWMs implemented in the hardware. The PWM frequency can be set using the PR2 register. This frequency is common for both PWMs. The upper eight bits of duty cycle are set using the register CCPRxL. The lower two bits are set in CCPxCON<5:4>. The third PWM is generated in the software and output to a port pin.

SOFTWARE PWM IMPLEMENTATION

Timer2 is an 8-bit timer used to control the timing of hardware PWMs. The main processor is interrupted when the Timer2 value matches the PR2 value, if a corresponding interrupt enable bit is set.

Timer1 is used for setting the duty cycle of the software PWM (PWM3). In the Timer2 to PR2 match Interrupt Service Routine (ISR), the port pin designated for PWM3 is set to high. Also, the Timer1 is loaded with the value which corresponds to the PWM3 duty cycle. In Timer1 overflow interrupt, the port pin designated for PWM3 is cleared. As a result, the software and hardware PWMs have the same frequency.

The software PWM will lag by a fixed delay compared to the hardware PWMs. To minimize the phase lag, the Timer2 to PR2 match interrupt should be given highest priority while checking for the interrupt flags in the ISR.

The ISR has a fixed entry latency of 3 instruction cycles. If the interrupt is due to the Timer2 to PR2 match then it takes 3 instruction cycles to check the flag and branch to the code section where the Timer2 to PR2 match task is present. Therefore, this makes a minimum of six instruction cycles delay, or phase shift between the hardware PWM and software PWM, as shown in Figure 5.

The falling edge of software PWM trails the hardware PWM by 8 instruction cycles. In the ISR, the TMR2 to PR2 match has a higher priority than the Timer1 overflow interrupt. Thus, the control checks for TMR2 to PR2 match interrupt first. This adds 2 instruction cycles when the interrupt is caused by Timer1 overflow, making a total delay of 8 instruction cycles. Figure 5 shows the hardware PWM and PWM generated by software for the same duty cycle.

A sine table is created in the program memory, which is transferred to the data memory upon initialization. Three registers are used as the offset to the table. Each of these registers will point to one of the values in the table, such that they will have a 120 degrees phase shift to each other as shown in the Figure 6. This forms three sine waves, with 120 degrees phase shift to each other.

After every Timer0 overflow interrupt, the value pointed to by the offset registers on the sine table is read. The value read from the table is scaled based on the motor frequency input, by multiplying by the frequency input value to find the ratio of PWM, with respect to the maximum DC bus. This value is loaded to the corresponding PWM duty cycle registers. Subsequently, the offset registers are updated for next access. If the direction key is set to the motor to reverse rotation, then PWM1 and PWM2 duty cycle values are loaded to PWM2 and PWM1 duty cycle registers, respectively. Typical code section of accessing and scaling of the PWM duty cycle is as shown in Example 1.

