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Current measurement applications handbook

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1 Introduction

Current measurement or monitoring within electronic circuitry is a common requirement spanning many types of applications. These may include anything from portable, handheld equipment through to automotive applications. This application handbook explores factors that are relevant for AC and DC current measurement and the implications on cost and performance for different approaches, and how to best use ZETEX current monitors in your applications. Basic application topologies are explored including typical example calculations.

1.1 Application types

There are two basic application types,

- Closed loop
- Open loop

1.2 Closed loop systems

In closed loop systems, current is measured compared with a reference value and then modified as necessary by some control element. Response time can be critical here especially where immediate actions need to be taken based on instantaneous current value.

Examples of closed loop current monitoring include:

- Switching power supplies with current limiting functions or switch mode battery charging circuits.
- PWM control of solenoids (automotive valve applications).
- RF transmit control loops in portable cellular equipment, where transmitted power is adapted with distance.
- Control of bias currents in (RF) power amplifiers.
- Electronic fuses for internal fault limiting in equipment on distributed power systems.
- Auto shutdown functions for DC motor control (replacing slipping mechanical clutches).

1.3 Open loop systems

Open loop current monitoring systems are characterised by the fact that the measured value is not acted upon immediately. It may, for example, be made available for some other system, usually less time critical. Examples include,

- Current measurement in instrumentation (e.g. bench power supplies, ammeters, current probes).
- Power consumption indication, especially portable battery powered consumer items.

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1.4 Measuring methods

There are basically three methods of monitoring current. Which of these three is used will depend on a number of factors both intrinsic and extrinsic to the application.

These requirements may sometimes also be conflicting. Therefore a careful balancing of requirements to select an optimum method is required.

These three basic methods, Resistive, Optical and Magnetic are tabulated in Table 1 to give a quick overview comparison in terms of their benefits and weaknesses.

1.5 Summary of methods and performance

Table 1 below shows the methods described in this handbook and a quick comparison between the most common factors found in current measuring application.

Table 1 Common current measuring methods

Type	Current range	Isolated	Accuracy	AC response	Non-Intrusive	Cost
Resistive	Very Low/ High	No	High	Medium/ High	No	Low
Optically isolated resistive	Medium/ High	Yes	Low/ Medium	Low/ Medium	No	Low/ Medium
Magnetic	Medium/ Very High	Yes	Medium	Medium/ High	Yes	High

1.6 Factors that determine the type of methods used

Deciding which of the methods is most appropriate for any given application would involve weighting these factors namely,

- Magnitude of current
- The need for galvanic isolation
- Accuracy
- Response time
- Cost

Regardless of which choice is made, all will require some signal pre- or post processing.

The applications addressed in this document include steady state DC and those requiring recovery of high frequency components from DC currents as well as bi-directional ones. We will very briefly consider each of the methods in turn.

2 Detailed discussion of methods

This Application Note is primarily concerned with resistive method because this is by far the most frequently used and also since it is supported by Zetex' wide range of current monitors. However, for completeness, the other two methods will be very briefly discussed before we look extensively at the resistive method compared to Zetex' range of current monitors.

2.1 Optically isolated resistive method

In the strictest sense, this can not really be considered as a current sensing method in its own right. This is because the opto-isolating device (usually an optically isolated transistor) does not directly measure the current but merely transfers the already sensed current information across a galvanically isolated barrier. It is discussed here to illustrate an often used method in isolated current monitoring.

Various configurations may be used but the simplest method is illustrated in Figure 1. Resistor R is the current sensing resistor. It is chosen such that, at the current that we want to limit the output to, it develops a voltage equal in magnitude to V_F , the forward voltage drop of the opto-isolator, IC1. V_F is typically approximately 2V.

This circuit is however so simple and basic that it is of rather limited use. The main reason being the 2V or so VF that is needed to drive the opto-coupler. For example, if this were to be a power supply required to supply a very modest 5A, R would have to dissipate at least 10W of power. This is just not acceptable for many practical reasons. If the output voltage were 5V, it would mean 40% of the available power is lost in the current sensing resistor!

Therefore, in practice, a much more lower voltage of the order of 50mV or less would be developed across R which will then be amplified and used to drive the optocoupler.

Where isolation is required, the use of an optical method provides the most cost effective solution. Its main limitation is that it is relatively low speed.

