AN2184

Universal Motor Drive with PIC16 Microcontrollers

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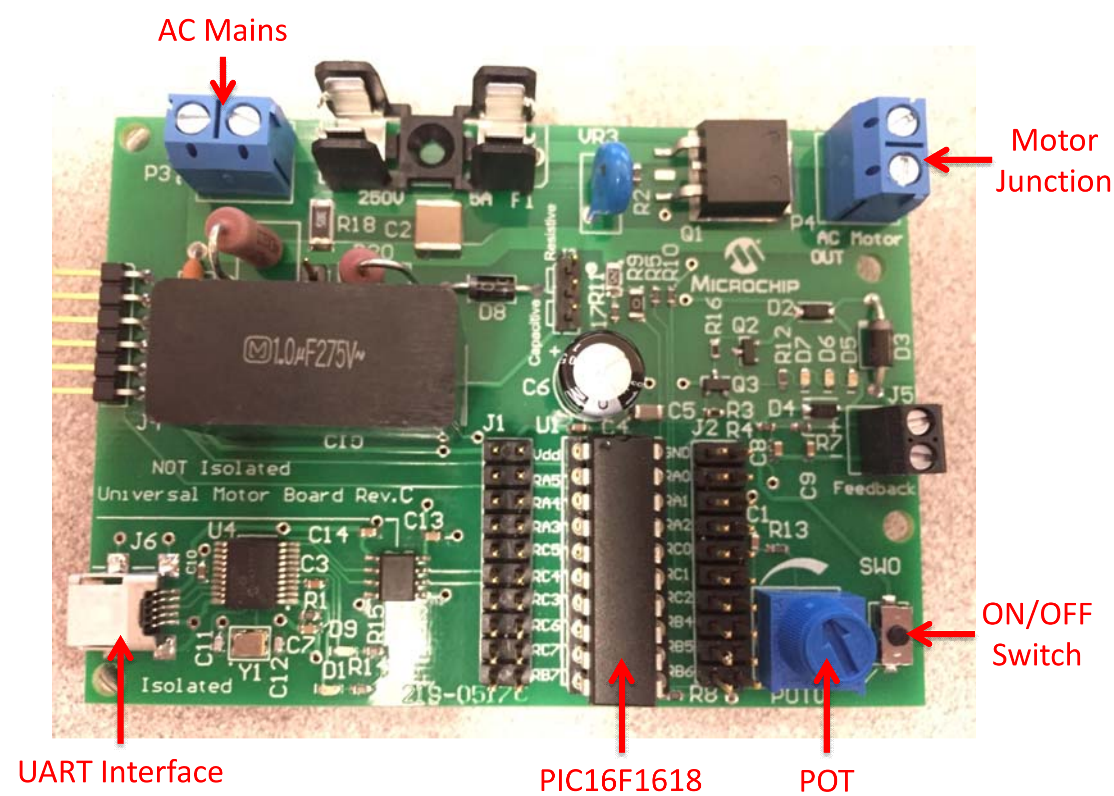
INTRODUCTION

This application note presents the design of an open-loop speed control TRIAC-driven universal motor driver board using a variety of core independent peripherals on an 8-bit microcontroller. The complete source code and reference design material are included.

The universal motor used in this application note runs from 120V-240V AC power and is driven from a TRIAC. A bench test for running a 220V universal motor has been done. The circuit is powered off the line from an non-isolated AC supply; therefore, safety precautions should be taken when working with this type of system. An isolated on-board UART connection is available for debugging on a live circuit.

The low-cost design and its type of motor are suitable for high-torque motor applications commonly used in blenders, food processors, drills and other home appliances.

FIGURE 1: UNIVERSAL MOTOR BOARD



FEATURES

The main features of this design include the following:

1. Precise zero-cross detection of the AC supply voltage using the zero-cross detect module
2. Simple firing angle calculation using the angular timer module
3. Small footprint (low cost)
4. Resistive/Capacitive power supply
5. Isolated UART interface for debugging

APPLICATION

TABLE 1: DESIGN SPECIFICATIONS

Specification	Value
Motor Type	10000 RPM AC Universal Motor (4A)(2)
Input Supply	120 VAC-240 VAC(1)
Control Method	Phase Control – Pulse Train – TRIAC
Power Supply	Capacitive or Resistive
Heat Sink	No
Isolation	UART only

Note 1: For the resistive power supply, the design can accommodate different input voltages if the resistive dropper (R19 and R20 in Figure 3) is changed accordingly. A jumper (J7) offers the selection between 120V and 240V.

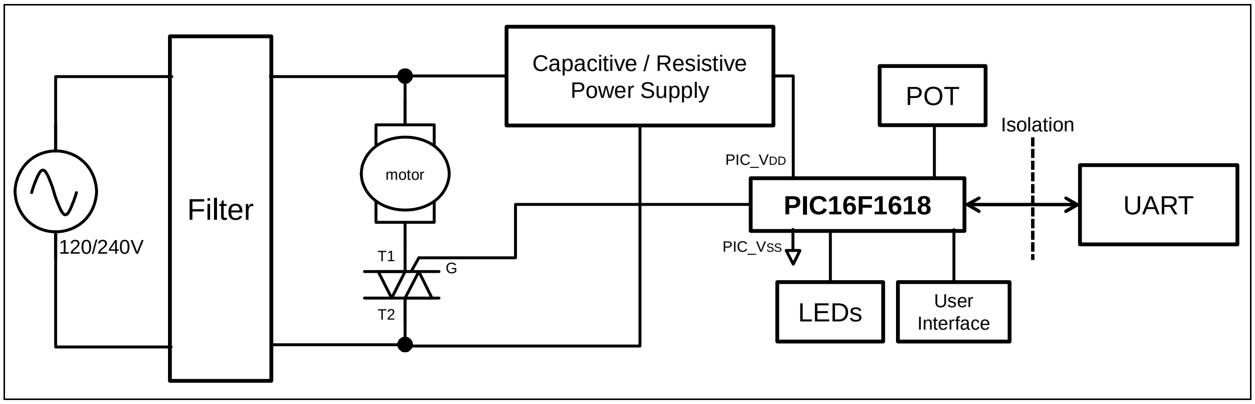
2: A heat sink is required for current above 1.5A.

Overall Block Diagram

As shown in Figure 2, the system consists of an AC supply as an input to a passive EMI filter. A selectable capacitive or resistive power supply creates a DC voltage for the microcontroller and its associated input controls. An isolated UART bridge connects to the microcontroller for debug purposes.

A single potentiometer (POT) controls the firing angle of the TRIAC. The Zero-Cross Detection (ZCD) hardware module provides the required synchronization. The TRIAC is pulse driven from multiple pins on the PIC16F1618. A few LEDs indicate the firing angle. A momentary switch toggles the motor ON or OFF.

FIGURE 2: SYSTEM BLOCK DIAGRAM



HARDWARE DESIGN

The resistive and capacitive power supply with the power indication LEDs require only a few parts. This section will discuss part selection with their associated power ratings.

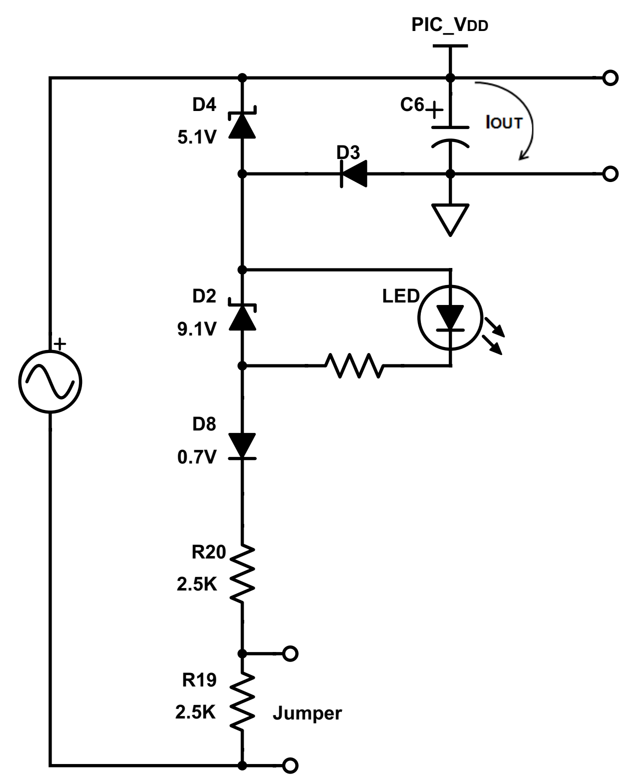
> **Note 1:** The calculations for current and power consumption use approximations for illustration only. The reader is advised to review in more detail, as required for the specific application.
>
> **2:** The power supply of the board is designed with a cost reduction consideration. Further power supply optimization could be implemented for specific designs.

Resistive Power Supply

The board includes both a resistive and capacitive power supply. Jumper J3 is provided to switch between the two power supplies.

A resistive, transformer-less power supply should be chosen for lower-cost applications. A capacitive one should be selected if the heat dissipation from a resistor is undesirable. Figure 3 shows the main components for the resistive power supply option. **Section Appendix A: "Schematics"** provides the complete schematic.

FIGURE 3: RESISTIVE POWER SUPPLY



This topology is taken from application note AN954, *"Transformerless Power Supplies: Resistive and Capacitive"* (DS00954). The reader should consult AN954 for further details. PIC_VDD will remain regulated as long as the output current is less than the input current.

The microcontroller consumes only a few milliamperes of current; however, the peak current to turn on a TRIAC and some LEDs may consume up to tens of milliamperes. The parts in Figure 3 must therefore be carefully selected in order to minimize cost and maximize efficiency as seen in Table 2.

