

Application Note AN-48

CAPZero™ Family



Design Considerations

Introduction

CAPZero is a family of self powered ICs designed to reduce the losses associated with the input filter capacitor discharge resistors when the AC voltage is present. Designed to be connected in series with existing discharge resistors each CAPZero device contains an integrated loss of AC detector and back-to-back MOSFETs in an SO-8 package.

When the AC input voltage is present, CAPZero remains in an OFF state, blocking current flow in the discharge path and eliminating power losses. When the AC is removed the CAPZero turns on, thereby switching in the resistors and allowing discharge of the input filter capacitance. CAPZero is self powered from the AC line with a power consumption of less than 5 mW at 230 VAC.

Given the small footprint of the package, it is possible to place the CAPZero IC on the bottom side of the printed circuit board (PCB) directly beneath the X capacitor. This eliminates the need for a major redesign of the PCB allowing existing designs to quickly benefit from reduced power consumption.

Background

Applications that contain off-line switching power electronics, for example motor drives, domestic appliances, industrial equipment and power supplies in general, have high voltage and high current switching waveforms that generate Electro Magnetic Interference (EMI).

To reduce this electro magnetic interference (EMI) a filter stage is included at the AC input (Figure 1). As part of this filter, capacitors are commonly placed directly across the AC input terminals to reduce differential mode EMI. Due to their location safety agency recognized X class capacitors are typically selected. X capacitors are rated to withstand the line surges that appear across the AC line with the numerical suffix indicating the specific voltage rating (X1, X2 or X3).

As the capacitor appears across the input terminals a voltage, up the peak of the incoming AC, can appear across the input prongs of the AC plug. This could potentially cause an electric shock to the user if touched or sparks should the prongs of the AC plug be shorted.

To prevent these risks once the supply is unplugged, safety agencies mandate that capacitance values above 100 nF be discharged automatically with a time constant of <1 second. Typically this is achieved by placing discharge resistors directly across the capacitor. The value of the resistance is selected to meet the 1 second time constant requirement and two resistors

are usually connected in series to meet safety agency single point failure testing. Should one resistor become shorted then the presence of the second prevents a short circuit across the AC input.

The presence of discharge resistors results in a constant power loss while AC is applied. With more stringent no-load and standby input power requirements, this power loss has become a significant portion of the overall power budget. For example, a power supply that uses a capacitance of 1 μF across the incoming AC will require a maximum discharge resistance value of 1 M Ω which dissipates 53 mW at 230 VAC independent of the output load. Figure 2 shows typical dissipation in the discharge resistors as a function of the X capacitor value with a 0.75 second RC time constant. The value of 0.75 seconds provides margin to account for capacitor and resistor tolerances such that the maximum time constant is <1 second.

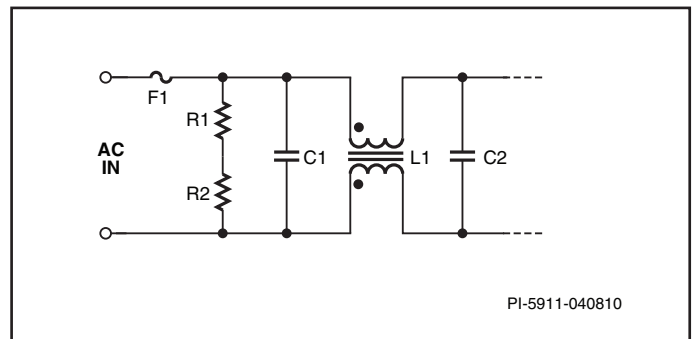


Figure 1. Example EMI Filter Stage of a Switching Power Converter Using Two X Class Capacitors (C1, C2) and Discharge Resistors (R1, R2).

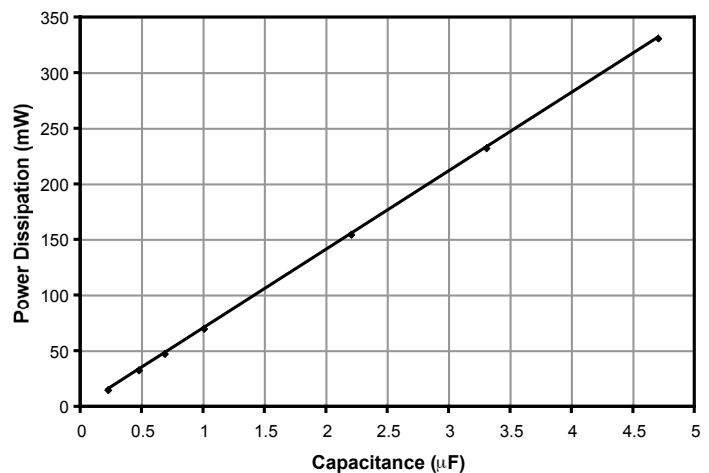


Figure 2. Losses in X Capacitor Discharge Resistors vs Line Voltage. Data Plotted for RC Time Constant of 0.75 Seconds.

Quick Start

Step – 1 Selecting the Correct CAPZero Device Size and Discharge Resistor Value

Select CAPZero device and discharge resistors from Table 1 based on the total input stage capacitance. Table 1 accounts for 5% tolerance of resistors and a 20% tolerance of the total capacitance by using a RC time constant of 0.75 seconds.

