TB3138

Zero-Cross Detection Module Technical Brief

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INTRODUCTION

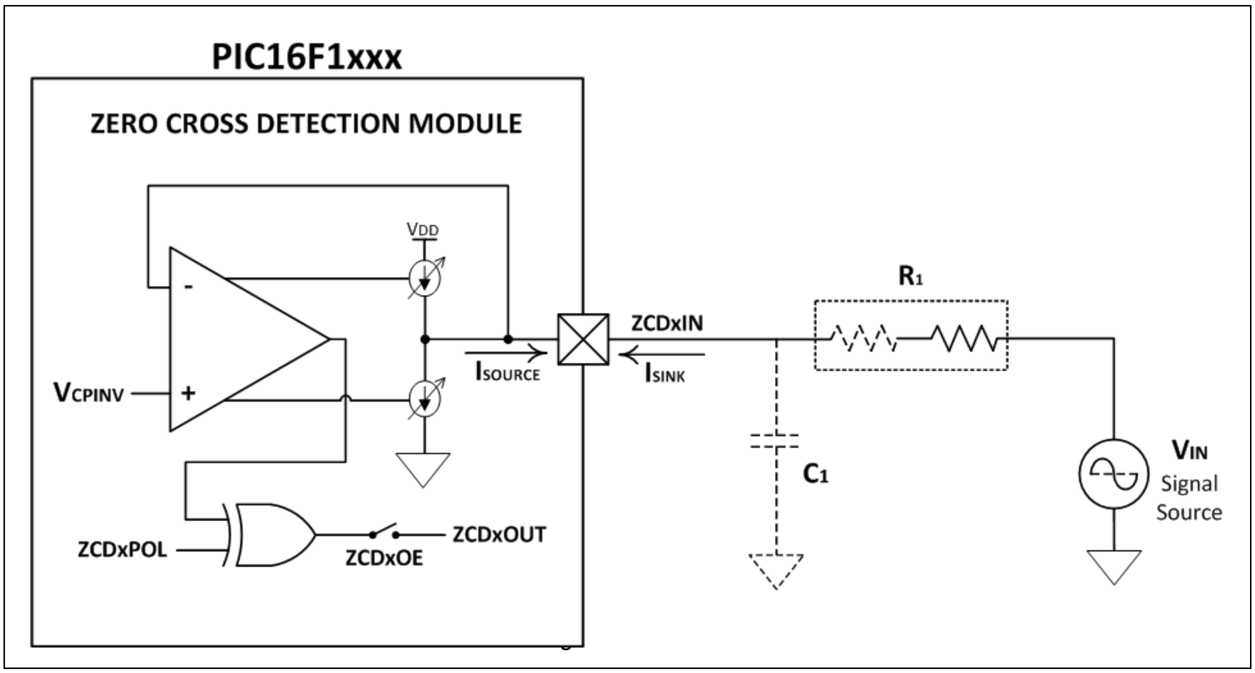
In earlier 8-bit PIC® microcontroller devices, the Zero-Cross Detection (ZCD) of high input voltage, such as the A/C line voltage, relies in the clamping ability of the parasitic electrostatic discharge ESD protection diode on the I/O pin. This method has been used successfully for many years. However, in the advent of recent micro-controller devices with additional analog pass-gates forbid the I/O pins voltage to exceed VDD and thus the conduction of parasitic ESD diode. Violating this specification may cause an unexpected behavior of the microcontroller. Refer to Microchip's Technical Brief TB3013 "*Using ESD Parasitic Diodes on Mixed Signal Microcontrollers*" (DS90003013) for more details about pass-gates and their roles in reducing the possibilities of using the voltage clamping ability of the parasitic ESD diode on the I/O pins.

For these reasons, Microchip provides a dedicated Zero-Cross Detection (ZCD) module on its 8-bit microcontroller devices. This module can detect zero crossing accurately, while preventing the parasitic ESD diode to conduct when interfacing with the high-voltage A/C input signals. This technical brief describes the ZCD module features, the method of configuration and the calculation of external components needed for the implementation.

ZCD OPERATING CIRCUIT

Figure 1 shows a simplified schematic diagram for the implementation of the ZCD module.The source signal VIN can be measured by the module through a series current-limiting resistor R_1. To safely interface VIN to the module's input pin (ZCDxIN), R_1 impedance must be carefully chosen to limit the input current to a value that the module can tolerate. The peak current that can be sourced or sinked in ZCDxIN is 300 µA. Refer to Equation 1 for selecting the R_1 value.