The example in Figure 1 (and Figure 2) is also a very good illustration of a closed loop current monitoring.

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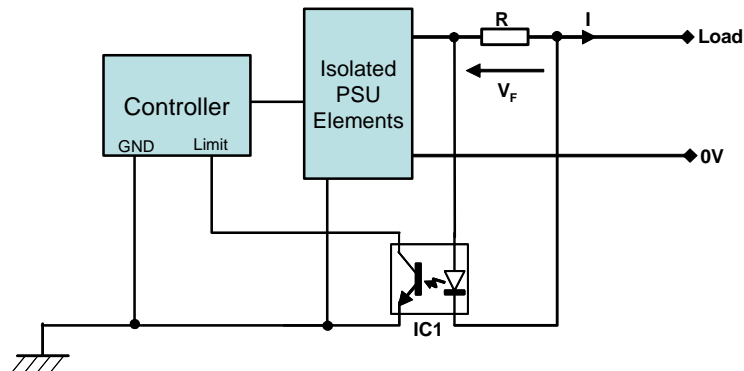


Figure 1 Principle of optical and closed loop current monitoring

2.2 Magnetic method

Like the optical method, the magnetic method also offers isolation but, unlike it, also directly senses its own current without the need for a current sensing resistor.

The magnetic method commonly uses a current transformer which produces an output voltage that is proportional to the current. A change in topology is immediately obvious when we compare Figure 2 with Figure 1. This type of magnetic method can only be used with AC measurements unlike resistive and optical methods which can be either. Even so, the use of the magnetic method is only practical at high frequencies rather than low frequencies. This is because the current transformer that would be required at low frequency would be so bulky and expensive as to make it a non-practical solution. To put things into perspective, you could imagine a scenario where the current monitoring transformer could be nearly as big or bigger than the circuit to be monitored.

For high frequencies however (e.g. switch mode power supplies) magnetic current monitoring becomes feasible and is often used although, even here, it is being replaced by other more cost effective methods such as the use of intelligent FET's to implement cycle-by-cycle current limiting and indeed the now ubiquitous current monitoring solutions from Zetex.

The main advantage of the magnetic method is that it is a relatively loss-less technique. Hence it is very useful where it is required to monitor very high currents in the hundreds or even thousands of amperes.

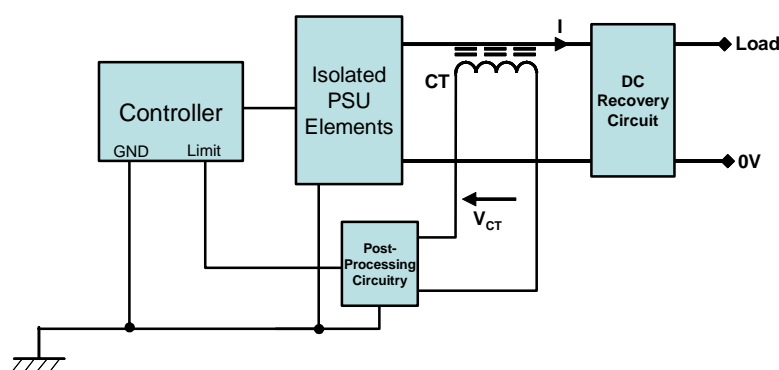


Figure 2 Principle of magnetic current monitoring

2.3 Resistive method

This is the simplest, cheapest and the most basic method of current sensing. It is also by definition the most accurate and linear method of all. Inserting a resistance into the current path has the advantage of converting that current into voltage in a linear way that inherently follows Ohm's law of $V = I \times R$.

It is however not without its own faults although these can be minimised for many given applications. The first and obvious one of these drawbacks is that it introduces additional resistance into an electrical circuit. This can result in unacceptable power loss manifested as heat and loss of efficiency.

Since power dissipation is a square function of resistance ($P=I^2R$), this power loss increases as an exponential function of current which is why the resistive method is rarely used beyond the low/medium current application. Figure 3 illustrates just how very quickly power dissipation builds up in a circuit using resistive current monitoring.

Another drawback is that the method inherently increases the source output resistance. The effect of this may range from the mildly undesirable (such as slightly reduced terminal voltage) to catastrophic, especially where the introduction of the resistor would interrupt the circuit from the ground plane (e.g. a very noisy design which fails to meet statutory EMC requirements).