Component Selection Table

| Product | BV _{DSS} | Max Total X Capacitance | Total Series Resistance (R1 + R2) |
|----------|-------------------|-------------------------|-----------------------------------|
| CAP002DG | 825 V | 500 nF | 1.5 MΩ |
| CAP012DG | 1000 V | | |
| CAP003DG | 825 V | 750 nF | 1.02 MΩ |
| CAP013DG | 1000 V | | |
| CAP004DG | 825 V | 1 μF | 780 kΩ |
| CAP014DG | 1000 V | | |
| CAP005DG | 825 V | 1.5 μF | 480 kΩ |
| CAP015DG | 1000 V | | |
| CAP006DG | 825 V | 2 μF | 360 kΩ |
| CAP016DG | 1000 V | | |
| CAP007DG | 825 V | 2.5 μF | 300 kΩ |
| CAP017DG | 1000 V | | |
| CAP008DG | 825 V | 3.5 μF | 200 kΩ |
| CAP018DG | 1000 V | | |
| CAP009DG | 825 V | 5 μF | 150 kΩ |
| CAP019DG | 1000 V | | |

Table 1. Component Selection Table.

Step 2 – Selecting the Appropriate CAPZero Voltage Rating

CAPZero is available in two voltage ratings, 825 V and 1 kV. The 825 V rating is ideal for most consumer applications with Metal Oxide Varistor (MOV) located in position 1 (see Figure 5 for MOV_{POS1}), where the differential line surge requirement is up to 3 kV. CAPZero devices with a 1 kV rating are applicable for <1 kV level without MOV, and for >3 kV with MOV at position 1 together with an optional external ceramic capacitor C_{EXT} to lower the surge stress voltage. For applications with no MOV for >1 kV and up to 3 kV level, either a 825 V or 1 kV rated part can be used depending on measured surge voltage across the CAPZero together with an external ceramic capacitor C_{EXT} of up to 47 pF.

| Differential Mode | CAPZero Voltage | | | Comments |
|-------------------|---|---------------------------------------|---------------------------------------|---|
| | MOV _{POS1} | MOV _{POS2} | No MOV | |
| <1 kV | 825 V | | 1000 V | C _{EXT} up to 47 pF, 1 kV increases Drain voltage margin |
| 1 to 1.5 kV | 825 V | 1000 V | 825 V or 1000 V with C _{EXT} | |
| 1.5 to 3 kV | 825 V | 825 V or 1000 V with C _{EXT} | | |
| >3 kV | 825 V or 1000 V + C _{EXT} (option) | Not Recommended | | |

Table 2. Selection of CAPZero Voltage Ratings vs Differential Surge Withstand Requirement. See Figure 5 for MOV position.

Tips for Design

Recommended Circuit Locations for CAPZero

For differential surge levels above 1 kV the use of a MOV is recommended. The presence of the MOV substantially reduces the voltage stress on both the X capacitor as well as the CAPZero. This can be seen from Figure 3 which shows the maximum voltage across the CAPZero device with differential surge voltages ranging from 1 kV to 3 kV.

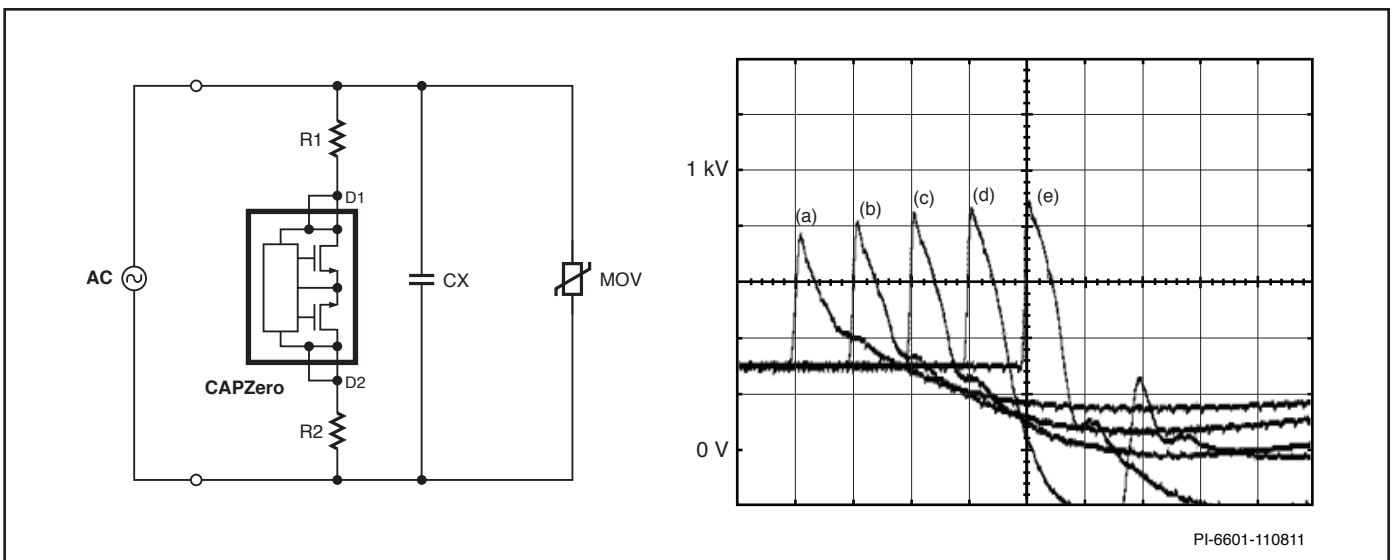


Figure 3. Recommended Position of CAPZero for a Single Stage EMI Filter. Waveforms Show Peak Voltage Across CAPZero in Presence of MOV. 200 V / Division and Time Base = 50 μs / div. Waveforms (a) Through (e) Represent Voltage Measured Across the CAPZero Device Under Differential Mode Input Surge Voltages of 1, 1.5, 2, 2.5 and 3 kV Respectively. MOV Used was 14 mm 275 VAC.