TABLE 2: RESISTIVE POWER SUPPLY

Symbol	Description	Purpose
Resistive Power Supply		
R19, R20	Current Limiting	Sets the amount of current allotted to IOUT
D4, C6	PIC_VDD Supply	Creates PIC_VDD a low voltage rail for the control circuitry
D2	LED Supply	Creates a voltage rail for the LEDs
D3		Blocks the discharge of C6
D8		Half-wave rectifier

Output current

The maximum output current IOUT must be less than the input current IIN or else the output voltage PIC_VDD will fail to regulate. Equation 1 shows the relation between input current and output current.

EQUATION 1: INPUT CURRENT FOR A RESISTIVE SUPPLY

$$I_{IN} = \frac{V_{HFRMS}}{R19 + R20} \geq I_{OUT(MAX)}$$

Where V_{HFRMS} is the half-wave RMS input voltage.

EQUATION 2: INPUT VOLTAGE

$$V_{HFRMS} = \frac{V_{PEAK} - V_{D4} - V_{D2} - V_{D8}}{2} = \frac{\sqrt{2}V_{RMS} - V_{D4} - V_{D2} - V_{D8}}{2}$$

The voltage dropped over current-limiting resistors (R19 and R20) is divided by 2 because of the half wave created by D3. D4 clamps the voltage to an approximate 5.1V – 0.7V = 4.4V to provide the DC voltage for the microcontroller.

The RMS voltage is used in Equation 2 instead of the peak since the average current is what dictates the maximum average amount of current drawn from C6. Note that the equation is based on an approximation that the waveform is still sinewave. The exact waveform is not a complete sinewave due to the Zener diodes.

IOUT must also be less than the maximum sink current of D4 minus its biasing current. These values are typically given in the diode's data sheet.

EQUATION 3: MAXIMUM OUTPUT CURRENT LIMITATION

$$I_{OUT(MAX)} \leq I_{D4(MAX)} - I_{D4(BIAS)}$$

EQUATION 4: CALCULATE MINIMUM POSSIBLE IIN

$$I_{IN} = \frac{V_{HFRMS}}{R19 + R20} \geq I_{OUT(MAX)}$$

The AC mains voltage has a tolerance of +10%/-6%. Assuming minimum values of VRMS (-6%) and maximum values for all diode forward voltage drops and resistances:

EXAMPLE 1: MINIMUM CURRENT CALCULATIONS FOR THE RESISTIVE POWER SUPPLY – 120 VAC – 6% CASE

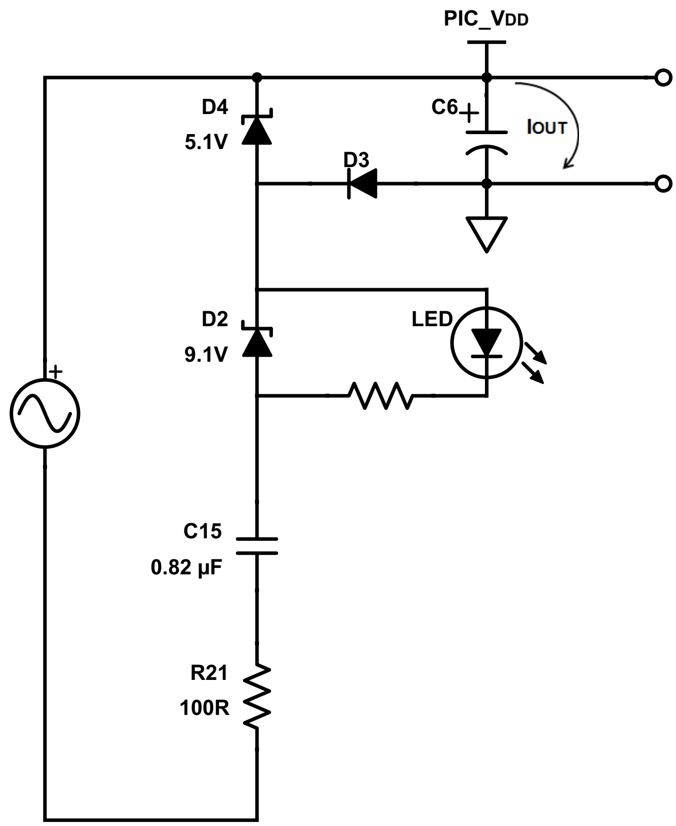
$$V_{RMS} = 112.8\ V_{AC}(-6\%)$$
$$V_{D4} = 5.35V(+5\%)$$
$$V_{D2} = 9.56V(+5\%)$$
$$V_{D8} = 0.7V$$
$$V_{HRMS} = 71.9V$$
$$R_{20} = 2.75\ k\Omega(+10\%)$$
$$\boldsymbol{I_{IN} \cong 26.15\ mA}$$

Different values of R19 or R20 must be tuned for different input voltages.

Capacitive Power Supply

The capacitive power supply shares similar equations to the resistive power supply with the exception of the input current calculation.

FIGURE 4: CAPACITIVE POWER SUPPLY



Output Current

EQUATION 5: INPUT CURRENT

$$I_{IN} = \frac{V_{RMS}}{X_{C15} + R_{21}} \geq I_{OUT(MAX)}$$

Where X_{C15} is the impedance of the non-polarized capacitor.

EQUATION 6: CAPACITOR IMPEDANCE

$$X_{C15} = \frac{1}{2\pi f C15}$$

Substituting the above equation and the V_{HRMS} equation and neglecting C15 series resistance.

EQUATION 7: INPUT CURRENT EXPANDED

$$I_{IN} = \frac{V_{HRMS}}{\frac{1}{2\pi f C_{15}} + R21} = \frac{\sqrt{2}V_{RMS} - V_{D4} - V_{D2}}{2 \bullet \left(\frac{1}{2\pi f C_{15}} + R21\right)}$$

EXAMPLE 2: CALCULATE MINIMUM POSSIBLE I_{IN} FOR THE CAPACITIVE POWER SUPPLY

$$V_{RMS} = 112.8\ V_{AC}(-6\%)$$

$$V_{D4} = 5.35V(+5\%)$$

$$V_{D2} = 9.56V(+5\%)$$

$$V_{HRMS} = \frac{\sqrt{2}V_{RMS} - V_{D4} - V_{D2}}{2} = 72.3V$$

$$f = 60\ Hz(-0.1\%)$$

$$C15 = 0.74\ \mu F(-10\%)$$

$$R21 = 110\Omega(+10\%)$$

$$\mathbf{I_{IN} \cong 19.6\ mA}$$

CURRENT CONSUMPTION

It is important to keep the average current drawn from the DC capacitor not to cause the DC voltage drop lower than the minimum operating voltage of the PIC® device and of other devices. Capacitor C6 must be suitably sized to work within the normal operating limits of the control circuit components. Therefore, the average current drawn from the latter is required. Table 3 below shows the average current consumption of the devices operating from PIC_VDD.

Note:	The component values chosen for current consumption are not optimized in this demo-purpose board. A production type design can be optimized further.

TABLE 3: CURRENT CONSUMPTION FROM 4.4V SUPPLY

Device	Average Current
PIC16F1618	10 mA @ 32 MHz (PLL)
TRIAC	0.6 mA @ 60 Hz, 5 pulses 100 µs wide
Q2+Q3	15 µA @ 60 Hz
Other devices (Switch, POT, Isolation Barrier)	7 mA

PIC® Device Operating Current

The core of the microcontroller running at its full speed will consume its maximum current of 3.6 mA, as specified in the Electrical Specifications, D020, in *14/20-Pin 8-Bit Advanced Analog Flash Microcontrollers* (DS40001715). Lower currents can be achieved if the operating speed is lowered. According to the bench test, the microcontroller could use up to 10 mA by driving the core and the I/O pins.

Brown-Out Reset Situation

The BOR circuit holds the device in Reset when VDD reaches a selectable minimum level. Low-Power Brown-out is enabled in the program. If a short mains supply interruption happens and the PIC_VDD drops below 2.45V, the microcontroller will be held in Reset and restart once the supply voltage is back to normal.

TRIAC Triggering Current

The BTA312B-E has a maximum gate trigger current of 10 mA. Assuming that, as an effective way to ensure it is turned on under various load conditions, the TRIAC will be fired five times every positive and negative edge zero-cross for a duration of 100 µs, the average driving current is therefore:

EQUATION 8: AVERAGE TRIAC FIRING CURRENT

$$I_{avg} = \int_{t0}^{t1} I_{TR} dt$$

$$I_{TR\_avg} = \left(\frac{Time\ On\ per\ Period}{Total\ Time}\right) \bullet I_{TR\_ON} = \frac{2 \bullet (5 \bullet 100\ us)}{\left(\frac{1}{60\ Hz}\right)} \bullet 10\ mA = 0.6\ mA$$

Note: The 10 mA peak drive current is controlled by the gate resistors R5 and R10 value and the number of driving pins (2).

The TRIAC peak firing current is therefore not negligible compared to the average operating current consumed by the microcontroller. In general, a lower cost TRIAC will require a larger gate trigger pulse current to be held for a longer time.

Q2 Biasing Current

Q2 is a transistor in series with the indication LEDs. This transistor is used to turn on the LEDs every positive half-cycle of the input voltage.

A gate current of 30 µA for a typical NPN general purpose transistor is all that is required to drive the transistor in its desirable saturation region. Assuming that the transistor is turned on every half-cycle, the average current can then be calculated as shown in Equation 9.

EQUATION 9: AVERAGE TRANSISTOR BIASING CURRENT

$$I_{Q\_avg} = \left(\frac{Time\ On\ per\ Period}{Total\ Time}\right) \bullet I_{Q\_ON} = \frac{\frac{\left(\frac{1}{60\ Hz}\right)}{2}}{\left(\frac{1}{60\ Hz}\right)} \bullet 30\ \mu A = 15\ \mu A$$

The biasing current is practically negligible.