Either of these problems could be alleviated by using a resistance as close to zero as possible. In accordance with this, the lowest value of resistance will produce the lowest power dissipation. However, with an extremely low resistance, the voltage developed across it is also very low and becomes comparable to circuit offset voltages, compromising accuracy. Therefore a balance between required accuracy and power dissipated for a given current must be found. Shunt resistors with values as low as 0.5Ω ($500\mu\Omega$) are available commercially.

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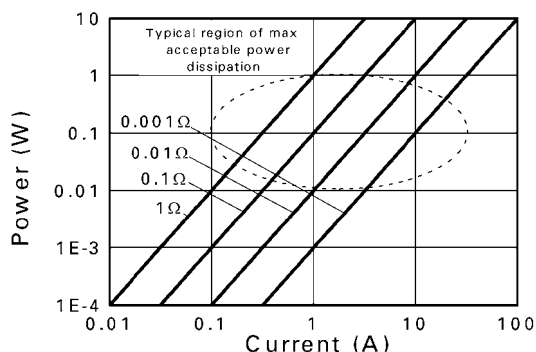


Figure 3 Power dissipated vs current measured

2.3.1 Low-side resistive measurement

Low-side (negative or ground potential) measuring circuits generally offer the simplest solutions because the resulting signal is already ground referenced. One such method is to insert a small resistance into the ground plane between the supply's ground and the load to be measured as illustrated in Figure 4. The resulting proportional voltage developed across that resistance can be used directly or amplified.

Care must be taken to add further circuitry on the correct side of the sense resistor. Circuit C will contribute additional current to that of Circuit B. This may or may not be desirable. To avoid this happening, other circuits should be placed in the position of circuit A so that their currents do not pass through the sense resistor.

A more subtle consequence of placing resistance in the ground plane is that any signal current that passes through R_{SENSE} will generate an offset voltage relative to true ground, 'VE rail' is now a virtual ground at the potential of V_{SENSE} , which will change with the load current. This may be unacceptable with many analogue signals or high frequency circuits from an EMC standpoint.

An important property of the current measurement circuitry is that it should be able to accept V_{SENSE} , a signal of typically tens of millivolts from ground. Input offset voltage can be a consideration here.

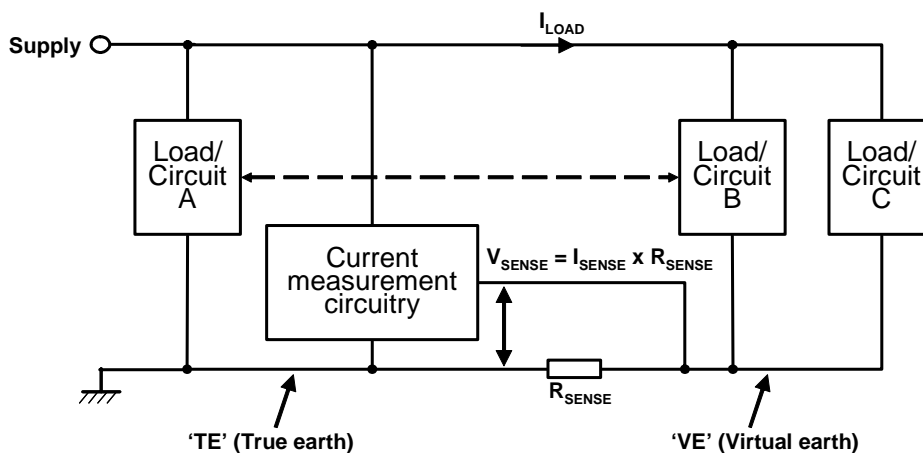


Figure 4 Low side resistive method

2.3.2 High-side resistive measurement

In some applications, the loss of true ground cannot be tolerated because of the inter-circuit offsets incurred, as mentioned earlier. Sometimes, regardless of whether the effects of disrupting the ground plane could be ignored or tolerated, it is not possible to adopt this method for physical reasons. For example, where a system uses a common ground in the form of a metal chassis (as in an automotive environment) components that are connected mechanically to it may not have the first method as an option. It is then necessary to measure the current in the supply (or high) side. In many applications, noisy sources, for EMC reasons, need to be firmly tied to true ground with as low impedance as is possible.