As large currents flow through the MOV when it is clamping there can be significant voltage drops across filter components in the input stage. Therefore it is recommended that the CAPZero be located close to the MOV to minimize the voltage across the device during differential surge events. For designs where the MOV is placed at the input side of the power supply (Figure 3), before any inductive filter components, the CAPZero can be placed directly underneath the X capacitor. For designs where the MOV is placed after a common-mode choke, differential choke or other EMI filter components (Figure 4), it is recommended that if possible the CAPZero also be placed after the common mode choke and be physically close to the MOV allowing the 825 V device to be used up to 3 kV differential surge. If CAPZero cannot be placed after the common mode choke, the 1000 V device is recommended up to a surge level of 1.5 kV. For surge levels greater than 1.5 kV, it is always recommended to have the MOV located on the same side of the common-mode choke as the CAPZero.

One exception is if the X capacitor is on the AC input side of a system input fuse. In these cases if the X capacitor is greater than 100 nF, to meet safety requirements, the CAPZero must typically also be placed before the system input fuse directly across the X capacitor and voltage ratings. CAPZero is designed to meet safety requirements in this position – see ‘Safety Considerations’ section below.

Adding an External Parallel Capacitor to Reduce CAPZero Voltage Stress

While the use of a MOV is recommended, an external capacitor C_{EXT} (Figure 5) may be placed across the CAPZero to reduce surge voltage stress and may be sufficient in some design. This capacitor does not have to be an X class type, since it is not directly placed across the AC input terminals, but should be rated at or above the CAPZero being used. Figure 6 shows the effect of adding external capacitance directly across a CAPZero device in a design without a MOV. With no external capacitor at

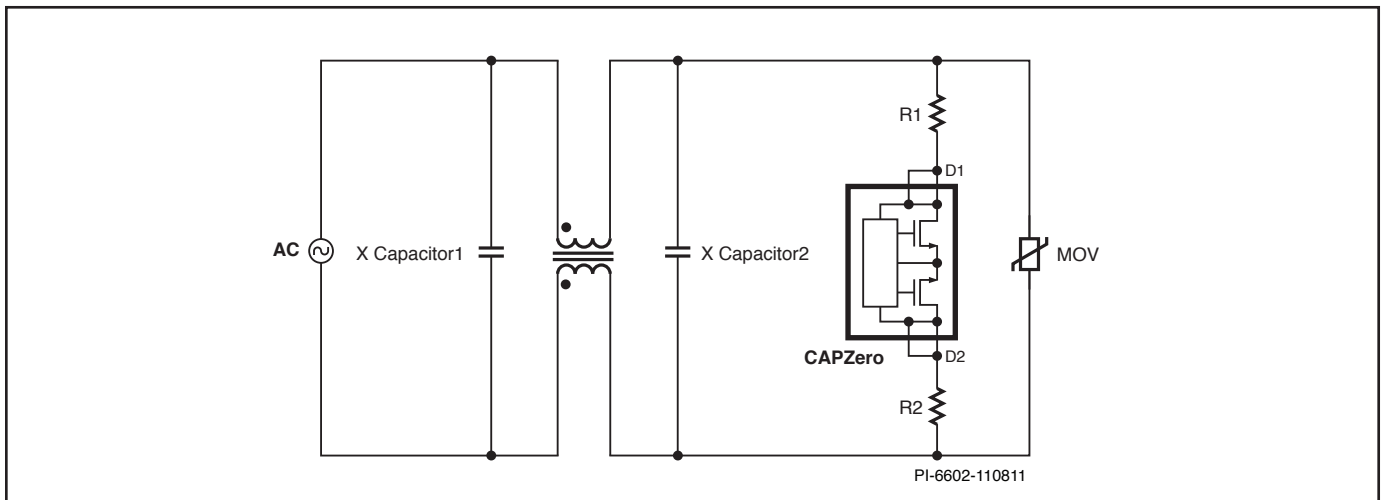


Figure 4. Recommended Location of CAPZero for a Two Stage EMI Filter With a MOV Located After Input Common Mode Choke.