FIGURE 1: ZCD SIMPLIFIED BLOCK DIAGRAM



EQUATION 1: ZCD CURRENT-LIMITING RESISTOR CALCULATION

$$R_1 = \frac{V_{IN(PEAK)}}{300\ \mu A}$$

The high-frequency noise signals from the external source can affect the module's operation at near zero-crossing point. To prevent these unwanted signals from causing chatter in the module's output (ZCDxOUT), an optional capacitor C_1 can be placed across ZCDxIN to form a simple low-pass filter with R_1. However, this additional capacitor may lag the input signal and trigger a phase delay. Equation 2 shows the equation of the phase delay where F_C is the cut-off frequency of the desired input signal and R_1 is the calculated current-limiting resistor. Based on the equation, the higher the value of C_1, the more it increases the phase delay (see Example 1). Therefore, the designer should choose an appropriate value for C_1 to meet the acceptable phase delay, based on their design tolerance.

EQUATION 2: PHASE DELAY EQUATION

$$T_{DELAY} = \frac{tan^{-1}(2\pi \times F_C \times R_1 \times C_1)}{2\pi \times F_C}$$

EXAMPLE 1: PHASE DELAY CALCULATION BASED ON THE VALUE OF C1

Time Delay of 110V AC, 60 Hz input source when C1 is 30 pF and 30 nF:

(1) $$R_1 = \frac{V_{IN(PEAK)}}{300\mu A} = \frac{110V \times \sqrt{2}}{300\mu A} = 518.5\ k\Omega$$

When C1=30 pF:

(2) $$T_{DELAY} = \frac{tan^{-1}(2\pi \times 60 \times 518.5\ k\Omega \times 30\ nF)}{2\pi \times 60} = \mathbf{15.5\ \mu s}$$

When C1=30 nF:

(2) $$T_{DELAY} = \frac{tan^{-1}(2\pi \times 60 \times 518.5\ k\Omega \times 30\ nF)}{2\pi \times 60} = \mathbf{3.71\ ms}$$

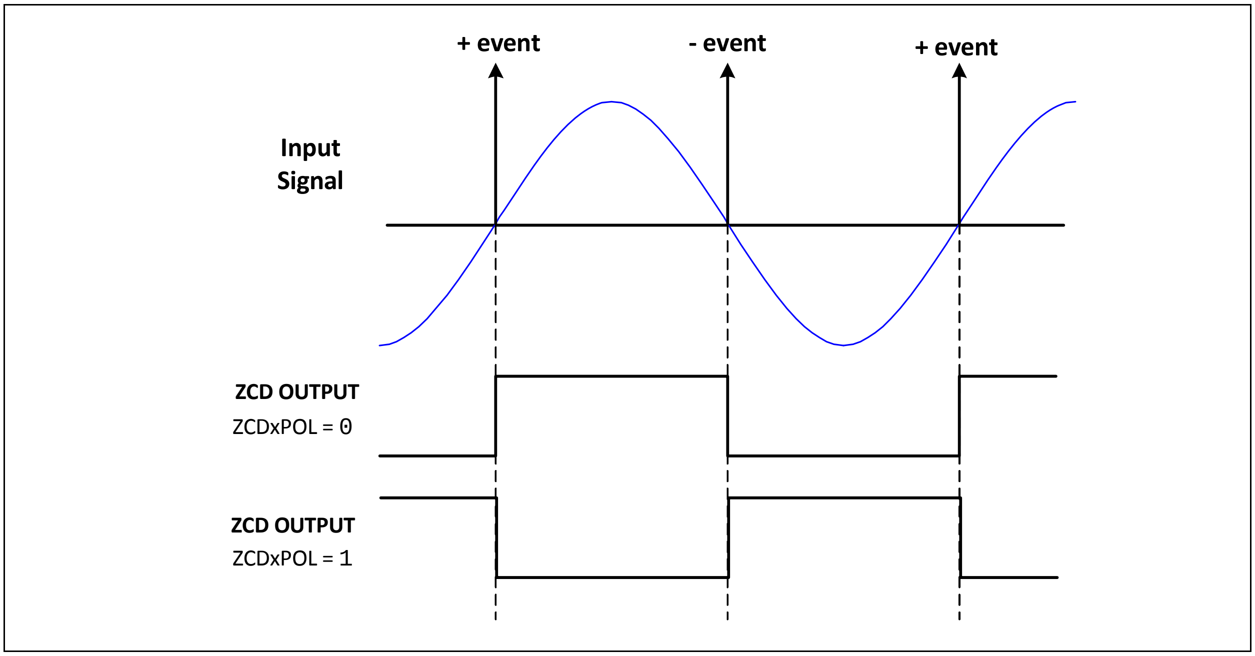
As stated earlier, the device I/O pin's parasitic ESD protection diode must not conduct while detecting the zero crossing of the A/C input signal. In order for the module to meet this requirement, the module applies a current source or sink to ZCDxIN. When V_{IN} is greater than the zero-crossing reference voltage (V_{CPINV}), which is typically 0.75V above ground, the module sinks current. When V_{IN} is less than V_{CPINV}, the module sources current. The current source and sink action keep the ZCDxIN pin voltage constant over the full-range V_{IN} while the detection of zero crossing happens when the current through ZCDxIN changes direction.