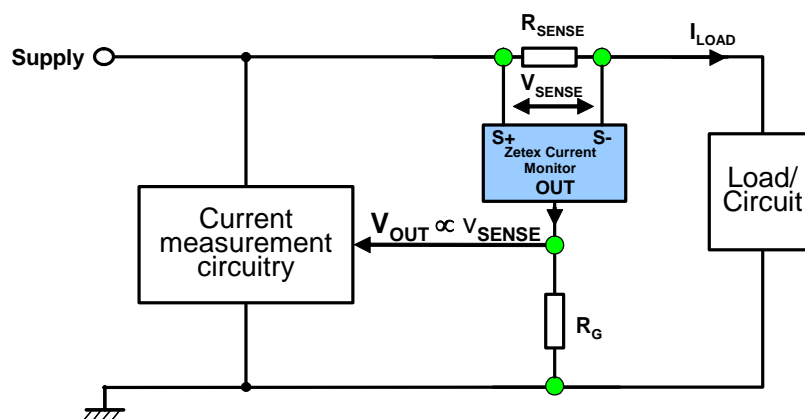


Figure 5 High side current measurement

The challenge now is to translate this small signal with a high common mode element on the supply rail to a ground referenced signal, as further circuitry in most cases will require this.

Zetex has created a wide range of very compact integrated circuit Current Monitors, the ZXCT series, for this requirement.

This means the complex task of processing the small current-related voltage signal is taken care of and the designer can concentrate instead on making use of this processed signal.

With Zetex' range of current monitors, high- or low-side current monitoring is now a very simple task. The devices are very small too coming in either SOT23 or SOT23-5 package, with very few exceptions in bigger packages because of higher pin count requirements.

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3 Properties of translation circuits for current monitors

3.1 Accuracy

Accuracy is conditional on the size of the sense voltage for a given circuit design. Consider a fixed input offset of say 2mV in a translation circuit. A 100mV sense voltage would then have a theoretical best accuracy of 2% while a 10mV sense voltage has 20%.

Discrete transistor circuits are not going to give more than a modest performance in this application. For any tolerance better than 5%, operational amplifiers and dedicated ICs are needed.

It is worth, at this point, calling attention to dynamic range limitations which will have to be taken into consideration always. For example a current monitor required to monitor current varying from, say, 100mA to 1A has a dynamic range of 10:1. What this means is that the offset error when measuring at 100mA would be at least ten times worse than when measuring at 1A. This relationship obviously gets worse the wider the dynamic range.

3.2 Frequency or transient response

This may not be at all important in some circuits. For example, automatic shutdown of DC motors probably won't require less than a few milliseconds response time. Whereas cycle by cycle current limiting in a switching power supply might well need small signal responses in the order of a microsecond or even down to the tens of nanoseconds. Closed loop power supply systems which are monitoring average current will require response times anything in the range of 10s to 1000s of microseconds.

3.3 Power consumption

Current is required to drive parasitic and load capacitances so the speed requirement will always be a balance with supply current usually only important in battery portable applications. For example to drive a signal of 1 volt into 5pF of load capacitance at 10kHz you need only hundreds of nanoamps of signal current and so bias currents will dominate. If you want to drive a signal with 10ns edges at a volt into the same load you'll need hundreds of microamps, changing the biasing of the circuit in a way which makes it less suitable for battery applications.

One circuit will not optimally provide both microamp operating currents and excellent AC performance, so a choice has to be made.

3.4 Maximum allowed sense voltage

Even if the magnitude of the sense voltage is not critical from a power dissipation perspective (because of the small currents being measured) there may be a maximum voltage drop for supply headroom in the measured circuit. For example, in a 3.3V circuit, it would not be desirable for the current monitor to drop 500mV which would represent a loss of 15% in both voltage and power terms.

3.5 Considerations for sense resistors

Power dissipation in resistors causes heating effects, the question is how much can be tolerated and what further consequences are experienced. For currents under 1A, in general this is unlikely to pose any problems as a typical sense voltage would yield power dissipations of less than 100mW which is easily handled by most surface mount and through-hole resistors. As Figure 3 shows, the power dissipation is directly linked to the accuracy required. It would be more critical for a large current to have a low sense voltage in order to minimise power dissipation and so, for a given accuracy, the translation circuit tolerances must be lower.