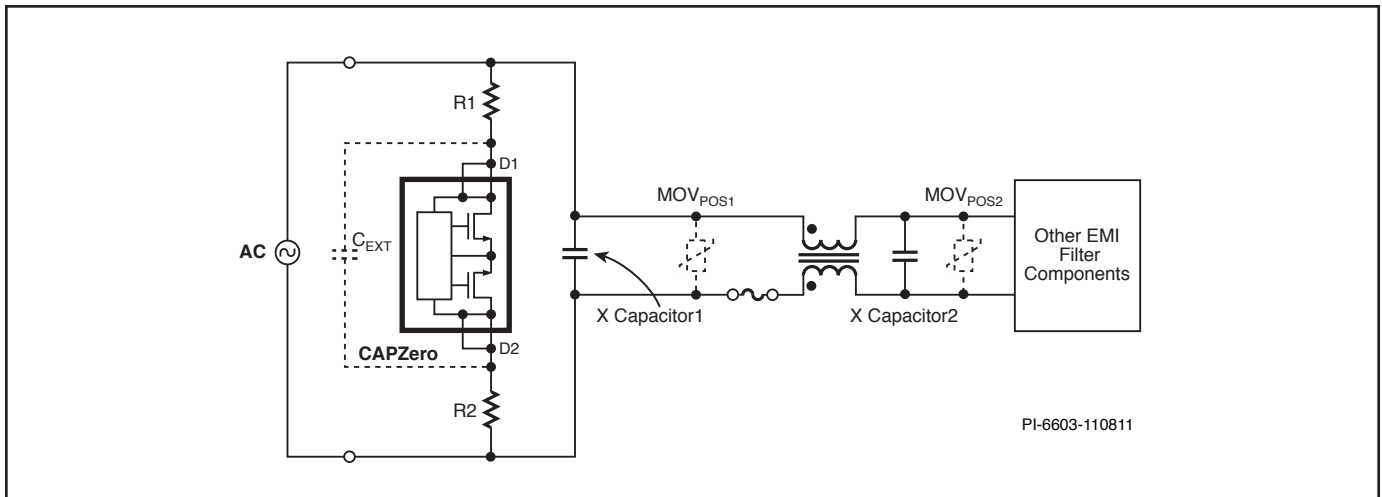


Figure 5. The Addition of an External Capacitor Across the CAPZero can Reduce Voltage Stress Across the Device During a Surge Event.

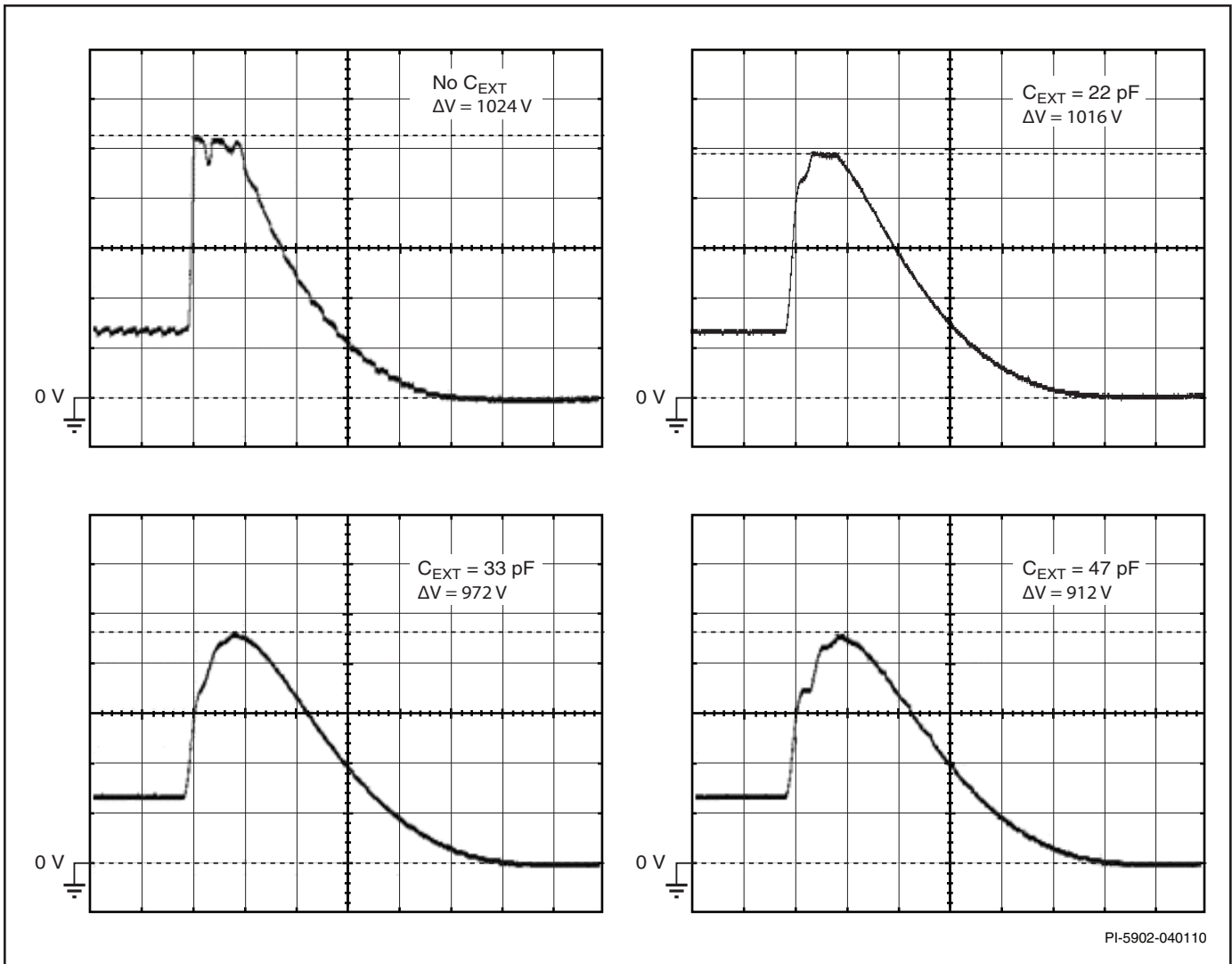


Figure 6. External Capacitor Placed Across CAPZero May Reduce Peak Voltage During Surge Event. No MOV present, 1.5 kV surge. 200 V / div., Time Base = 50 μ s / div.

a 1.5 kV surge level, the CAPZero device exceeds its BV_{DSS} rating however as the value of C_{EXT} is increased to voltage level reduces.

Recommended values of C_{EXT} are between 22 pF and 47 pF. The use of 47 pF capacitor is not recommended in applications where the ambient temperature is in excess of 85 °C. Values above 47 pF are not recommended.