FIGURE 5: TIMING DIAGRAM OF HARDWARE AND SOFTWARE PWMS

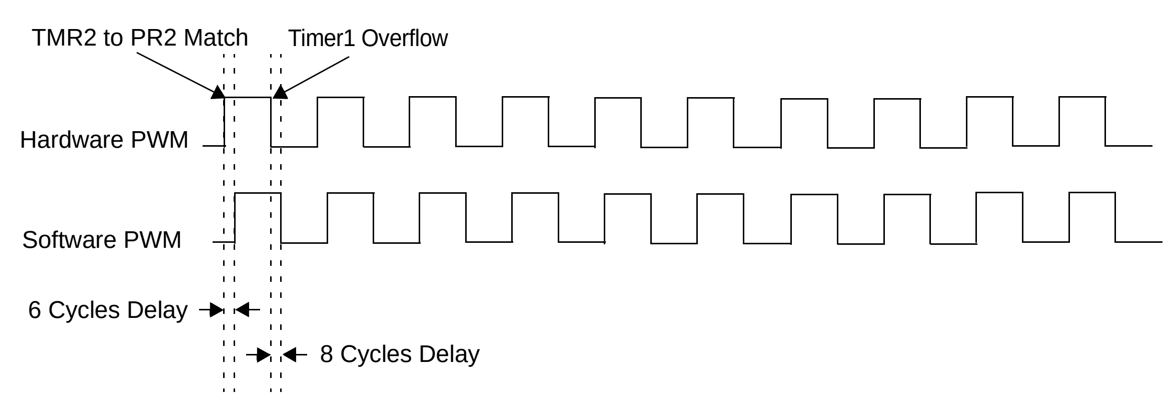
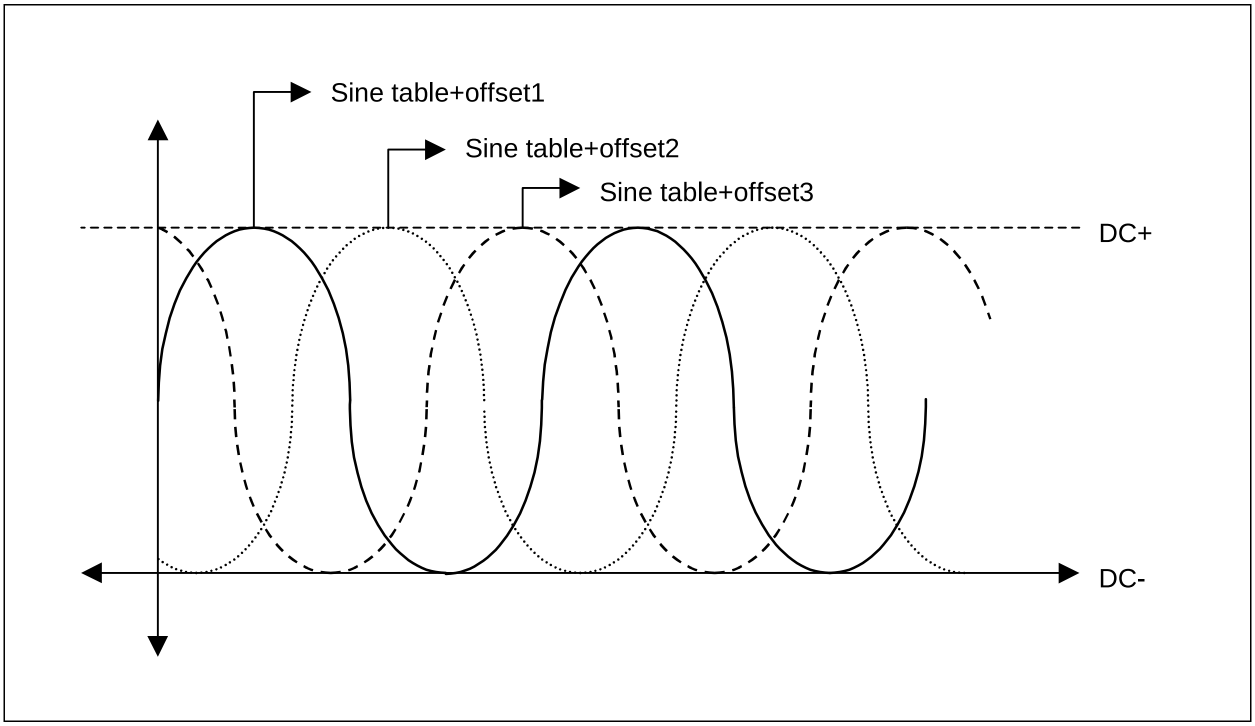