Example:

20A current must be sensed with maximum 500mW of dissipated power and with a best 3% accuracy. We must determine the allowable input offset.

$$P = I^2 \cdot R_s \quad \text{Equation 1}$$

$$R_s = \frac{P}{I^2} = \frac{0.5}{400} \quad \text{Equation 2}$$

$$R_s = 1.25m\Omega \quad \text{Equation 3}$$

$$V_{SENSE} = I \cdot R_s = 25mV \quad \text{Equation 4}$$

Therefore, for a best accuracy of 3% the input offset voltage can not be more than 3% of 25mV, that is, 0.75mV.

Many of Zetex' range of current monitors have much better offset voltages than this and thus would either give a better accuracy at sense voltage of 25mV or could be used at lower sense voltages. For example the ZXCT1021 and ZXCT1022 are rated at 3% accuracy at a 10mV sense voltage.

Another important reason to keep the self-heating of the resistors low is to minimise any further loss of accuracy caused by the temperature coefficient of the sense resistor. Component to ambient thermal resistances of surface mount resistors on a PCB could be in the order of 200°C/W - i.e. a 250mW dissipation would cause a temperature rise of 50 degrees above ambient.

Consider a resistor with a temperature coefficient of 100ppm/°C, this would give a further 0.5% error from the self-heating effects which must be factored into the assessment of circuit tolerances, this does not take into account the ambient operating temperature range.

3.5.2 Type of resistor

In most cases surface mount resistors are preferred and, for larger currents and their associated power levels, small arrays of series or parallel resistors can be used to share the dissipation. Wire-wound resistors provide higher operating temperatures, but usually have higher temperature coefficients and higher inductance, which might cause problems for high frequency signals. Beware of carbon film (or, much less common these days, carbon composition) resistors. Their temperature coefficient can be thousands of parts per million!

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4 Zetex ZXCT series product description

4.1 Introduction

The Zetex ZXCT series current monitors have been designed specifically for resistive DC current measurement discussed in chapter 1. Most of these are line powered, meaning that there is no need for a separate power source when using them to monitor current. However some, due to the need to offer enhanced features such as short-circuit current and/or low-side current monitoring, have provisions for a separate V_{CC} supply.

All of the devices in the series provide a basic function by taking a very small differential voltage with a relatively high common mode content and converting it to an amplified ground referenced voltage. All devices are high-side sensing capable whilst some are also capable of either low-side sensing or are able to continue to provide an output in case of a high-side short circuit.

Table 2 in the Appendix (page 37) shows the range of current monitoring solutions that are available from Zetex. The range includes, broadly, two types: Current Output Current Monitors (COCM) and Voltage Output Current Monitors (VOCM). There are also the special function current monitors (SFCM) which are basically current monitors with added functions for specialised applications such as the ZXCT1030 (with built-in voltage reference and comparator) and the ZXCT1032 (for inrush current control and use as an electronic fuse).

4.2 Current Output Current Monitor (COCM)

The current output device converts the sense voltage into an output current. This arrangement offers unique advantages in that the overall gain of the circuit can now be set by a single resistor connected to the output pin. Furthermore, although this resistor will in most cases be grounded for a ground referenced output, in reality it does not have to be, making it possible for the output to be referenced to some other arbitrary level within the circuit.

The simplest devices in the series are high-side current sense monitors with only 3 pins (SOT23 - see Table 2 on page 37). They are intended for cost effective applications. The current output versions produce a constant current output which is proportional to the voltage across a sense resistor. This allows a wide current range to be measured accurately when the appropriate sense resistor is chosen.

For example, consider a 50mV sense voltage. A 1mA current could be sensed with a 50Ω sense resistor or a 50A current could be measured with a 1mΩ sense resistor. This output current is then converted into a voltage with a single user defined output resistor allowing flexible scaling.

In general, the COCM has a transfer function given by:

$$I_{OUT} = G_T \cdot V_{SENSE} = G_T \cdot R_S \cdot I_{LOAD} \quad \text{Equation 5}$$

Where G_T is the transconductance value in A/V or Siemens (S).

Since V_{SENSE} is proportional to the current being measured, it is obvious that the monitor's output current is also proportional to it. Hence, I_{OUT} is a scaled down image of the load current.