Note that the LEDs do not consume any current from the microcontroller voltage rail PIC_VDD. This helps alleviate the current demand and hence size and cost of C6. The LEDs will flicker at a 50/60 Hz rate since they are only biased during one half-cycle.

Miscellaneous

The potentiometer and switch are the other devices pulling current from the DC capacitor. Their estimated current consumption depends on the expected user interaction and are not considered here due to the low level required.

PART SELECTIONS

It is important that the correct size of the components is chosen so that the lifetime of the electronics meets its expectations. The calculations in this section model a maximum ambient operating temperature of 25°C only.

TRIAC

The TRIAC chosen in this application is the BTA312B-600E, due to its low-gate trigger threshold as well as its high blocking voltage. The following analysis assumes a D²Pak package with values from the manufacturer's data sheet.

EQUATION 10: TRIAC GENERIC THERMAL POWER CALCULATIONS

$$P_{MAX} = \frac{(T_{J-MAX} - T_A)}{\theta_{JA}}$$

where

Symbol	Description	Units
P_{MAX}	Maximum Operating Power	W
T_{J-MAX}	Maximum Junction Temperature	°C
T_A	Ambient Temperature	°C
θ_{JA}	Thermal Resistance From Junction to Ambient	°C/W

Solving for the BTA312B-600E in a D²Pak package in ambient temperature of 25°C with the maximum junction temperature of 125°C.

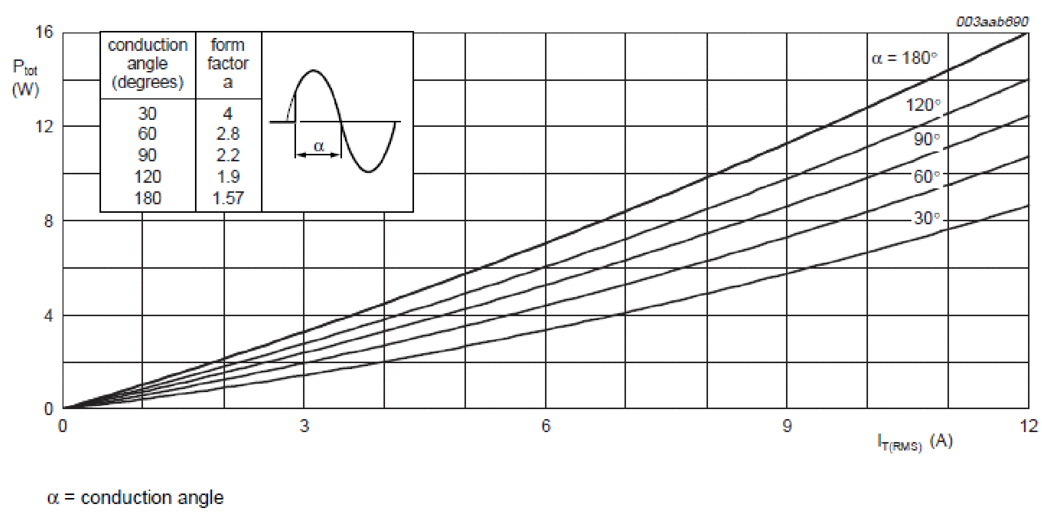
EQUATION 11: TRIAC PACKAGE POWER DISSIPATION

$$P_{max} = \frac{(125\,°C - 25\,°C)}{55\,°C/W} = 1.8W$$

Therefore, to safely use this TRIAC in the D²Pak package, the maximum power must be limited to 1.8W. Power consumption higher than 1.8W would require reducing the ambient temperature or adding a heat sink.

The total RMS current that the TRIAC can withstand can be obtained after extrapolating data from the manufacturer's Total Power Dissipation versus RMS on-state current graph as seen below. [Reference: http://www.nxp.com/documents/data_sheet/BTA312B-600E.pdf].

FIGURE 5: TRIAC RMS ON-STATE CURRENT



A full-wave conduction angle of 180 degrees is the worst case scenario since the TRIAC is ON continuously. Looking at Figure 5 and considering the maximum dissipation of the TRIAC calculated in Equation 11, the maximum current allowed is approximately 1.5A. Provision of a heat sink would increase the maximum current accordingly. Equation 11 can be adjusted to include the coefficients of the heat sink resistance constants and a similar procedure can then be done to calculate the theoretical maximum RMS current from the resulting maximum power dissipation.

R19 and R20

For power consumption calculation, the maximum possible value of the AC line voltage is used since it consumes the most power. In Europe, the AC line can be as high as 253 VRMS. Therefore, 253 is used as the RMS voltage for R19 and R20. Based on Equation 2:

EQUATION 12: R19/R20 POWER CONSUMPTION

$$P_{R20} = R_{R20} I_{R20}^2 = R20 \bullet \left(\frac{\sqrt{2}V_{RMS} - V_{D4} - V_{D2} - V_{D8}}{2 \bullet (R19 + R20)}\right)^2 = 2.5k \bullet \left(\frac{\sqrt{2} \bullet 253 - 5.1 - 9.1 - 0.7}{10k}\right)^2 = 2.5k \bullet (34.3\ mA)^2 = 2.94W$$

Both R19 and R20 should have their power ratings exceed 4 watts to derate them adequately.

D4 and D2

With no load, the current through D4 and D2 will be equal to the RMS half-wave current through R20.

EQUATION 13: D4 AND D2 POWER CONSUMPTION

$$P_{D4} = V_{D4} I_{R20} = 5.1V \bullet 34.3\ mA = 0.17W$$

$$P_{D2} = V_{D2} I_{R20} = 9.1V \bullet 34.3\ mA = 0.31W$$

Two ½W diodes should be used.

D8

Using the maximum current calculated in Equation 12 and assuming a typical 0.7V drop across the rectifying diode:

EQUATION 14: D8 POWER CONSUMPTION

$$P_{D8} = V_{D8} I_{R20} = 0.7V \bullet 34.3\ mA = 24.0\ mW$$

A ¼W diode should be used.

C6

The voltage rating is recommended to be 20% higher than D4, making a 10V or 16V choice suitable. The capacitance size depends on the desirable output ripple.

EQUATION 15: C6 CURRENT

$$I_{C6} = C6\frac{dv}{dt} = C6\frac{\Delta V}{\Delta t} = C_6 \bullet \Delta V_{OUT} \bullet f$$

Rearranging:

EQUATION 16: C6 CAPACITANCE CONSOLIDATED

$$C_6 = \frac{I_{OUT}}{f \bullet V_{OUT}}$$

Symbol	Description	Units
VRIPPLE	Ripple Voltage between C6 and GND	V
IOUT	Total load current as seen by C6	A
f	Input Frequency as seen by the capacitor	Hz
C	Total capacitance of C6	f

A ripple voltage of 20% is decided to be tolerable. The frequency is 60 Hz since it is only half-wave rectified. The maximum output current load should be no higher than the minimum input current, which is 18.9 mA. According to the value calculated in Equation 17, a 390 µF (nearest preferred value) capacitor is chosen in the circuit to supply sufficient current.

EQUATION 17: C6 CAPACITANCE

$$C_6 = \frac{18.9\ mA}{60\ Hz \bullet (0.2 \bullet 4.4V)} = 358\ \mu F$$

LED Indicators

A few LEDs can be placed between the terminals of D2. Their combined voltage drops should be closely matched to the reverse breakdown voltage of D2. When Q2 is ON, the current will flow through the LEDs on each half cycle of the AC input.

C15

Assuming a maximum wall voltage of 240 VAC, a 305 VAC X Class film capacitor or equivalent will suffice.

R21

The current through R21 is full-wave current. It serves to limit inrush current, and a secondary function might

EQUATION 18: R21 POWER

$$P_{R21} = R_{R21} I^2_{R21} = R21 \bullet \left(\frac{V_{HRMS}}{\frac{1}{2\pi f C_{15}} + R21} \right)^2 = 100 \bullet \left(\frac{\sqrt{2} \bullet 253 - 5.1 - 9.1}{2 \bullet 3336} \right)^2 = 100\Omega \bullet (51.5\ mA)^2 = 0.27W$$

A 1W resistor should suffice.

Zero-Cross Resistor

The design guidance for the limiting resistor is 300 µA at the peak voltage. The data sheet provides guidance on resistor selection when the peak voltage is expected to vary. Equation 19 applies that guidance to select a resistor that works for both 120 and 240 volt environments. Since the zero-cross event is actually triggered at 0.7V instead of 0V and the external signal is related to VDD (PIC_VDD), a capacitor is used to AC couple the input signal.

The ZCD source/sink currents will self-bias the PIC device side of the coupling capacitor to the ZCD pin voltage. According to the calculation, a 750K series resistor is preferred. For a more detailed explanation, check the PIC16F161X family data sheet for the ZCD module chapter.

EQUATION 19: ZERO-CROSS RESISTORS CALCULATION

$$R_{SERIES} = \frac{V_{MAXPEAK} + V_{MINPEAK}}{7 \times 10^{-4}} = \frac{\sqrt{2} \times (240 + 120)}{7 \times 10^{-4}} = 730K$$

TRIAC Gate Resistors

The minimum gate trigger current must be met or exceeded in order to turn on the TRIAC, assuming the latching current conditions have also been met. For the BTA312B-600E, this requirement is 10 mA in all firing quadrants.

Each microcontroller pin can source 10 mA. Two pins are used to drive the gate, however one high-current drive I/O pin can suffice. More current allows the TRIAC to trigger faster and hence lowering the conduction losses while transitioning. Equation 20 shows the calculation of the current limit resistors. VGT is the TRIAC gate voltage drop specified in the data sheet. VOL is the output low voltage of an I/O pin. Its maximum value is described in the PIC16F1618 data sheet. Specifying a overall 10 mA drive current on the two pins will require a 5%, ¼W resistor of approximately 500Ω.