The module includes a Status bit through the ZCDxOUT bit to determine whether the current source or the sink is active. When the ZCDxOUT bit is set, the ZCDxIN pin is sinking current and when cleared, the ZCDxIN pin is sourcing current. This bit can also be affected by the ZCD Logic Output Polarity (ZCDxPOL) bit relative to the current source and sink output. When ZCDxPOL is set, the polarity of ZCDxOUT is reversed, as shown in Figure 2.

The ZCD interrupt can be generated based on the ZCDxOUT bit and if the associated enable bits are set. When the Positive Edge Interrupt (ZCDxINTP) bit is set and the ZCDxOUT bit changes from logic low to high, the ZCD interrupt will be triggered. Likewise, when the Negative Edge Interrupt (ZCDxINTN) bit is set and the ZCDxOUT bit changes from logic high to low, the ZCD interrupt will also be triggered.

Note:	Internal weak pull-up on ZCDxIN (if available in the device) should be disabled so that it will not interfere with the current source/sink action.

FIGURE 2: ZCD OUTPUT WAVEFORM



ZCD EVENT OFFSET

The ZCD triggers at V_{CPINV} and not at 0V. Assuming that V_{IN} is sinusoidal and relative to the V_{SS} pin, the voltage offset from zero to V_{CPINV} causes the zero-cross event to occur too early as the V_{IN} waveform falls, and too late as the V_{IN} waveform rises. The actual offset time produced can be calculated using Equation 3. Refer to Example 2 for the example ZCD event offset calculation.

EQUATION 3: ZCD EVENT OFFSET EQUATION

$$T_{OFFSET} = \frac{sin^{-1}\left(\frac{V_{CPINV} - V_{Desired\ Reference}}{V_{PEAK}}\right)}{2\pi \times Frequency}$$

EXAMPLE 2: ZCD EVENT OFFSET EXAMPLE CALCULATION

Input AC voltage at 110 VRMS with 60 Hz frequency and desired threshold of 0V:

$$(3) \quad T_{OFFSET} = \frac{sin^{-1}\left(\frac{750\ mV - 0V}{110 \times \sqrt{2}}\right)}{2\pi \times 60\ Hz} = \mathbf{12.7886\ \mu S}$$

Equation 3 is derived from the instantaneous voltage of a sine wave, as seen in Equation 4. The product of angular velocity, ω , and the instant time t determines the angular measurement or the position of the instantaneous voltage $v(t)$ at a given time. In detecting the zero cross, the $v(t)$ value of interest is near zero voltage or approaching zero voltage, therefore the angular measurement will be relatively small. Since the angle is small, the calculation of sin (ωt) will be approximately equal to ωt (small-angle approximation of sine functions). In this case, Equation 3 can be further reduced to Equation 5. Recalculating the given values in Example 2 using Equation 5 will arrive at approximately the same result, as seen in Example 3.