The presence of the external capacitor can for example reduce the voltage stress on the CAPZero by up to 100 V with 2 x 390 k Ω external resistors (1 μ F X capacitor) and 47 pF C_{EXT} . It should be also noted that the use of C_{EXT} will cause a slight increase in no load power consumption.

Measuring Device Voltage Stress

To measure the voltage stress across the CAPZero IC during differential line surge testing, it is recommended that the CAPZero be placed such that one terminal (D1 or D2) is connected to AC neutral. This reduces any effects due to common-mode noise. The area between the oscilloscope probe tip and the ground lead should be minimized. Finally it is necessary to float the oscilloscope or to use a battery powered oscilloscope while performing the surge tests. Please note that if using a floating scope proper care must be exercised as the scope chassis will assume high potential with respect to earth ground.

| Class | Differential Mode Surge | Common Mode Surge | Comments |
|-------|-------------------------|-----------------------|--|
| | $Z_{OUT} = 2 \Omega$ | $Z_{OUT} = 12 \Omega$ | |
| 1 | No requirement | 0.5 kV | Protected environment |
| 2 | 0.5 kV | 1 kV | Electrical environment where cables are well separated |
| 3 | 1 kV | 2 kV | Electrical environment where cables (power and electronic) run in parallel (residential environment) |
| 4 | 2 kV | 4 kV | Electrical environment where cables (power and electronic) run in parallel (industrial environment) |
| 5 | >2 kV | >4 kV | Severe surge environment (rural/sparsely populated areas) |

Table 3. Surge Voltage Levels.

Ensure that the surge voltage measured across the CAPZero device is less than its BV_{DSS} rating.

Surge Severity

The severity of the surge signal is defined in the IEC61000-4-5 standard published by the International Electrotechnical

Commission (IEC). The surge voltage levels are described in Table 3 depending on the operating environment of the power supply.

Certain applications may require surge levels higher than those described in Class 4. For surge voltages greater than 3 kV the use of external capacitors across the CAPZero will help reduce voltage stress across its terminals by a few hundreds of volts as discussed above. It should be noted that at higher surge voltages the energy involved is very high and the MOV should be appropriately selected to handle this excess energy. Varistors have an energy rating which should exceed the applied energy to the system to ensure that this energy can be safely absorbed by the MOV.

Use in DC Input Environments

Since CAPZero relies on detecting the AC voltage at the input, under DC input the CAPZero will remain on all the time. This is a perfectly acceptable mode of operation for CAPZero although this operation will remove any energy savings from the use of CAPZero.

Use with Uninterruptable Power Supplies (UPS)

UPS systems often have a pseudo square wave output waveform, which although AC in nature are not sinusoidal. CAPZero can accept this type of input waveform.

Safety Considerations and Single Point Failure Testing

As with all offline power supplies, all safety requirements must

| Test | Test With Existing System | CAPZero Equivalent | Comments |
|--|---------------------------|-----------------------|---|
| <p>Open Circuit: Disconnect one pin of any device to see effect on system</p> | <p>PI-5907-041310</p> | <p>PI-6604-110811</p> | <p>Lifting any one pin of the CAPZero device has no effect as 2 pins are connected to each drain terminal. The only way to create an open circuit is by lifting the leads of one of the discharge resistors. This is therefore equivalent to existing system without CAPZero.</p> |
| <p>Short Circuit: Short any 2 adjacent pins to see effect on system</p> | <p>PI-5908-041310</p> | <p>PI-6605-110811</p> | <p>Shorting D1 and D2 pins creates a condition equivalent to an existing system not using CAPZero.</p> |

Table 4. Single Point of Failure (SPOF) Tests as Pertaining to Failure Modes of CAPZero. CAPZero Passes Both Tests.

still be met when including CAPZero. To achieve this CAPZero has two dedicated pins for the D1 and D2 terminals which add redundancy during single point of failure testing (pin short / pin open testing). Thus if one pin is physically disconnected from the device or PCB, the IC will continue to function normally. During pin shorting the outcome is the same as if CAPZero had not been used and simply results in the discharge resistors being connected in series continuously; a safe condition. Table 4 summarizes the results of single point fault testing.

Accurate Measurement of No-load Input Power

X capacitors do not consume real power but they do cause a substantial reactive current to flow from the AC source. This reactive current leads to real power loss in the cables that connect the power supply to the AC source and power meter as shown in Figure 7. This cable loss can cause inaccurate measurements of no-load and light load input power. Normally the consumption of the discharge resistors is much larger as compared to this loss. However when CAPZero is used, and this loss is eliminated, the cable loss may become the most dominant component of no-load losses.

Also, at such low levels of input power, the leakage current of the MOV must also be considered. Typically this leakage current is approximately 10 μA and is large enough to increase no-load consumption by 1 – 2 mW at 265 VAC.

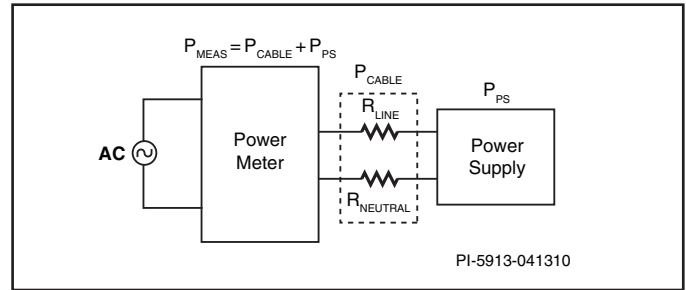


Figure 7. Measured Power can be Misleading Due to Significant RMS Current Resulting in Measurable Power Loss in Cables.