EQUATION 20: TRIAC GATE RESISTOR

$$R_g = \frac{V_{pin} - V_{GT} - V_{OL}}{I_{drive}} = \frac{4.4V - 1.0V - 0.6V}{10mA} = 280\Omega$$

TRIAC Gate Current

The gate pulse width required to trigger a TRIAC also depends upon the time required for the anode current to reach the latching value (*Thyristor Theory and Design Considerations,* HBD855/D, published by ON Semiconductor®). The rise of the load current is slowed when an inductive load such as a universal motor is attached, since the current lags the voltage. The TRIAC does not remain in the On state because the load current does not reach the TRIAC latching current level before the gate current removal. A train of pulses is used instead to approximate the correct firing location.

Pulse Firing

Using multiple short pulses to fire the TRIAC can reduce the overall current consumption. This is very useful for the capacitive or resistive power supply application.

The inrush current has the highest chance in arming the TRIAC. One short trigger pulse may not enable the TRIAC holding current state, so having multiple pulses increases the probability of triggering the TRIAC successfully.

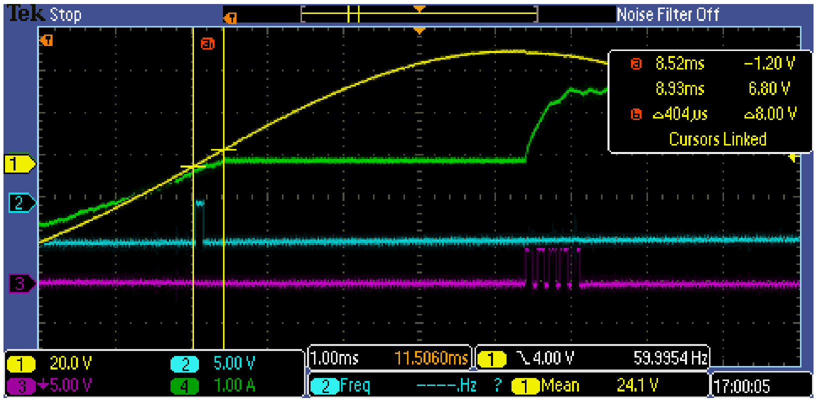
FIGURE 6: TRIAC PULSE FIRING

Plot	Description
Green	Motor current
Yellow	Input Voltage(1)
Blue	ZCD output
Pink	TRIAC gate pulses from the PIC® device

Note 1: The input voltage was scaled down in a 3:1 ratio.

Notice how the current lags the input voltage by a few hundred microseconds. Upon a closer inspection, the delay can be approximately 400 µs, as shown in Figure 7.

FIGURE 7: CURRENT DELAY BETWEEN VOLTAGE AND CURRENT ZERO CROSS



It is important to consider this delay when configuring the firing angle. If there is no voltage applied to the TRIAC's gate when the current through the TRIAC terminals crosses zero, the TRIAC will turn off.

Therefore, simply firing the TRIAC immediately following a ZCD event may have no effect due to the motor's inductance. A more practical approach is to use a train of pulses to fire the TRIAC in order to estimate the approximate turn on of the gate.

SOFTWARE

The code is written in the 'C' language and is fully documented. Table 4 shows the important developer information.

TABLE 4: SOFTWARE BUILD INFORMATION

Property	Description
Language	ANSI C89
Compiler	XC8 V1.36
Integrated Development Environment (IDE)	MPLAB® X v3.20

Later versions of the compiler and IDE are also compatible.

Table 5 shows the software resources used for the PIC16F1618.

TABLE 5: SOFTWARE RESOURCE ALLOCATION

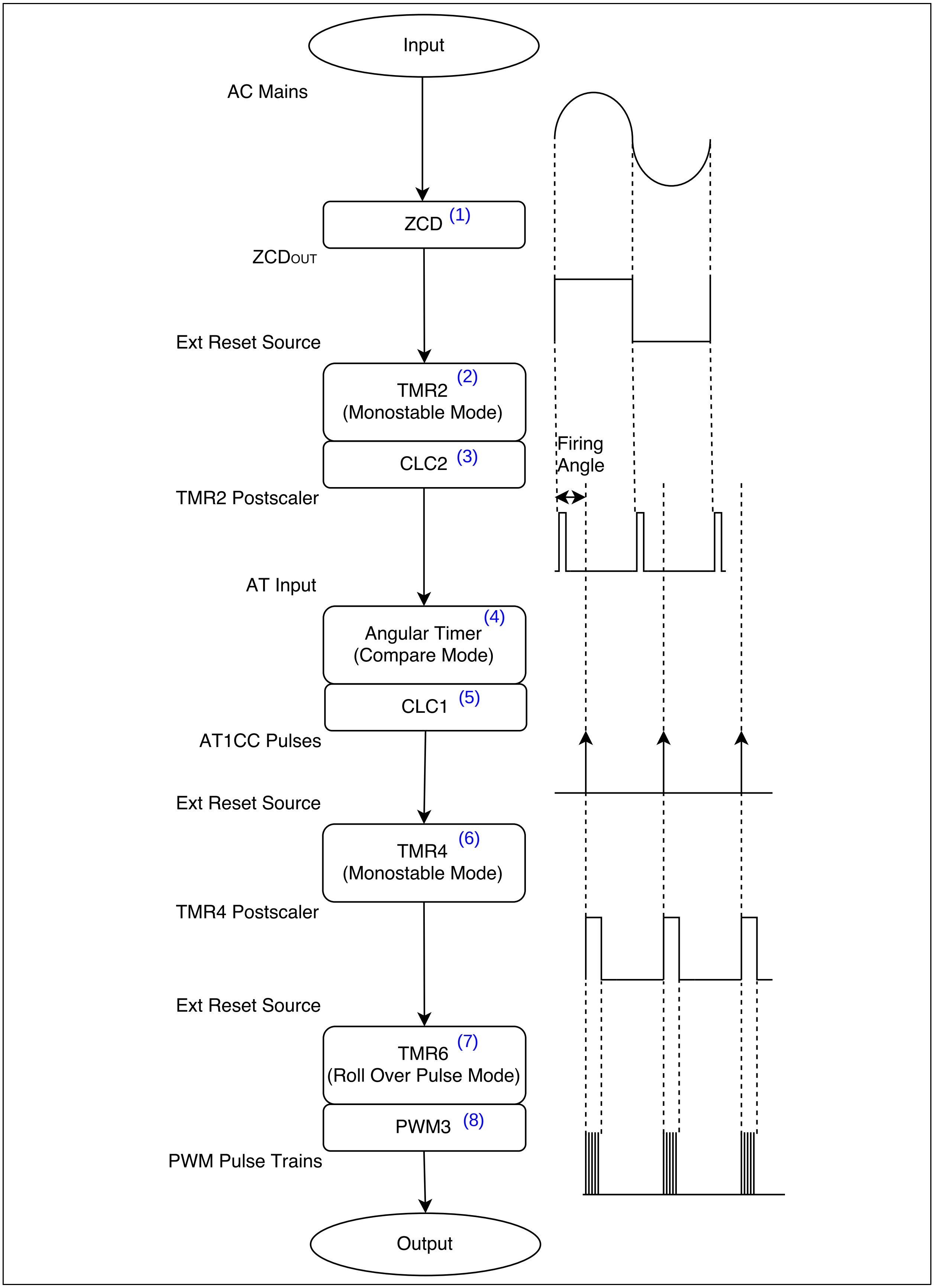
Resource	Used	Available to User
Program Memory	784 words (19%)	3312 words
Data Memory	74 bytes (14%)	438 bytes
CPU Processing (FOSC = 32 MHz)	15%	85%

The project is mostly Core Independent Peripheral (CIP) based to optimize the processing speed and free up the CPU usage. The TRIAC firing sequence is eased with the selected CIPs and minimum software calculation is involved. MPLAB® Code Configurator (MCC) is used to generate the configuration code for all the CIPs. Eight CIPs are used to generate the output signals. The entire program is lightweight and is easily adaptable to applications that require more advanced features. Figure 8 shows the flowchart of how the CIPs coordinate with each other to create the TRIAC firing sequence.

The Zero-Cross Detect (ZCD) module is used to detect the zero crossing of the AC mains(1). Since the angular timer needs to be triggered at both the rising and falling edge of the ZCDOUT signal, Timer2 (Hardware Limit Timer) is used to generate a short ON time at every rising/falling edge of ZCDOUT(2).

CLC2 is used to bring out the Timer2 postscaler output, and the output is used as the angular timer input signal(3). The Angular Timer Compare mode will generate a pulse at a certain firing angle after each zero crossing(4). CLC1 is used to bring out the angular timer pulses(5). The pulses are then used as the external Reset source of Timer4. The Timer4 postscaler output is set high for a short time after each pulse(6). Timer6 runs at Roll Over Pulse mode and uses Timer4 postscaler output as the external Reset source(7). Timer6 runs only when the Timer4 postscaler output is high, and it is used as the clock source for PWM3(8). Therefore, PWM3 will generate a PWM pulse train for a certain amount of time (TMR4 postscaler ON time) at each firing angle.