EQUATION 4: INSTANTANEOUS VOLTAGE EQUATION

$$v(t) = V_{PEAK} \times \sin(\omega t)$$

$$where: \ \omega = 2\pi ft$$

EQUATION 5: SIMPLIFIED ZCD EVENT OFFSET EQUATION

$$T_{OFFSET} = \frac{V_{CPINV} - V_{Desired\ Reference}}{V_{PEAK} \times 2\pi \times Frequency}$$

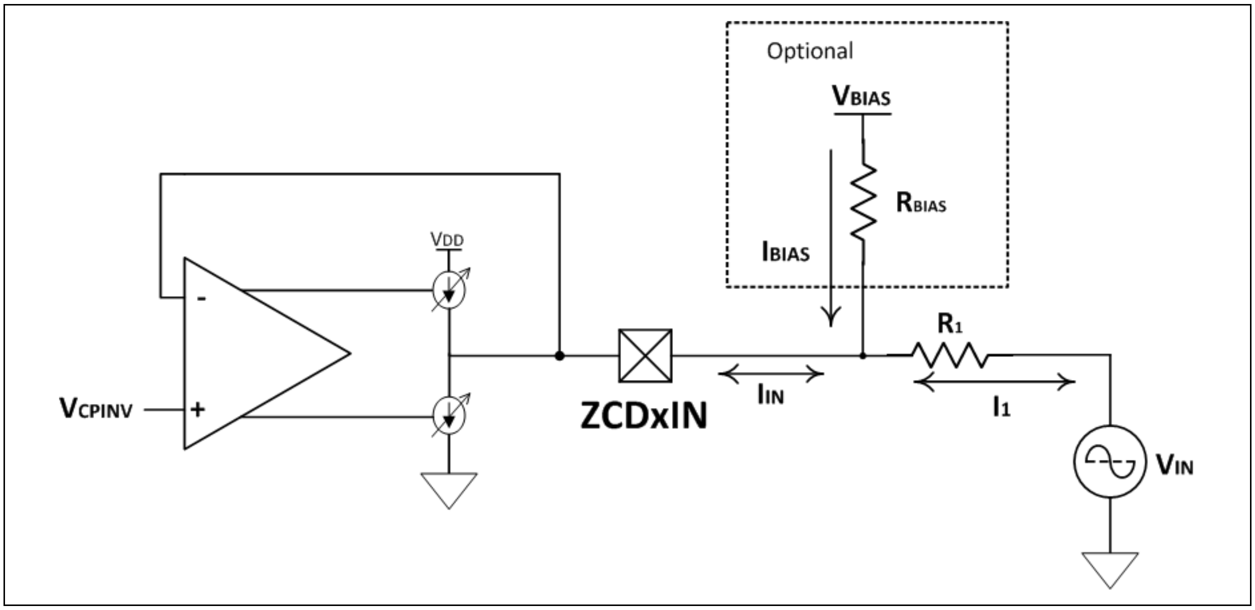
EXAMPLE 3: SIMPLIFIED EVENT OFFSET EXAMPLE CALCULATION

$$(5) \quad T_{OFFSET} = \frac{750\ mV - 0V}{110 \times \sqrt{2} \times 2\pi \times 60\ Hz} = \mathbf{12.7885\ \mu S}$$

OPTIONAL BIASING RESISTOR

The ZCD event offset described in the previous section can be compensated by adding an optional external bias resistor (see Figure 3). The bias resistor can alter the V_{CPINV} detection threshold to 0V or to any desired set point.

FIGURE 3: OPTIONAL BIASING RESISTOR



The purpose of the external biasing resistor (R_{BIAS}) is to provide a current (I_{BIAS}) that is equal to the current flowing through the current-limiting resistor (I_1) at the desired threshold of detection ($V_{Desired\ Reference}$). Therefore, when the input voltage is equal to $V_{Desired\ Reference}$, the total input current (I_{IN}) that will be produced at the node will be equal to zero, thus leaving no current entering the ZCDxIN.

In Figure 3, I_{IN} is the combination of the current I_1 and I_{BIAS} (see Equation 6). I_1 and I_{BIAS} can be replaced by their equivalent voltage-resistor equations to calculate the I_{IN}, as seen in Equation 7. Simplifying Equation 7 by replacing I_{IN} with 300 µA and rearranging the equation to find R_1, the R_1 value is obtained (see Equation 8). Now that R_1 is already determined, the voltage-resistor equivalent of I_{BIAS} from Equation 7 can be used to find I_{BIAS}, as seen in Equation 9. Finally, the value of R_{BIAS} can be determined using the calculated I_{BIAS} value, as shown in Equation 10.

