Low-component-count zero-crossing detector is low power

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There are many circuits published showing zero-crossing detectors for use with 50- and 60-Hz power lines. Though the circuit variations are plentiful, many have shortcomings. This Design Idea shows a circuit that uses only a few commonly available parts and provides good performance with low power consumption.

In the circuit shown in Figure 1, a waveform is produced at $V_o$ with rising edges that are synchronized with the zero crossings of the line voltage, $V_{AC}$. The circuit can be easily modified so that it produces a falling-edge waveform that is synchronized with $V_{AC}$.

![Figure 1](image)

The zero-crossing detector uses few components and consumes very little power. The $V_o$ signal has a rising edge that is coincident with each zero crossing of the line voltage, $V_{AC}$.

The circuit operates as follows. At the zero crossings of $V_{AC}$, the current through the capacitor and the LED of the HCPL-4701 optocoupler satisfies Equation 1 below. Equation 2 shows the standard conversion between radians per second and hertz; it also shows the derivation and explanation for $v(t)$. Equations 3 and 4 show the simplification used in Equation 1. Because the voltage across the LED is close to constant, differentiation of that value with respect to time results in a zero value.
The peak value of the current through the LED is a function of the capacitor, C, so you must choose a value for C under the constraint that at the initial time (t=0) and for a given minimum supply-voltage value, the intensity exceeds the triggering threshold value for the optocoupler. In the case of the HCPL-4701, it is $I_{\text{F(ON)}}=40 \, \mu\text{A}$.

Diode D₁ not only allows for the capacitor to discharge but also prevents the application of a reverse voltage on the LED. The maximum reverse input voltage of the HCPL-4701 is 2.5V.

Resistor R₁ is included in order to discharge the energy stored in the capacitor in the latter portion of each cycle of $v_i(t)$ when $i_c(t)<0$ (Figure 1). Its maximum value is limited by the capacitor, by the peak value of the supply voltage ($V_{\text{AC-PEAK}}$), and by the maximum acceptable time delay of the current rising edges through the LED with respect to the corresponding ac-voltage zero crossing (Figure 2). Its minimum value is limited by the maximum allowable power dissipation in R₁ ([$V_{\text{AC-RMS}}$]²/R₁). A practical compromise has to be reached.

![Figure 1](image1.png)

**Figure 1** The graph shows the relationship between $v_i(t)$ and $i_c(t)$ for different values of R₁. The figure illustrates how the current through the LED is affected by the resistance.

![Figure 2](image2.png)

**Figure 2** The relationship between $v_i(t)$ and $I_{\text{LED}}(t)$ is a function of the value of R₁. The time delay between the zero crossing and the LED current is shown.

\[
\begin{align*}
    i_c(t) &= i_{\text{LED}}(t) = C \frac{d}{dt} [v_i(t) - v_{\text{LED}}] = C \frac{d}{dt} v_i(t) \\
    &= C \omega V_{\text{AC-PK}} \cos(\omega t) \rightarrow i_c(0) = C \omega V_{\text{AC-PK}}, \quad (1)
\end{align*}
\]

where $\omega = 2 \pi f_{\text{AC}}$ and

\[
    v_i(t) = |V_{\text{AC}}(t)| = |V_{\text{AC-PK}} \sin(\omega t)|. \quad (2)
\]

\[
\begin{align*}
    C \frac{d}{dt} [v_i(t) - v_{\text{LED}}] &= C \frac{d}{dt} v_i(t) - C \frac{d}{dt} v_{\text{LED}} = C \frac{d}{dt} v_i(t), \quad (3)
\end{align*}
\]

because $C \frac{d}{dt} v_{\text{LED}} = 0$ ($v_{\text{LED}}$ constant). \quad (4)
Table 1 shows the time delay ($t_{\text{delay}}$) of the current rising edges through the LED and the power dissipation for three different values of $R_i$. Notice that the time delay of the rising edges of $V_o$ with respect to the zero crossings of $V_{ac}$ must include an additional delay for the optocoupler’s propagation time delay. The HCPL-4701 has a typical propagation time delay of 70 μsec.

<table>
<thead>
<tr>
<th>$R_i$ (kΩ)</th>
<th>$t_{\text{delay}}$ (μSEC)</th>
<th>$V_{ac\text{rms}}/R_i$ (mW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>470 kΩ</td>
<td>60</td>
<td>112.5</td>
</tr>
<tr>
<td>820 kΩ</td>
<td>100</td>
<td>64.5</td>
</tr>
<tr>
<td>4.7 MΩ</td>
<td>450</td>
<td>11.2</td>
</tr>
</tbody>
</table>

Based on the previous information, the following practical values for $C$ and $R_i$ are obtained:

- For $V_{ac}=230V_{\text{rms}}\pm20\%$ (Figure 3): $C=0.5$ nF/400V (MKT-HQ 370 polyester metallized, MKT● series), $R_i=560$ kΩ/0.25W, $t_{\text{delay}}=114$ μsec (the time delay in the rising edges of $V_o$ with respect to the zero crossings of $V_{ac}$), and $P\approx100$ mW (average power from the ac line).

Figure 3 shows empirical results for $V_{ac}=230V_{\text{rms}}$, $C=0.5$ nF, and $R_i=560$ kΩ.

- For $V_{ac}=115V_{\text{rms}}\pm20\%$ (Figure 4): $C=1$ nF/200V, $R_i=220$ kΩ/0.25W, $t_{\text{delay}}=130$ μsec (time delay in the rising edges of $V_o$ with respect to the zero crossings of $V_{ac}$), and $P\approx65$ mW (average power from the ac line).
Empirical results are shown for $V_{AC} = 115\text{V RMS}$, $C = 1\ \text{nF}$, and $R_1 = 220\ \text{k}\Omega$.

For operation from 80 to $280\text{V RMS}$: $C = 1\ \text{nF}/400\text{V}$ and $R_1 = 330\ \text{k}\Omega/0.25\text{W}$.

Empirical results are shown for $V_{AC} = 267\text{V RMS}$, $C_1 = 1\ \text{nF}$, and $R_1 = 220\ \text{k}\Omega$ (Figure 5). See Figures 6 and 7 for additional empirical results.

Figure 5 Empirical results are shown for $V_{AC} = 267\text{V RMS}$, $C = 1\ \text{nF}$, and $R_1 = 220\ \text{k}\Omega$. 
Figure 6 Empirical results are shown for $V_{ac} = 114V_{RMS}$, $C = 1$ nF, and $R_1 = 560$ kΩ.

Figure 7 Empirical results are shown for $V_{ac} = 228V_{RMS}$, $C = 1$ nF, and $R_1 = 560$ kΩ.

Note that as with any device connected directly to the mains, exercise extreme caution while bench testing the circuit. Follow proper guidelines when laying out a printed circuit board.