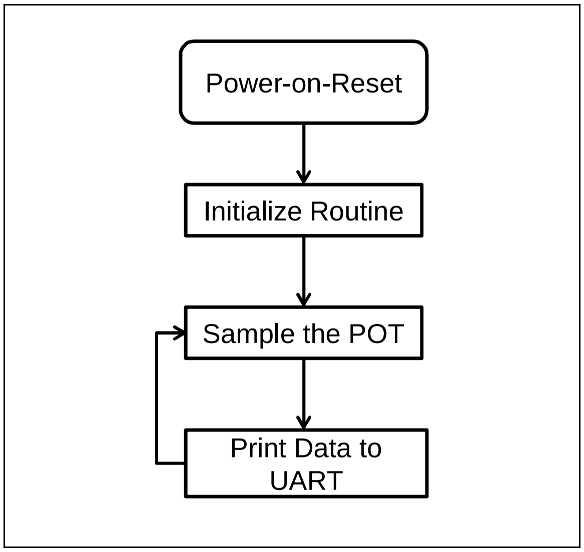
FIGURE 8: CIP FLOWCHART



Main Program

Upon Power-on-Reset (POR), the microcontroller initializes the ports and modules. The program will then simply poll the potentiometer for an ADC reading representing the TRIAC firing angle and prints (transmits) it over the isolated UART for optional debugging purposes. Other debug variables can also be printed to the UART. This firing-angle variable is then used to delay the TRIAC firing angle. The motor ON/OFF control is handled by an Interrupt-on-Change (IOC) of an I/O pin.The user may wish to put the PIC device to Sleep instead and wake-up when the button is pushed to cause an IOC, which would lower power consumption. The block diagram of the flow can be seen below in Figure 9.

FIGURE 9: MAIN FLOW DIAGRAM



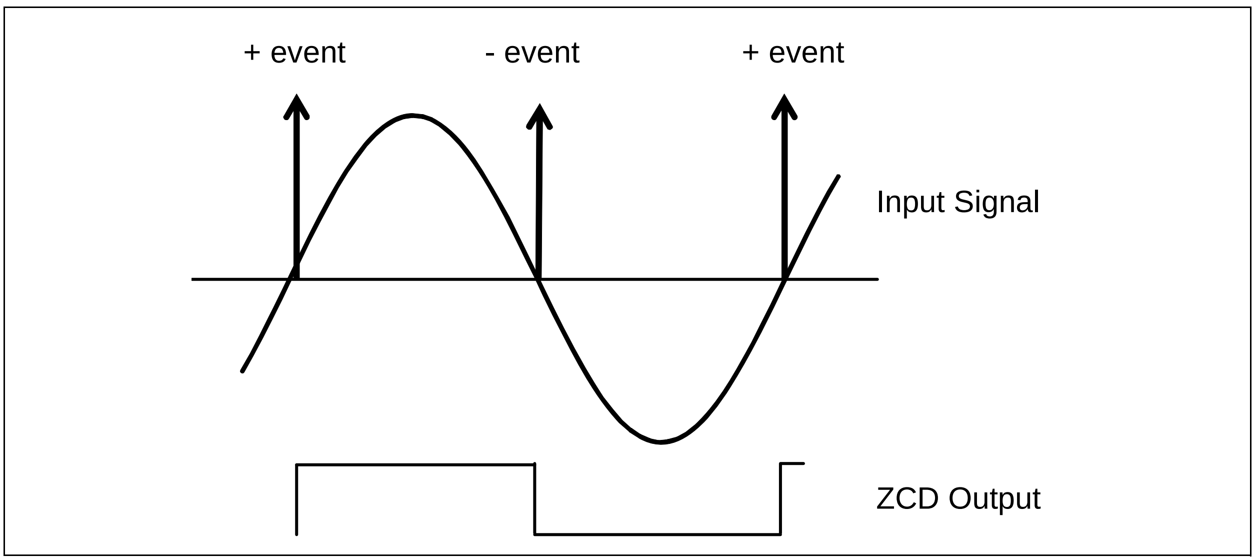
Zero-Cross Synchronization

The Zero-Cross Detect module is used to trigger the angular timer input signal (TMR2) when there is a positive and negative voltage detected. A capacitor between the ZCD input pin and the ZCD series resistor is implemented to couple the AC input signal. Be aware that it also causes a phase shift, which results in a ZCD trigger shifted by a fixed amount of time. If the user needs precise zero-cross detection, a software adjustment should be applied. The calculation of the phase shift is shown in Equation 21.

EQUATION 21: PHASE-SHIFT CALCULATION

$$Phase\ Shift\ \wp = -arctan\left(\frac{1}{2\pi fRC}\right)$$

FIGURE 10: ZERO-CROSS DETECTION OUTPUT IN RELATION TO INPUT SIGNAL



Angular Timer

The angular timer module provides the necessary timing for controlling the firing angle. This module saves the microcontroller from performing complicated timing and realignments for the firing angle which depend on the line input frequency. The angular timer divides a periodic signal automatically and thus can generate a pulse at the precise angle to fire the TRIAC. The placement of the pulse can be designed to correlate with a certain degree, 0–360, with a single degree of resolution.

A traditional approach would use the ZCD event to start a timer to keep a “heartbeat”. Each count of the timer would correspond to increments of five degrees and would be compared to a set point every time the timer rolls over. Once the scaled set point is below the timer, the TRIAC firing sequence would be initiated.

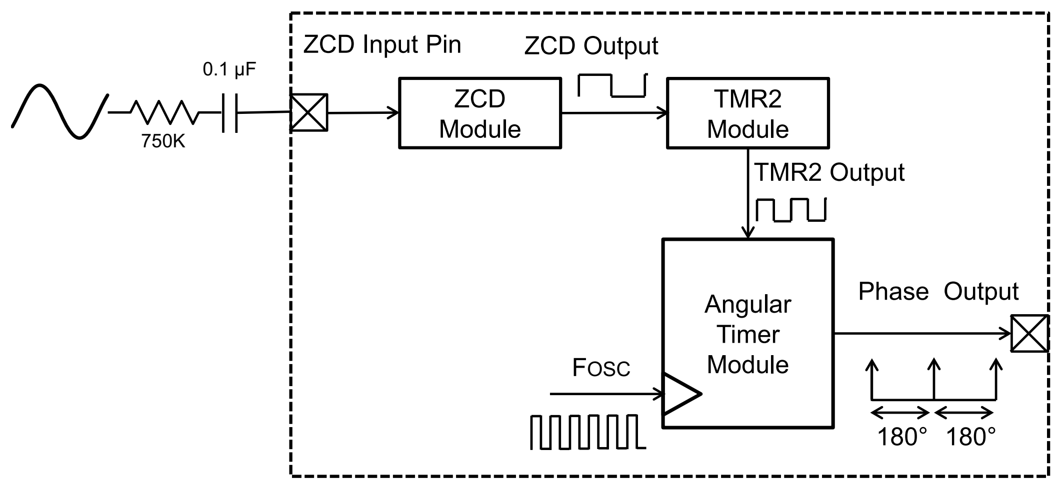
A drawback of this method is that the accuracy of the firing delay is dependent on the timer’s resolution as well as the needed extra instruction cycles to accommodate the constant increment/compare routines.

The needed scaling of the timer is also dependent on the frequency and needs to be recalculated if it changes during runtime.

The angular timer translates a time-based signal into a phase-based angle signal. Its number of desired output intervals stays constant even when the input signal changes frequency. This means that a desired firing angle of 60 degrees for example can be ensured even as the frequency changes.

Figure 11 shows how to link the angular timer with the ZCD module. Note that in this application, since the angular timer needs to be triggered at both falling and rising edge of the ZCD output, Timer2 is implemented to preprocess the ZCD output before it feeds into the angular timer.

FIGURE 11: ANGULAR TIMER AND ZERO-CROSS DETECTION MODULE INTERACTION



Note that the phase output is used as an optional debug trace to verify the correct operation of the module. The microcontroller uses the module’s pulse to fire the TRIAC. This debug pin is available on RC3.

The periodic ZCD square wave is preprocessed by Timer2 and then routed internally into the angular timer. The system clock, FOSC, is selected as the module’s clock. The ZCD module toggle’s its output whenever a zero crossing is detected.

One of the features of the angular timer is to be able to set a compare value. The module will trigger a pulse when the specified compare value is matched with its internal angle calculation. For example, Figure 12 shows an instance where three compare values, 90, 180, and 270 degrees were selected to generate a pulse in-between the ZCD output’s rising and falling edges.

FIGURE 12: ANGULAR TIMER COMPARE OUTPUTS IN RELATION TO THE ZCD OUTPUT EVERY HALF-CYCLE

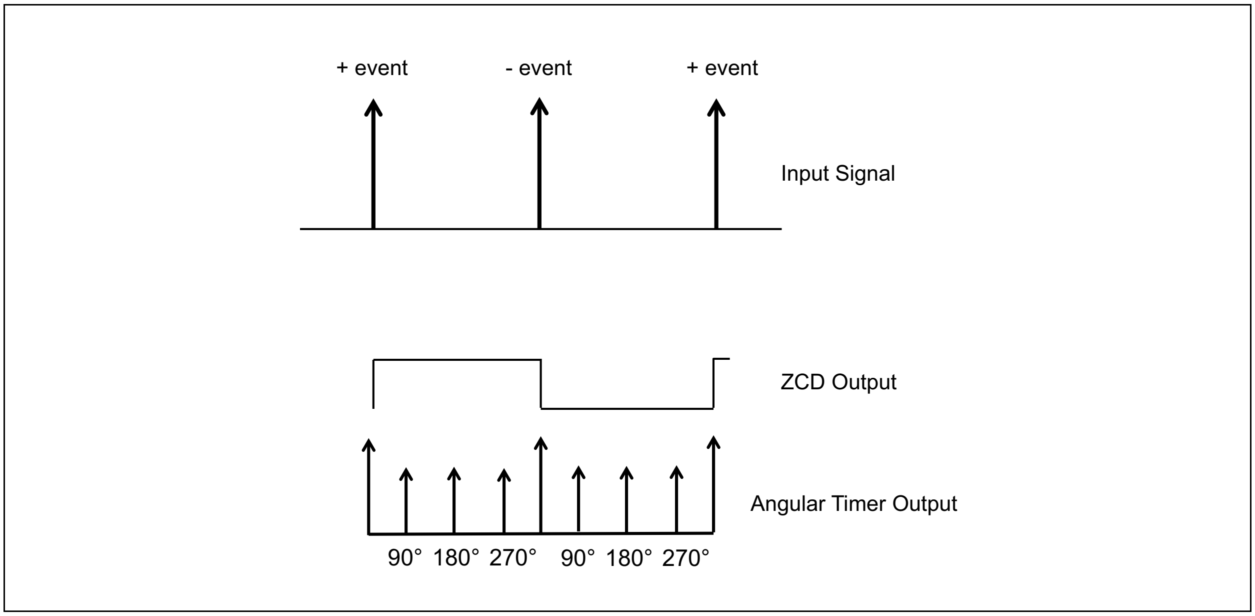


TABLE 6: ANGULAR TIMER REGISTERS

Symbol	Description
ATxRES	Specifies how many interrupts or outputs in-between the period signal edges
f(ATxCLK)	Frequency of the selected module clock
f(ATxSIG)	Input frequency of the waveform

The selected module clock and input waveform frequency must be sufficient enough in order to yield an accurate output. The accuracy of the module's output can be explained by using the figure of merit equation.