To measure the power consumption of a CAPZero IC, the X capacitor and the MOV (if used) should therefore be physically disconnected from the circuit.

Also ensure that the power meter is configured such that the current drawn by the voltage sensing element is not included in the measurement.

CAPZero Selection for Different X Capacitor Discharge Time Constants

In cases where a faster discharge time constant is required the curves of Figure 8 can be used to select CAPZero for worst case discharge time constants and X capacitor values ranging

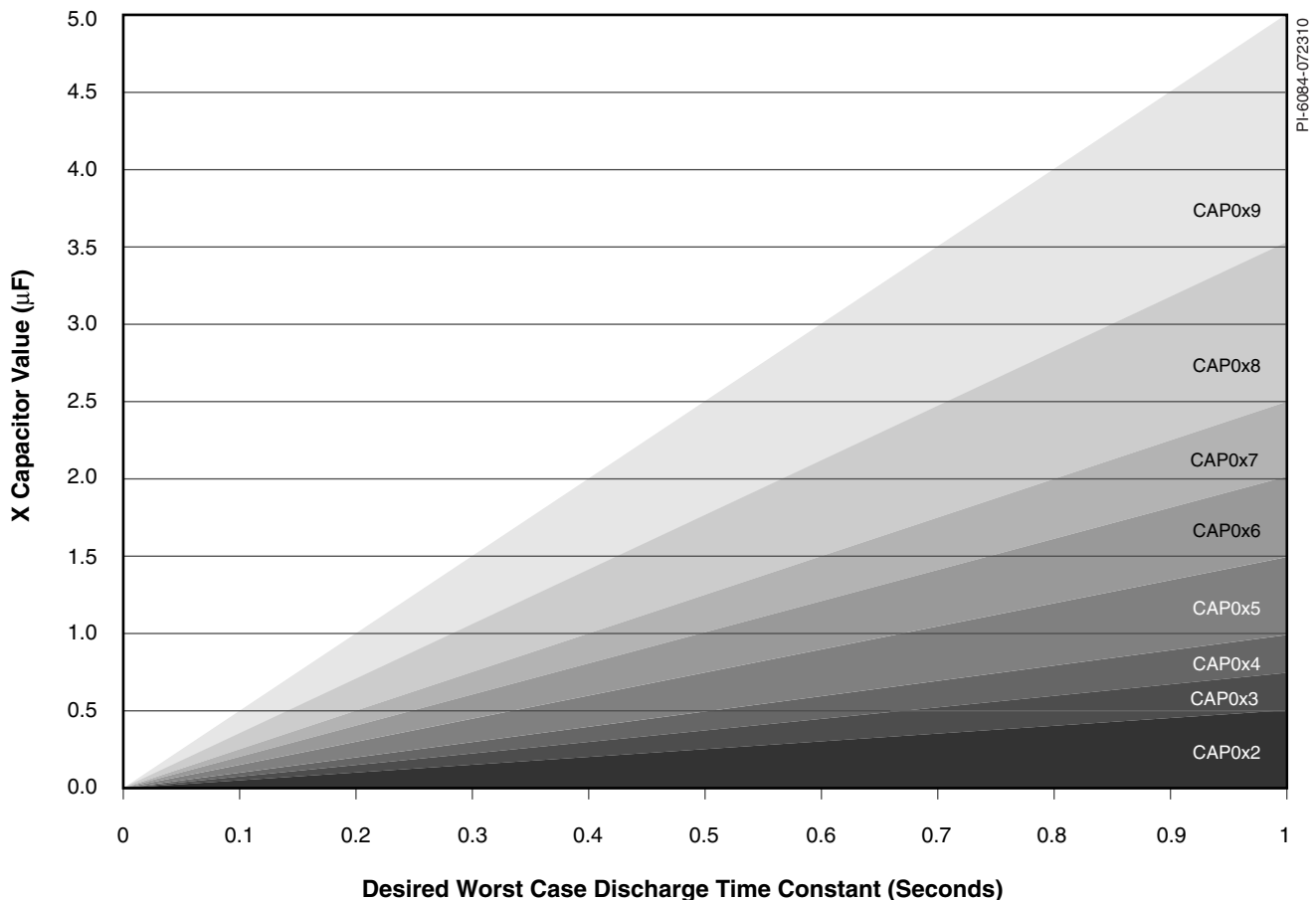


Figure 8. Required Worst Case Discharge Time Constant vs X Capacitor Value.

from 0 to 5 μF . Although safety standards do not generally require discharge resistors for X capacitors values up to 100 nF, data to zero capacitance is included for completeness.

The use of the curves is best demonstrated by an example. Referring to Figure 9, an example is illustrated for a 680 nF X capacitor with a desired worst case discharge time constant of 0.5 seconds. The solid arrows illustrate how the intersection of the 680 nF (on Y axis) and 0.5 seconds (on X axis) provide the CAP0x5 as the correct device. The dotted lines shows the CAP0x3 recommendation as provided on the data sheet which assumes a worst case discharge time constant of 1 second.

The discharge resistor value can be determined from Table 1 based on the required CAPZero. In this example, the CAP0x5

external discharge resistance is 480 $\text{k}\Omega$. This choice of external resistance will actually provide a worst case discharge time constant of about 0.45 seconds as illustrated by the dotted arrow in Figure 9. Since this has no impact on the power consumption, it is recommended to use the Table 1 resistor choice for simplicity.