EQUATION 6: TOTAL INPUT CURRENT EQUATION

$$I_{IN} = I_{BIAS} + I_1$$

EQUATION 7: SIMPLIFIED TOTAL INPUT CURRENT EQUATION

$$I_{IN} = \frac{V_{CPINV} - V_{Desired\ Reference}}{R_1} + \frac{V_{IN\_PEAK} - V_{CPINV}}{R_1} = \frac{V_{IN\_PEAK} - V_{Desired\ Reference}}{R_1}$$

EQUATION 8: R_1 EQUATION

$$R_1 = \frac{V_{IN\_PEAK} - V_{Desired\ Reference}}{I_{IN}} = \frac{V_{IN\_PEAK} - V_{Desired\ Reference}}{300\ \mu A}$$

EQUATION 9: IBIAS EQUATION

$$I_{BIAS} = \frac{V_{CPINV} - V_{Desired\ Reference}}{R_1}$$

EQUATION 10: RBIAS EQUATION

$$R_{BIAS} = \frac{V_{BIAS} - V_{CPINV}}{I_{BIAS}}$$

For a given VIN of 110 VRMS and VBIAS of 5V, Example 4 shows the calculation of RBIAS and R_1 when the detection threshold is set at 0V.

EXAMPLE 4: SAMPLE EXTERNAL BIASING RESISTOR CALCULATION

$$V_{IN\_PEAK} = V_{RMS} \times \sqrt{2} = 110V \times \sqrt{2} = 155.5V$$

$$(7)\ I_{IN} = \frac{750\ mV - 0V}{R_1} + \frac{155.5V - 750\ mV}{R_1} = \frac{155.5V + 0V}{R_1}$$

$$(8)\ R_1 = \frac{155.5V - 0V}{300\ \mu A} = 518.5\ k\Omega$$

$$(9)\ I_{BIAS} = \frac{750\ mV - 0V}{518.5\ k\Omega} = 1.44\ \mu A$$

$$(10)\ R_{BIAS} = \frac{5V - 750\ mV}{1.44\ \mu A} = 2.9\ M\Omega$$

Using the calculated R_1 and RBIAS values in Example 4, the total current flowing through ZCDxIN can be determined. Example 5 shows the input current value based on the transition of the input source VIN from the positive to the negative cycle. If the VIN is at the desired detection threshold, the total input current should be equal to zero for the ZCD module to toggle state. This is to check if the R_1 and RBIAS values are correct.

EXAMPLE 5: CHECKING FOR THE RESISTOR VALUES

$$(7)\quad I_{IN} = \left(\frac{V_{BIAS} - V_{CPINV}}{R_{BIAS}}\right) + \left(\frac{V_{IN} - V_{CPINV}}{R_1}\right)$$

At VIN = 155.5 V_{PEAK}:

$$I_{IN} = \left(\frac{5 - 0.75}{2.9\ M\Omega}\right) + \left(\frac{155.5 - 0.75}{518.5\ k\Omega}\right) \approx 300\ \mu A$$

At VIN = 0V:

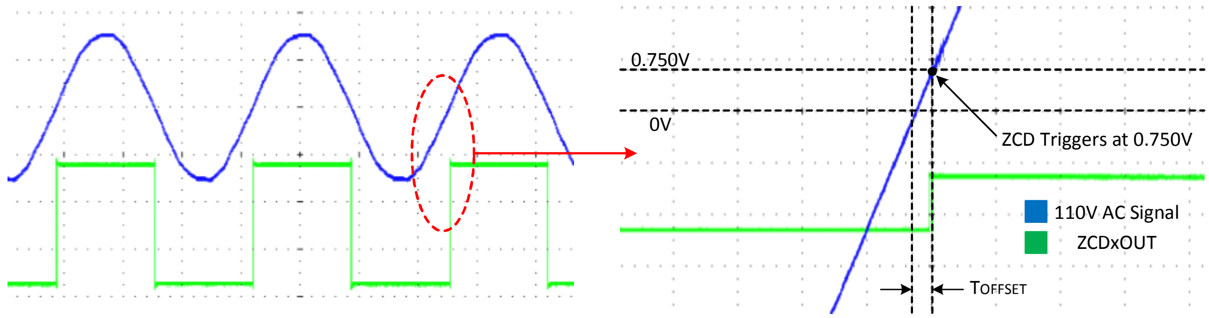
$$I_{IN} = \left(\frac{5 - 0.75}{2.9\ M\Omega}\right) + \left(\frac{0 - 0.75}{518.5\ k\Omega}\right) \approx 0\ \mu A$$ (ZCD will switch state)