EQUATION 22: FIGURE OF MERIT FOR ANGULAR TIMER ACCURACY

$$FOM = 100 \bullet \frac{ATxRES}{\frac{f(ATxCLK)}{f(ATxSIG)}}$$

In the code, ATxRES is loaded with a value of 255, which means that the module will give the user a resolution of 1.41 degrees. A phase pulse will be generated every 39.2 µS (10 ms/255), assuming an input frequency of 100 Hz.

The module clock can be either HFINTOSC (16 MHz) or the system clock (up to 32 MHz). In this application note, the system clock was selected as 32 MHz.

The input frequency into the module is 100 Hz. The ZCD module will toggle twice in a sinewave's period since the waveform crosses the zero point twice. A 50 Hz line frequency will therefore cause the ZCD output waveform to be 100 Hz.

Plugging these numbers into Equation 22:

EQUATION 23: FIGURE OF MERIT

$$FOM = 100 \bullet \frac{255}{\frac{32\ MHz}{100\ Hz}} = 0.0797$$

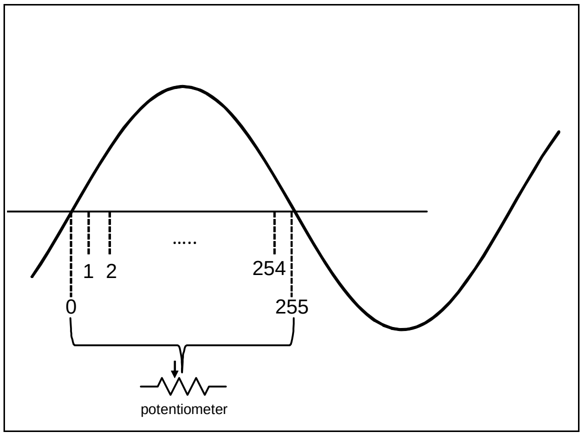
This means that the TRIAC can be fired off of every degree (1, 2, 3…360) with a maximum possible cumulative error of 0.0797%. This figure of merit is impressive due to the high-clock frequency and low-signal input frequency. The operation of the angular timer module is simple, however understanding its limitations are beyond the scope of this application note.

TRIAC Firing Angle

The 10-bit ADC value is scaled by shifting it to the right two times, hence dividing by 4. The scaled value now exists between 0 and 255 (see Figure 13).

One of the three compare registers, AT1CC1, is then assigned the scaled ADC value. Since AT1RES has a value of 255, the maximum POT value of 255 corresponds to the largest firing angle of 360 degrees. Hence the resolution is 360/255 = 1.41°.

FIGURE 13: FIRING ANGLE CONTROLLED BY THE POT



TRIAC Firing Sequence

The firing sequence is controlled via a multiplexed PWM, (see Figure 15). Two digital pins are set up as the output from the PWM module. This is achieved by using the Peripheral Pin Select feature of the PIC16F1618, which allows any digital module to have its output multiplexed to different pins.

This output can also change during runtime and is software controllable.

A 40 kHz PWM with five pulses on two output pins triggers the TRIAC's gate whenever the capture register in the angular timer matches the set point as designated from the potentiometer. Figure 14 shows the PWM firing sequence.

FIGURE 14: PWM SIGNAL ONTO TRIAC GATE

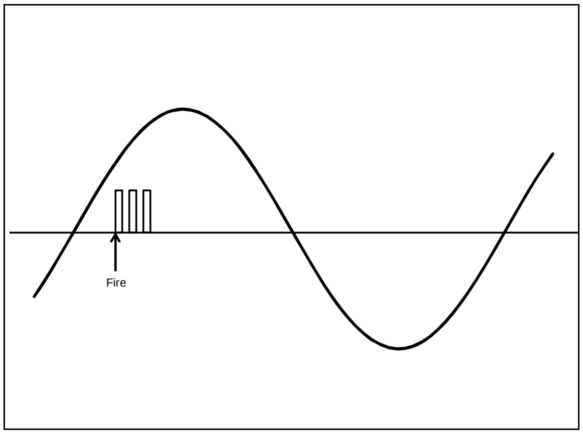
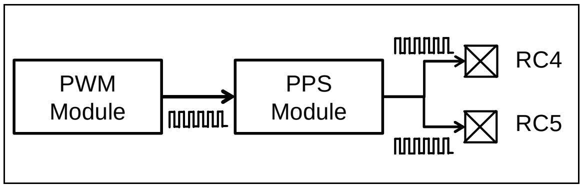


FIGURE 15: THE PWM SIGNAL IS MULTIPLEXED ONTO TWO PINS



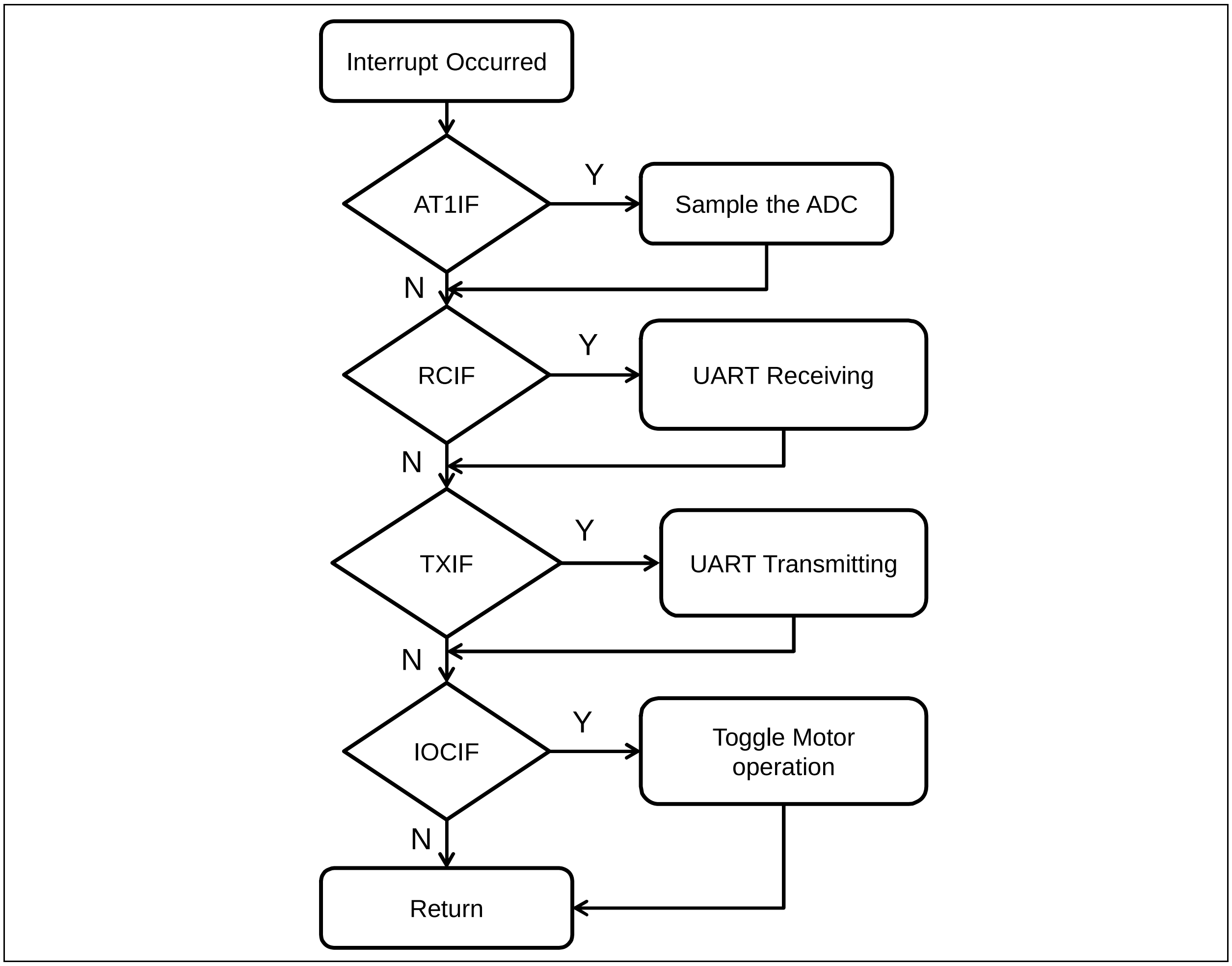
Interrupt Service Routine

The amount of time taken inside of the Interrupt Service Routine should be kept to a minimum.