FIGURE 6: REALIZATION OF 3-PHASE SINE WAVEFORM FROM A SINE TABLE



EXAMPLE 1: SINE TABLE UPDATE

```
;*********************************************************************************************
;This routine updates the PWM duty cycle value according to the offset to the table by
;0-120-240 degrees.
;This routine scales the PWM value from the table based on the frequency to keep V/F constant.
;*********************************************************************************************
    lfsr    FSR0,(SINE_TABLE)  ;Initialization of FSR0 to point the starting location of
                               ;Sine table
;---------------------------------------------------------------------------------------------
UPDATE_PWM_DUTYCYCLES
    movf    TABLE_OFFSET1,W    ;Offset1 value is loaded to WREG
    movf    PLUSW0,W           ;Read the value from the table start location + offset1
    bz      PWM1_IS_0
    mulwf   FREQUENCY          ;Table value X Frequency to scale the table value
    movff   PRODH,CCPR1L_TEMP  ;based on the frequency
    bra     UPDATE_PWM2
PWM1_IS_0
    clrf    CCPR1L_TEMP        ;Clear the PWM1 duty cycle register
;---------------------------------------------------------------------------------------------
UPDATE_PWM2
    movf    TABLE_OFFSET2,W    ;Offset2 value is loaded to WREG
    movf    PLUSW0,W           ;Read the value from the table start location + offset2
    bz      PWM2_IS_0          ;
    mulwf   FREQUENCY          ; Table value X Frequency to scale the table value
    movff   PRODH,CCPR2L_TEMP  ;based on the frequency
    bra     UPDATE_PWM3
PWM2_IS_0
    clrf    CCPR2L_TEMP        ;Clear the PWM2 duty cycle register
;---------------------------------------------------------------------------------------------
UPDATE_PWM3
    movf    TABLE_OFFSET3,W    ;Offset2 value is loaded to WREG
    movf    PLUSW0,W           ;Read the value from the table start location + offset3
    bz      PWM3_IS_0
    mulwf   FREQUENCY          ;Table value X Frequency to scale the table value
    comf    PRODH,PWM3_DUTYCYCLE;based on the frequency
    bra     SET_PWM12
PWM3_IS_0
    clrf    PWM3_DUTYCYCLE     ;Clear the PWM3 duty cycle register
;--------------------------------------------------------------------------------------------
SET_PWM12
    btfss   FLAGS,MOTOR_DIRECTION  ;Is the motor direction = Reverse?
    bra     ROTATE_REVERSE         ;Yes
    movff   CCPR1L_TEMP,CCPR1L     ;No, Forward
    movff   CCPR2L_TEMP,CCPR2L     ;Load PWM1 & PWM2 to duty cycle registers
    bsf     PORT_LED1,LED1         ;LED1-ON indicating motor running forward
    return
;---------------------------------------------------------------------------------------------
ROTATE_REVERSE                 ;Motor direction reverse
    movff   CCPR2L_TEMP,CCPR1L ;Load PWM1 & PWM2 to duty cycle registers
    movff   CCPR1L_TEMP,CCPR2L
    bcf PORT_LED1,LED1;LED1-OFF indicating motor running reverse
    return
;---------------------------------------------------------------------------------------------
```

The three PWMs are connected to the driver chip (IR21362). These three PWMs switch the upper three switches of the power inverter. The lower switches are controlled by the inverted PWM signals of the corresponding upper switch. The driver chip generates 200 ns of dead time between upper and lower switches of all phases.