Note that the Y axis of Figures 8 and 9 are the typical X capacitor value. However, the CAPZero recommendations allow for worst case X capacitor and discharge resistor tolerances to provide a worst case discharge time constant as shown on the X axis. Typical discharge time constants will be ~30% lower than this.

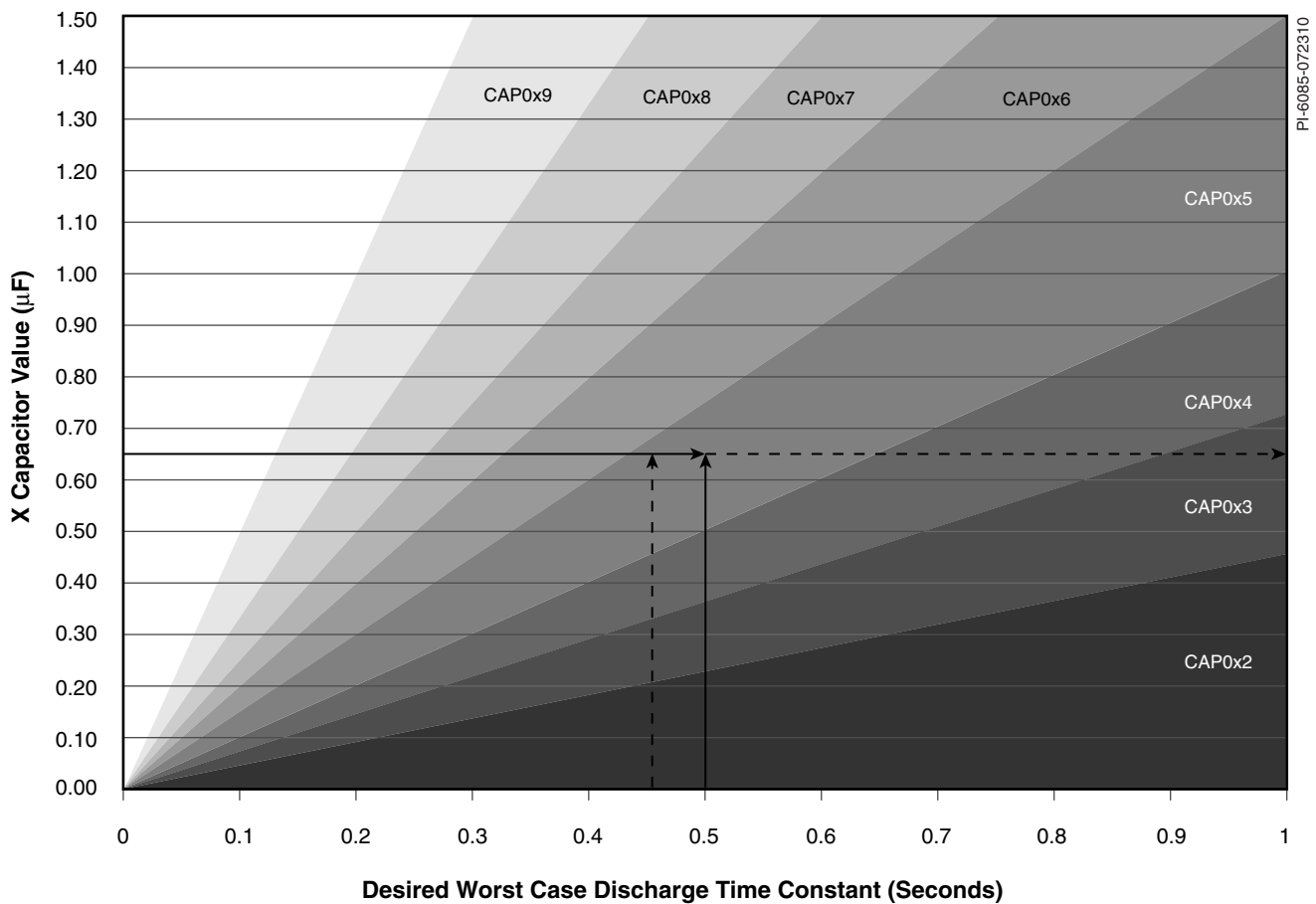


Figure 9. Magnified View of Figure 8 for 0 to 1.5 μF .

Use of CAPZero for AC Line Voltage Zero-Crossing Detection

Any CAPZero can be used for AC line voltage zero-crossing detection when an AC voltage is present. At the same time it can be used as an X capacitor discharging circuit when the AC voltage is removed. The zero-crossing detection circuit uses CAPZero supply current with no additional power consumption in a non-isolated system (it consumes slightly more power when a detector circuit is used in an isolated system).

A simple example of CAPZero used as a zero-crossing detector in a non-isolated application is shown in Figure 10. The zero-crossing signal is generated by a low voltage Zener diode (VR1) which is placed in between the CAPZero device and the AC neutral. The voltage across the Zener is used to drive a small signal MOSFET thereby obtaining the zero crossing signal. Figure 11 shows an example where the zero crossing detection circuit is required with isolation from the input line. While the concept of generating the signal remains the same, an opto-coupler and a bias supply are required for isolation.