TABLE 7: INTERRUPTS

Interrupt Flag	Module	Purpose
AT1IF	Angular Timer	Read the POT value at the beginning of each angular timer period
RCIF	EUSART	UART Receiving
TXIF	EUSART	UART Transmitting
IOCIF	Interrupt-on-Change	Button press service

FIGURE 16: INTERRUPT SERVICE ROUTINE FLOW



AT1IF

This interrupt occurs at the beginning of every angular timer period. Then the reading of the POT is scaled and set to AT1CC.

IOCIF

The SW0 push button is used to turn on and off the TRIAC. A press of SW0 causes this interrupt. A global flag is set in the ISR and is then checked and debounced in the main loop to prevent blocking code inside of the ISR.

Microcontroller

The board features a 20-pin DIP socket that can be fitted with the PIC16F1618. This device has plenty of free software space as well as hardware space for custom features to be added. Figure 17 shows the pin designators and their purposes.

Table 8 shows a complete listing of the pin functionality. As seen below, there are five free unallocated pins not including the programming ones. A production build of a similar product may want to use the smaller 14-pin PIC16(L)F1614 as the design is optimized.

FIGURE 17: PIC16(L)F1618 PIN DESIGNATORS

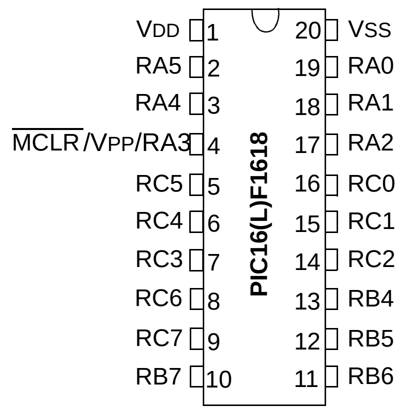


TABLE 8: MICROCONTROLLER PIN ALLOCATION

Pin	Input/Output	Digital/Analog/ Both	Function
RA5			Unused
RA4	IN	Digital	Button
RA3			$\overline{\text{MCLR}}$
RC5	IN	Digital	Motor Feedback (not implemented)
RC4	OUT	Digital	UART TX
RC3	OUT	Digital	Angular Timer Debug
RC6			Unused
RC7			Unused
RB7			Unused
RB6	OUT	Digital	ZCD Debug Out
RB5			Unused
RB4	IN	Analog	Potentiometer
RC2	OUT	Digital	TRIAC Drive
RC1	OUT	Digital	LED
RC0	OUT	Digital	TRIAC Drive
RA2	IN	Analog	Zero-Cross Detect
RA1			PGC
RA0			PGD

APPENDIX A: SCHEMATICS

FIGURE A-1: SCHEMATIC – UNIVERSAL MOTOR DRIVER

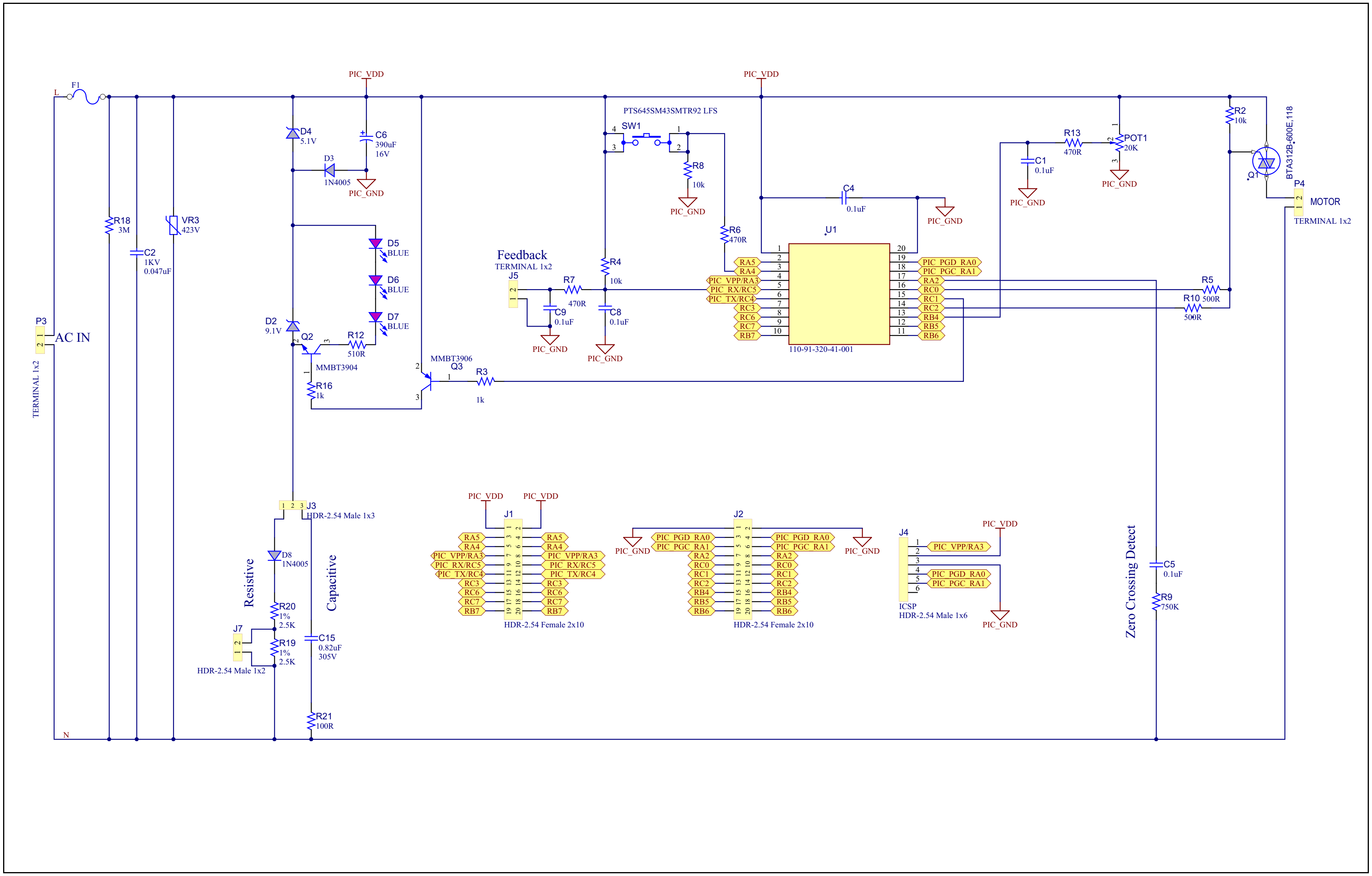
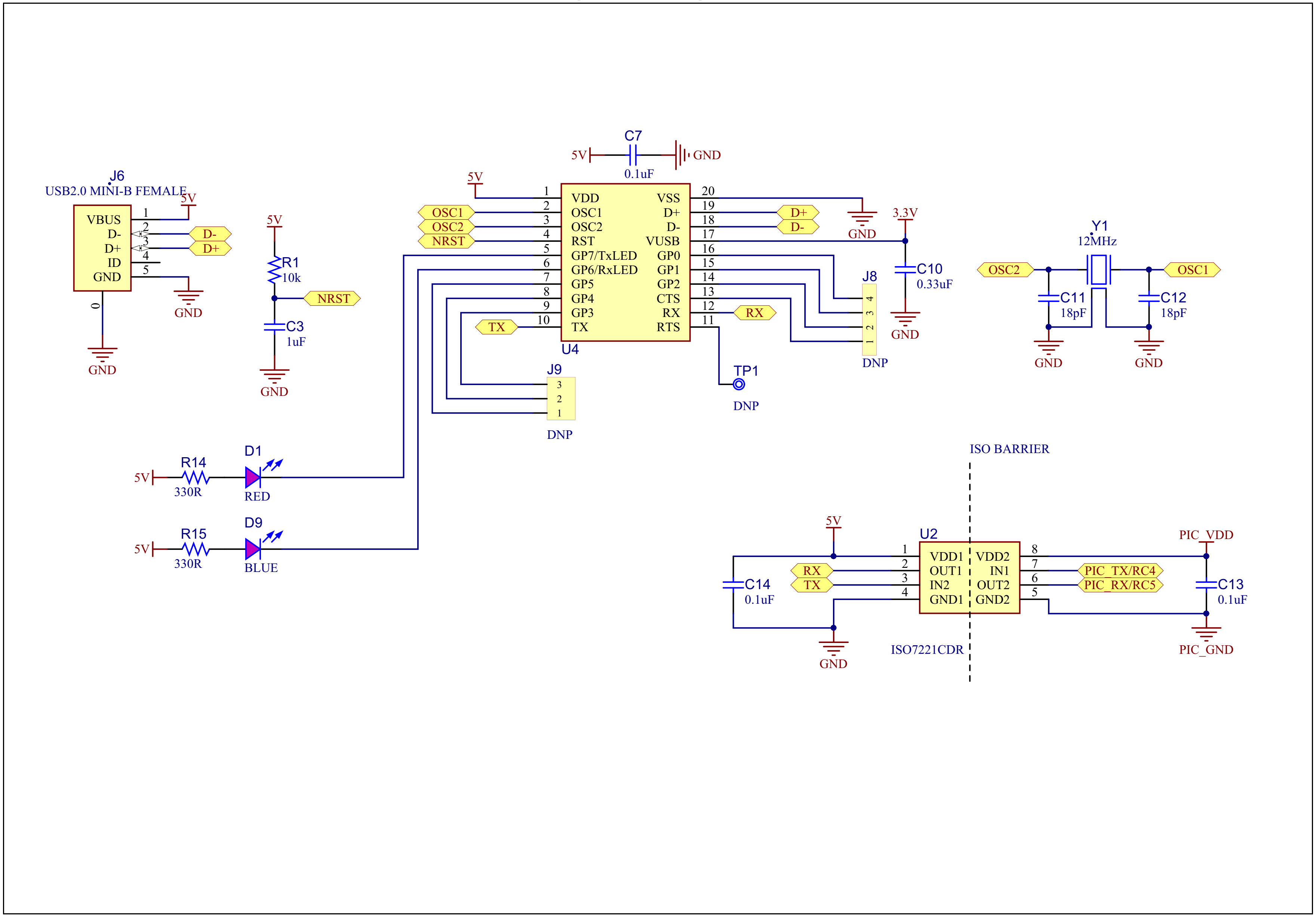