At VIN = -155.5 V_{PEAK}:

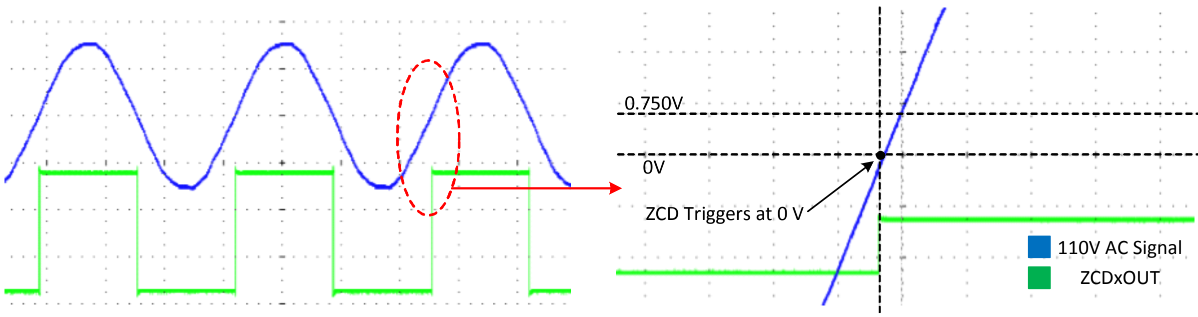
$$I_{IN} = \left(\frac{5 - 0.75}{2.9\ M\Omega}\right) + \left(\frac{-155.5 - 0.75}{518.5\ k\Omega}\right) \approx -300\ \mu A$$

Figure 4 shows the actual generated ZCD output signal based on Example 4.

FIGURE 4: ZCD OUTPUT



(No external Biasing) *VIN=110 VRMS;* R_1*=518 kΩ;* T_{OFFSET}*=12.78 µS*



VIN=110 VRMS; R_1*=518 kΩ; RBIAS=2.9 MΩ*

CONFIGURATION BIT

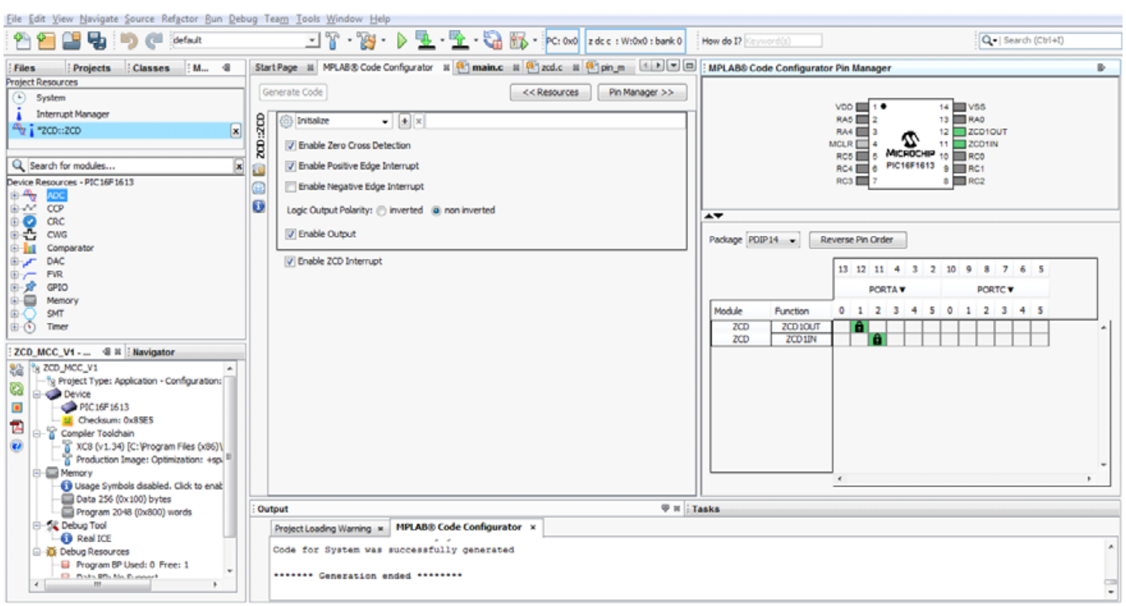
The ZCD module can be permanently enabled upon power-up by clearing the ZCD Disable bit (ZCDDIS/$\overline{\text{ZCD}}$) in the Configuration Word. Clearing this bit ensures that ZCDxIN will be kept at a regulated and safe voltage as soon as the device is powered on. Therefore, ZCDxIN cannot be multiplexed with any other functionality. However, when ZCDDIS/$\overline{\text{ZCD}}$ is set, the ZCD can be enabled or disabled during firmware runtime by setting or clearing the Zero-Cross Enable (ZCDxEN) bit, respectively.