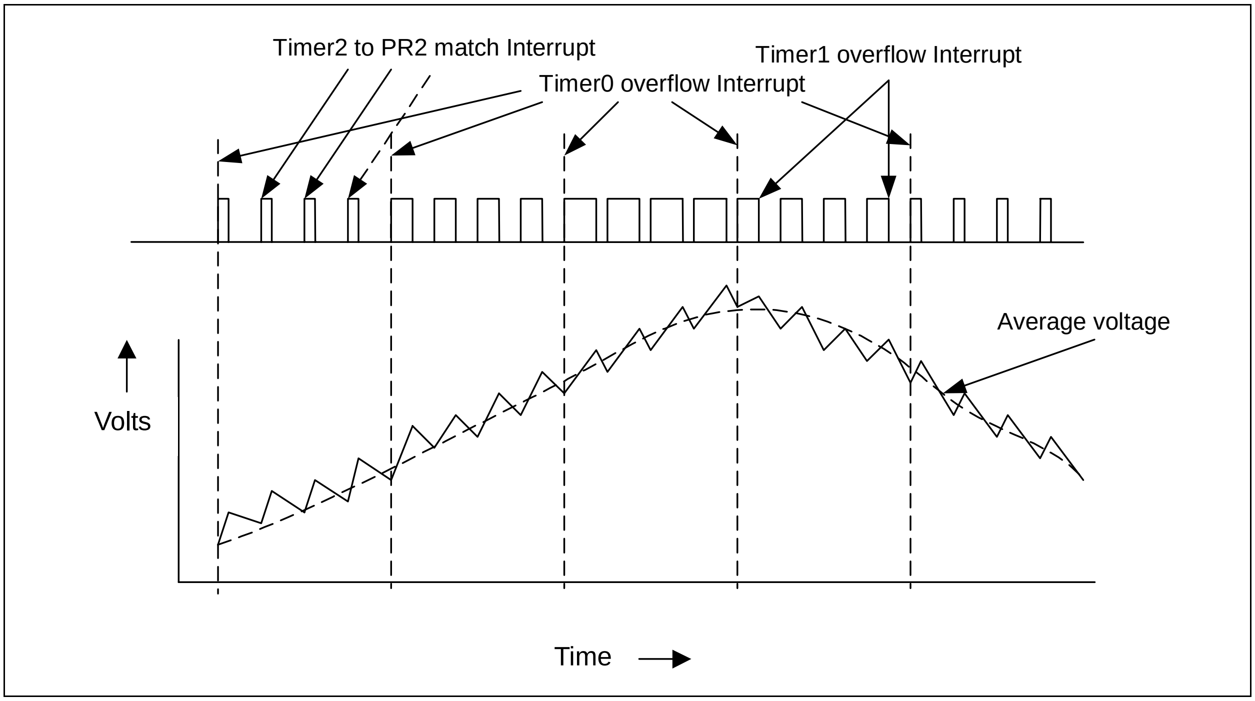
A potentiometer connected to a 10-bit ADC channel on the PICmicro microcontroller determines the motor speed. The microcontroller uses the ADC results to calculate the duty cycle of the PWMs and thus, the motor frequency. The ADC is checked every 2.2 milliseconds, which provides smooth frequency transitions. Timer0 is used for the timing of the motor frequency. The Timer0 period is based on the ADC result, the main crystal frequency, and the number of sine table entries. New PWM duty cycles are loaded to the corresponding duty cycle registers during the Timer0 overflow Interrupt Service Routine. So, the duty cycle will remain the same until the next Timer0 overflow interrupt occurs, as shown in Figure 7.

EQUATION 4:

Timer0 Reload Value =

$$\text{FFFFh} - \frac{\left[\dfrac{\text{FOSC}}{4}\right]}{\text{Sine samples per cycle x Timer0 Prescaler x ADC}}$$