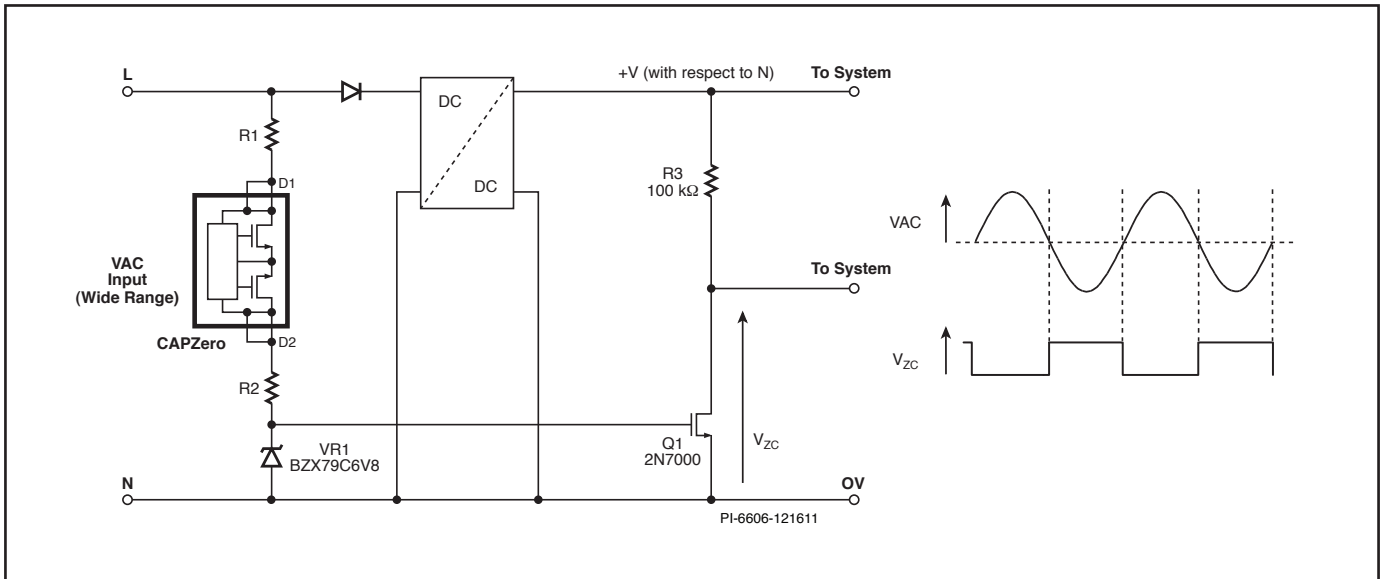


Figure 10. Example of CAPZero for AC Line Voltage Zero-Crossing Detection in a Non-Isolated System.

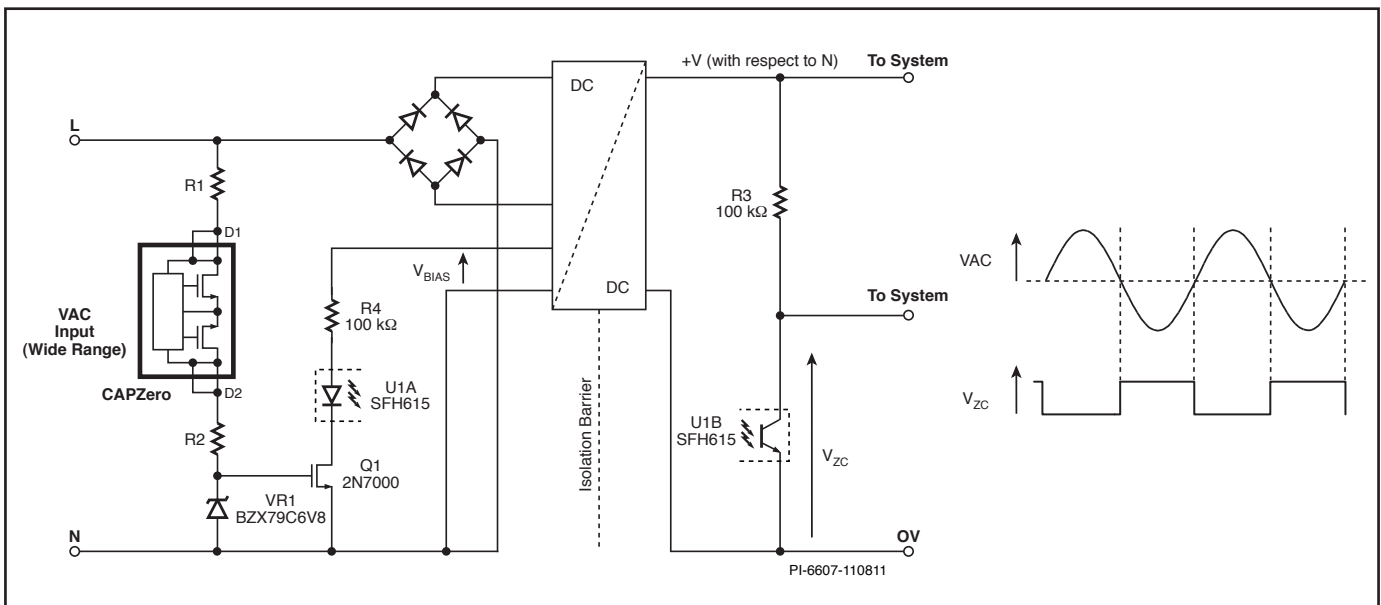


Figure 11. Example of CAPZero for AC Line Voltage Zero-Crossing Detection in an Isolated System.

| Revision | Notes | Date |
|----------|--|----------|
| A | Initial Release | 04/14/10 |
| B | Updated Surge Application Information. Added Discharge Resistor Selection Information. | 07/28/10 |
| C | Updated Step 2 paragraph and Table 2 on page 2. | 9/28/10 |
| D | Updated Figures 3, 4, 5 and Table 4. Added ZCD section. | 12/16/11 |

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