IMPLEMENTING ZCD USING MICROCHIP'S MPLAB® CODE CONFIGURATOR (MCC)

In this section, MPLAB® Code Configurator (MCC) is utilized to easily configure the ZCD module. The MCC is a user-friendly plug-in tool for MPLAB® X IDE which generates drivers for controlling and driving peripherals of PIC microcontrollers, based on the settings and selections made in its Graphical User Interface (GUI). Refer to the *"MPLAB® Code Configurator User's Guide"* (DS40001725) (http://www.microchip.com/pagehandler/en_us/devtools/code_configurator/home.html) for further information on how to install and setup the MCC in MPLAB X IDE. The following steps will guide on how to configure the ZCD module in PIC16F1613 using MCC:

1. Navigate to: "*Tools> Embedded> MPLAB Code Configurator*" to launch the MCC.
2. Set the desired Configuration registers and the system clock source on the System label inside of MPLAB X under the Project Resources window.
3. Under the Device Resources panel, expand ZCD and then double-click on **ZCD::ZCD** to bring the module up to the Project Resources panel.
4. In the center panel, after clicking the **ZCD::ZCD** in the Project Resources panel, check the Enable Zero-Cross Detection and Enable Output checkbox.
5. Select **non-inverted** as the Logic Output Polarity.
6. To enable ZCD interrupt detection on the rising edge, check the Enable ZCD Interrupt and Enable Positive Edge Interrupt checkbox.
7. To configure the ZCD input and output pins, expand the MPLAB® Code Configurator Pin Manager on the right side of the screen. Click the **green lock** next to ZCD1OUT and ZCD1IN to assign them as following: ZCD1OUT = PORTA(R_1), ZCD1IN = PORTA(R_2).
8. Click the **Generate Code** button in the top left corner of the center panel. This will generate a `main.c` file to the project automatically. It will also initialize the module and leave an empty while(1) loop for custom code entry. See Figure 5 for the User Interface of ZCD in MCC and Example 6 for the generated initialization code for the ZCD module.

FIGURE 5: MCC USER INTERFACE FOR ZCD



EXAMPLE 6: MCC GENERATED INITIALIZATION CODE FOR ZCD

```
void ZCD_Initialize (void)
{
    // Set the ZCD to the options selected in the User Interface
    // ZCD1EN enabled; ZCD1POL not inverted; ZCD1INTP enabled; ZCD1OE
enabled; ZCD1INTN disabled;
    ZCD1CON = 0xC2;

    // Clearing IF flag before enabling the interrupt.
    PIR3bits.ZCDIF = 0;

    // Enabling ZCD interrupt.
    PIE3bits.ZCDIE = 1;
}
 void ZCD_ISR(void)
{
    // Clear the ZCD interrupt flag
    PIR3bits.ZCDIF = 0;
}
 void PIN_MANAGER_Initialize(void)
{
    LATA = 0x00;
    TRISA = 0x3D;
    ANSELA = 0x15;
    WPUA = 0x00;
    LATC = 0x00;
    TRISC = 0x3F;
    ANSELC = 0x0F;
    WPUC = 0x00;
    OPTION_REGbits.nWPUEN = 0x01;
}
```

CONCLUSION

This technical brief covers the Zero-Cross Detection (ZCD) module in PIC microcontrollers. It provides ways on how to implement and interface the modules along with the external components needed. The calculations of external component values such as the current-limiting resistor and the external biasing resistor are also provided in this technical brief to alter the detection threshold to any set point. The configuration of ZCD is demonstrated using the MPLAB Code Configurator (MCC). An example initialization code is generated using the MCC, as well.

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