FIGURE 7: TIMER0 OVERFLOW AND PWM

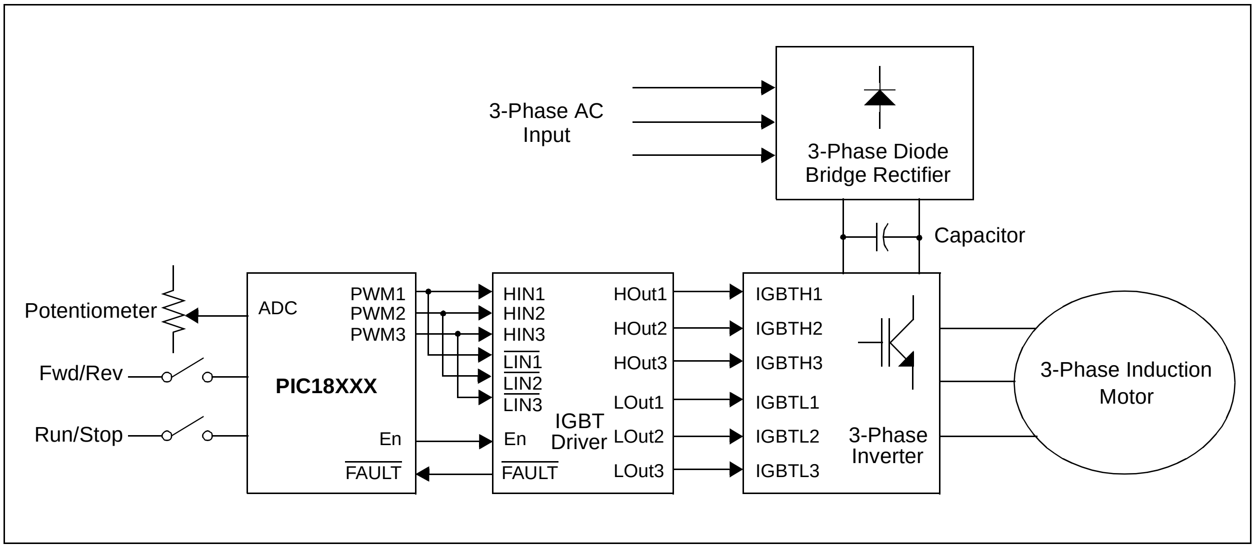


System Overview

Figure 8 shows an overall block diagram of the power and control circuit. A potentiometer is connected to AD Channel 0. The PICmicro microcontroller reads this input periodically to get the new speed or frequency reference. Based on this AD result, the firmware determines the scaling factor for the PWM duty cycle. The Timer0 reload value is calculated based on this input to determine the motor frequency. PWM1 and PWM2 are the hardware PWMs (CCP1 and CCP2). PWM3 is the PWM generated by software. The output of these three PWMs are given to the higher and lower input pins of the IGBT driver as shown in Figure 8. The IGBT driver has inverters on the lower input pins and adds dead-time between the respective higher and lower PWMs. This driver needs an enable signal, which is controlled by the microcontroller. The IGBT driver has two FAULT monitoring circuits, one for over current and the second for under voltage. Upon any of these FAULTS, the outputs are driven low and the FAULT pin shows that a FAULT has occurred. If the FAULT is due to the over current, it can be automatically reset after a fixed time delay, based on the resistor and capacitor time constant connected to the RCIN pin of the driver.

The main 3-phase supply is rectified by using the 3-phase diode bridge rectifier. The DC ripple is filtered by using an electrolytic capacitor. This DC bus is connected to the IGBTs for inverting it to a V/*f* supply.

FIGURE 8: BLOCK DIAGRAM OF 3-PHASE INDUCTION MOTOR CONTROL



CONCLUSION

To control the speed of a 3-phase induction motor in open loop, supply voltage and frequency need to be varied with constant ratio to each other. A low cost solution of this control can be implemented in a PICmicro microcontroller. This requires three PWMs to control a 3-phase inverter bridge. Many PICmicro microcontrollers have two hardware PWMs. The third PWM is generated in software and output to a port pin.

TABLE 1: MEMORY REQUIREMENTS

Memory	Bytes
Program	0.9 Kbytes
Data	36 bytes

APPENDIX A: TEST RESULTS

TABLE A-1: TEST RESULTS

Test #	Set Frequency (Hz)	Set Speed (RPM)	Actual Speed (RPM)	Speed Regulation (%)
1	7.75	223	208	-1.875
2	10.5	302	286	-0.89
3	13.25	381	375	-0.33
4	16.75	482	490	+0.44
5	19.0	546	548	+0.11
6	20.75	597	590	+0.39
7	24.0	690	668	-1.22
8	27.0	776	743	-1.83
9	29.0	834	834	0.0
10	33.0	949	922	-1.5
11	38.0	1092	1078	0.78
12	45.75	1315	1307	-0.44
13	55.5	1596	1579	-0.94
14	58.25	1675	1644	-1.72
15	60	1725	1712	-0.72

Above tests are conducted on the motor with the following specifications:

- Terminal voltage: 208-220 Volts
- Frequency: 60 Hz
- Horsepower: ½ HP
- Speed: 1725 RPM
- Current: 2.0 Amps
- Frame: 56 NEMA