FIGURE A-2: SCHEMATIC – UNIVERSAL MOTOR DRIVER (CONTINUED)



APPENDIX B: BILL OF MATERIALS

TABLE B-1: BILL OF MATERIALS

Quantity	Designator	Description	Manufacturer 1	Manufacturer Part Number 1	Supplier 1	Supplier Part Number 1	Quantity	Quantity Override
7	C1, C4, C5, C7, C8, C9, C13, C14	CAP CER 0.1 µF 50V 10% X7R SMD 0603	Murata	GRM188R71H104KA93D	Digi-Key®	490-1519-1-ND	7	1
1	C2	CAP CER 0.047 µF 1.2 KV 10% X7R SMD 2220	KEMET	C2220C473KDRACTU	Digi-Key	399-4856-1-ND	1	1
1	C3	CAP CER 1 µF 25V 20% X5R SMD 0603	Panasonic	ECJ-1V41E105M	Digi-Key	PCC2354CT-ND	1	1
1	C6	CAP ALU 470 µF 16V 20% RAD P3.5D8H11.5	Nichicon	UVZ1C471MPD	Digi-Key	493-1286-ND	1	1
1	C10	CAP CER 0.33 µF 16V 10% X7R SMD 0603	Murata	GRM188R71C334KA01D	Digi-Key	490-3294-1-ND	1	1
2	C11, C12	CAP CER 18 pF 50V 5% NP0 SMD 0603	KEMET	C0603C180J5GACTU	Digi-Key	399-1052-1-ND	2	1
1	C15	CAP FILM 0.82 µF 305V 10% RAD P22.5L26.5W12H22	Epcos	B32933A3824K	Digi-Key	495-4361-ND	1	1
1	D1	DIO LED RED 2V 30 mA 12 mcd Clear SMD 0603	Kingbright	APT1608EC	Digi-Key	754-1117-1-ND	1	1
1	D2	DIO ZNR MMSZ4696 9.1V 500 mW SMD SOD-123	Micro Commercial Co	MMSZ4696-TP	Digi-Key	MMSZ4696-TPMSCT-ND	1	1
2	D3, D8	DIO RECT 1N4005 1.1V 1A 600V DO-41	Micro Commercial Co	1N4005-TP	Digi-Key	1N4005-TPMSCT-ND	2	1
1	D4	DIO ZNR MMSZ4689 5.1V 500 mW SMD SOD-123	Fairchild Semiconductor	MMSZ4689	Digi-Key	MMSZ4689CT-ND	1	1
4	D5, D6, D7, D9	DIO LED BLUE 2.65V 2 mA 65 mcd Clear SMD 0603	Kingbright	APTD1608LVBC/D	Digi-Key	754-1948-1-ND754-1948-1-ND	4	1
1	F1	FUSE BLOK CARTRIDGE 500V 10A PCB	Schurter Inc	0031.8201	Digi-Key	486-1258-ND	1	1
2	J1, J2	CON HDR-2.54 Male 2x10 Gold 5.84 MH TH VERT	Samtec	TSW-110-07-G-D-020	Samtec	TSW-110-07-G-D-020	2	1
1	J3	CON HDR-2.54 Male 1x3 Gold 5.84 MH TH VERT	FCI	68000-103HLF	Digi-Key	609-3461-ND	1	1
1	J4	CON HDR-2.54 Male 1x6 Gold 5.84 MH TH R/A	FCI	68016-106HLF	Digi-Key	609-3313-ND	1	1
1	J5	CON TERMINAL 3.5 mm 6A Female 1x2 TH R/A	On-Shore Technology Inc	ED555/2DS	Digi-Key	ED1514-ND	1	1
1	J6	CON USB MINI-B Female SMD R/A	Hirose	UX60-MB-5ST	Digi-Key	H2959CT-ND	1	1
1	J7	CON HDR-2.54 Male 1x2 Gold 5.84MH TH VERT	FCI	77311-118-02LF	Digi-Key	609-4434-ND	1	1
2	P3, P4	CON TERMINAL 5.08 mm 16A Female 1x2 TH R/A	On-Shore Technology Inc	OSTVI022152	Digi-Key	ED2768-ND	2	1

TABLE B-1: BILL OF MATERIALS (CONTINUED)

Quantity	Designator	Description	Manufacturer 1	Manufacturer Part Number 1	Supplier 1	Supplier Part Number 1	Quantity	Quantity Override
1	POT0	RES Variable CC 20K 10% 1/2W TH 3386P	Bourns Inc.	3386P-1-203TLF	Digi-Key	3386P-203TLF-ND	1	1
1	Q1	TRA TRIAC SENS GATE 600V 12A D2PAK	NXP Semiconductors	BTA312B-600E,118	Digi-Key	568-5834-1-ND	1	1
1	Q2	TRANS BJT NPN MMBT3904 40V 200 mA 310 mW SOT-23-3	Diodes Incorporated	MMBT3904-7-F	Digi-Key	MMBT3904-FDITR-ND	1	1
1	Q3	TRANS BJT PNP MMBT3906 -40V -200mA 300mW SOT-23-3	Diodes Incorporated	MMBT3906-7	Digi-Key	MMBT3906DITR-ND	1	1
4	R1, R2, R4, R8	RES TKF 10k 1% 1/10W SMD 0603	Panasonic	ERJ-3EKF1002V	Digi-Key	P10.0KHCT-ND	4	1
2	R3, R16	RES TKF 1k 1% 1/10W SMD 0603	Panasonic	ERJ-3EKF1001V	Digi-Key	P1.00KHCT-ND	2	1
2	R5, R10	RES TKF 500R 5% 1/10W SMD 0603	Stackpole Electronics Inc.	RMC 1/16 500 5% R	Digi-Key	RMC1/165005%R-ND	2	1
5	R6, R7, R13	RES TKF 470R 1% 1/10W SMD 0603	Yageo	RC0603FR-07470RL	Digi-Key	311-470HRCT-ND	5	1
1	R9	RES TKF 750k 1% 1/4W SMD 1206	Stackpole Electronics Inc.	RMCF1206FT750K	Digi-Key	RMCF1206FT750KCT-ND	1	1
1	R11	RES TKF 150k 1% 1/4W SMD 1206	Panasonic	ERJ-8ENF1503V	Digi-Key	P150KFCT-ND	1	1
1	R12	RES TKF 510R 1% 1/10W SMD 0603	ROHM	MCR03EZPFX5100	Digi-Key	RHM510HCT-ND	1	1
2	R14, R15	RES TKF 330R 1% 1/10W SMD 0603	Panasonic	ERJ-3EKF3300V	Digi-Key	P330HCT-ND	2	1
1	R18	RES TKF 3M 5% 3/4W SMD 2010	Panasonic Electronic Components	ERJ-12ZYJ305U	Digi-Key	P3.0MWCT-ND	1	1
2	R19, R20	RES WW 2.5K 1% 5W AX P16.5L22.3D8	Vishay Dale	ALSR052K500FE12	Digi-Key	ALSR5F-2.5K-ND	2	1
1	R21	RES MF 100R 1% 1W AX P10L5.3D3.8	Vishay Dale	CPF1100R00FKEE6	Digi-Key	CPF100CCT-ND	1	1
1	SW0	SWITCH TACT SPST 32V 50 mA KSR231GLFS SMD	C&K Components	KSR231GLFS	Digi-Key	401-1706-1-ND	1	1
1	U1	SOCKET IC PUSH DIP 20 TH	Mill-Max	110-99-320-41-001	Digi-Key	ED3120-ND	1	1
1	U2	IC DGTL ISO 2.5KV ISO7721C 8SOIC	Texas Instruments	ISO7221CDR	Digi-Key	296-21956-1-ND	1	1
1	VR3	RES VARISTOR MO 423V 30J DISC 7 mm	Bourns Inc.	MOV-07D471KTR	Digi-Key	MOV-07D471KCT-ND	1	1
1	Y1	CRYSTAL 12MHz 8pF SMD NX3225SA	NDK	NX3225SA-12.000000MHZ	Digi-Key	644-1047-1-ND	1	1

Microchip Parts listed below								
1	U4	MCHP INTERFACE USB UART MCP2200-I/SS SSOP-20	Microchip	MCP2200-I/SS	Digi-Key	MCP2200-I/SS-ND	1	1

TABLE B-1: BILL OF MATERIALS (CONTINUED)

Quantity	Designator	Description	Manufacturer 1	Manufacturer Part Number 1	Supplier 1	Supplier Part Number 1	Quantity	Quantity Override
Mechanical Parts to be added in the package								
1	LABEL1	No Label					1	1
PCB								
1	PCB1	Printed Circuit Board		04-219-0517-RD			1	1

RESOURCES

1. AN954, *Transformerless Power Supplies: Resistive and Capacitive* (DS00954).
2. *Thyristor Theory and Design Considerations,* HBD855/D, ON Semiconductor.

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