APPENDIX B: MOTOR CONTROL SCHEMATICS

FIGURE B-1: CONTROL AND DISPLAY

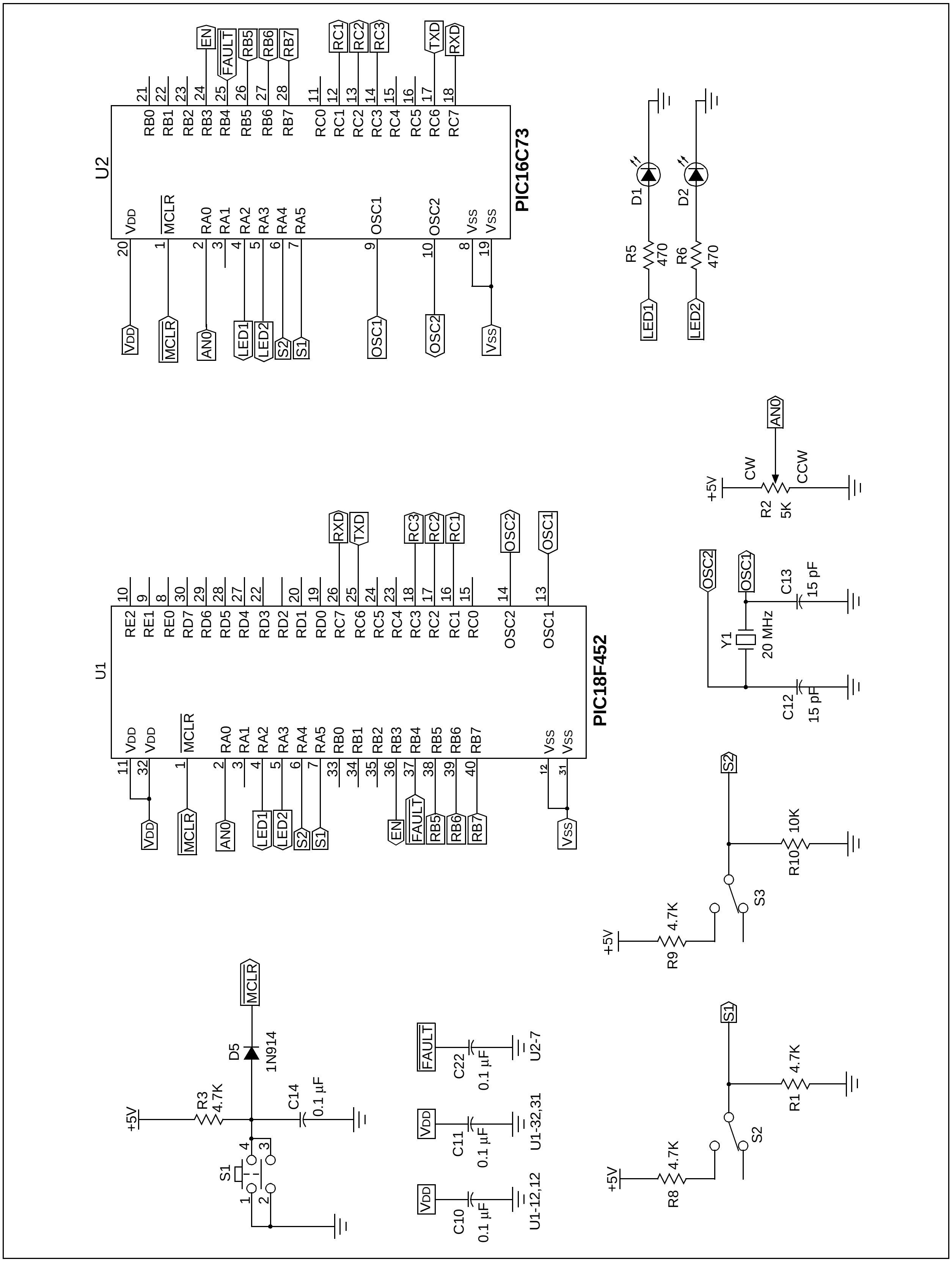


FIGURE B-2: POWER SUPPLY

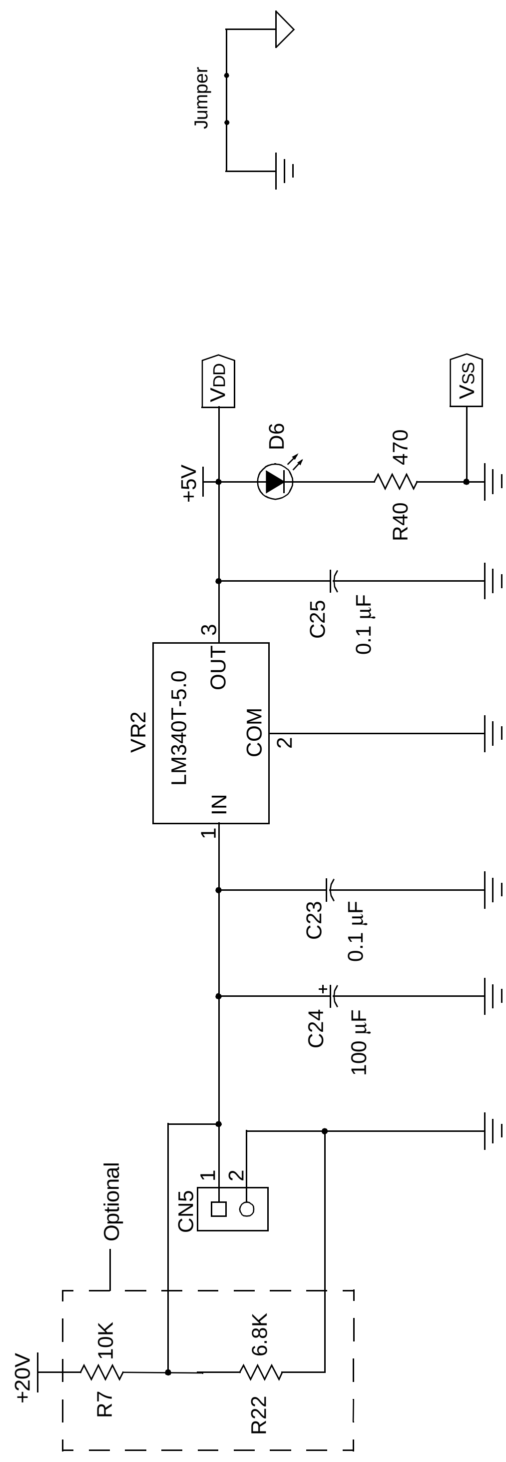
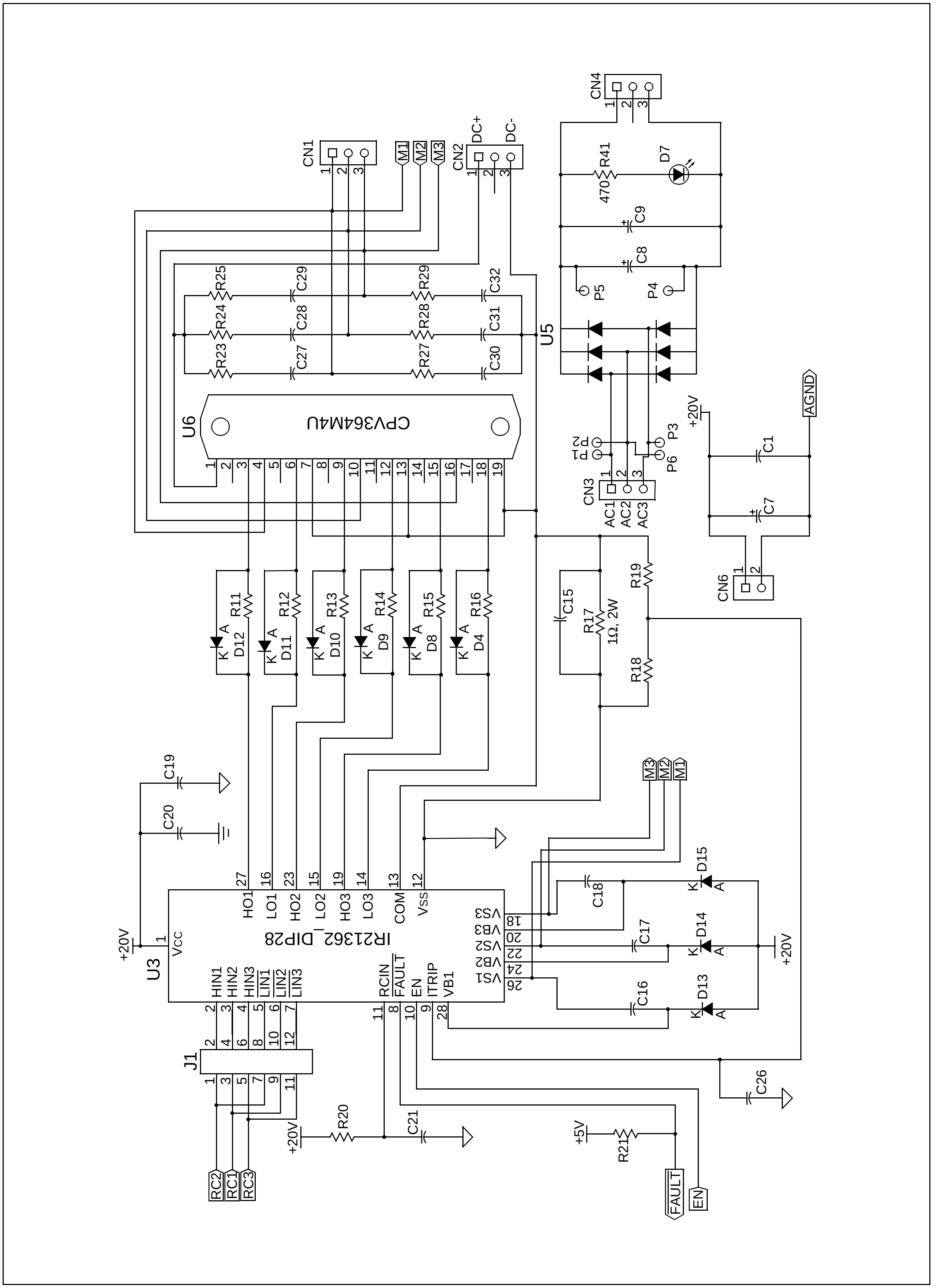


FIGURE B-3: POWER SECTION



APPENDIX C: GLOSSARY

Air Gap

Uniform gap between the stator and rotor.

Angular Velocity

Velocity in radians ($2\pi \times$ frequency).

Asynchronous Motor

Type of motor in which the flux generated by the stator and rotor have different frequencies.

Base Speed

Speed specified on the nameplate of an induction motor.

Break Down Torque

Maximum torque on the speed-torque characteristics at approximately 80% of base speed.

EMF

Electromotive Force. The potential generated by a current carrying conductor when it is exposed to magnetic field. EMF is measured in volts.

Full Load Torque

Rated torque of the motor as specified on the nameplate.

IGBT

Insulated Gate Bipolar Transistor.

Lenz's Law

The Electromotive force (EMF) induced in a conductor moving perpendicular to a magnetic field tends to oppose that motion.

Locked Rotor Torque

Starting torque of the motor.

Pull-up Torque

Torque available on the rotor at around 20% of base speed.

Rotor

Rotating part of the motor.

Slip Speed

Synchronous speed minus base speed.

Stator

Stationary part of the motor.

Synchronous Motor

Type of motor in which the flux generated by the stator and rotor have the same frequencies. The phase may be shifted.

Synchronous Speed

Speed of the motor corresponding to the rated frequency.

Torque

Rotating force in Newton-Meters or Pound-Inches.

APPENDIX D: SOFTWARE DISCUSSED IN THIS TECHNICAL BRIEF

Because of its overall length, a complete source file listing is not provided. The complete source code is available as a single WinZip archive file, which may be downloaded from the Microchip corporate web site at:

www.microchip.com

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