For some devices (e.g. ZXCT1008, ZXCT1009), G_T is internally set, typically at 0.01S. For other devices (e.g. ZXCT1011, ZXCT1020), G_T is set by a single external resistor whilst overall gain is set by another resistor.

Consider Figure 6 below. The output current is proportional to the sense voltage (**Equation 5** above) which itself can be seen to be proportional to the load current, I_{LOAD} . Combining this

information and noting that the output voltage is a product of the output current and R_G , we have an overall transfer function given by

$$V_{OUT} = R_G \cdot G_T \cdot R_S \cdot I_{LOAD} \quad \text{Equation 6} \\ \text{(Transfer function for COCM)}$$

This shows that the output voltage, V_{OUT} , is directly proportional to the current being measured.

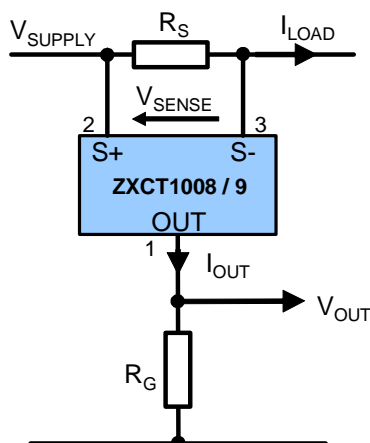


Figure 6 Simplest current output current monitor (COCM)

From this basic and simple concept, some other devices with some additions and/or refinements are offered.

For example, the ZXCT1010 adds a separate ground connection to the ZXCT1009 to remove the IC's quiescent supply current from the output, reducing the output current offset component.

Some devices (e.g. ZXCT1050) provide for a VCC pin separate from the supply voltage whose current is being monitored. The advantage of this arrangement is that the common mode range of the sensed current can now include ground thus allowing low-side current monitoring as well as high-side. Table 2 (page 37) gives a complete overview of all current monitors.

4.3 Voltage Output Current Monitor (VOCM)

The voltage output device is straightforward in its operation, it simply translates the small high side (or low side in some cases) sense voltage into an amplified ground referenced representation. The gain is fixed, typically 10 or 100.

For a VOCM device the gain setting resistor (and transconductance resistor) has been integrated. Therefore the transfer function reduces to

$$V_{out} = k \cdot V_{SENSE} \quad \text{Equation 7}$$

Where k is a gain constant, typically 10 (e.g. ZXCT1021) or 100 (e.g. ZXCT1022). Compared with the transfer function of a COCM ($V_{OUT} = R_G \cdot G_T \cdot V_{SENSE}$) it can be seen that $k = R_G \cdot G_T$.

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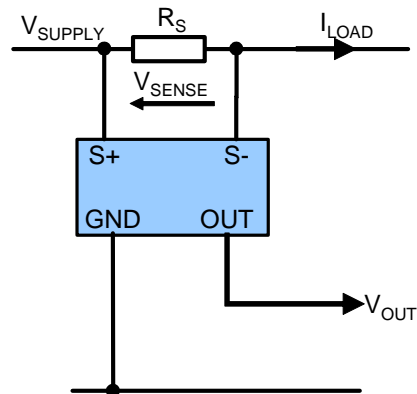


Figure 7 Simplest voltage-output current monitor (VOCM)

Again combining the information above with Equation 7, we see that the transfer function of the V_OCM is given by

$$V_{out} = k \cdot R_S \cdot I_{LOAD}$$

Equation 8
(Transfer function for COCM)

Unlike its COCM counterpart, it is clear that it is not possible to have a 3-terminal V_OCM. However, other than the sense resistor R_S , the V_OCM does not require any external component at all whereas the COCM always requires at least one. Therefore, where space and component count are critical, the V_OCM will have a definite advantage.

5 Design examples and procedures

5.1 Basic calculations

COCM

Example 1

Consider a requirement to measure a current of 5A to be represented by a 1V output.

Using a purely resistive method on its own would require a 200mΩ resistor. The supply voltage would be dropped by 1V and the power loss would be 5W. Not an ideal set of circumstances for most applications.

However using one of Zetex' current monitors changes all of this. Let us consider the ZXCT1008 with reference to Figure 6 on page 13. For best accuracy, we require a V_{SENSE} of 200mV. Therefore the required value of R_S is given by

$$R_S = \frac{0.2V}{5A} = 40m\Omega \quad \text{Equation 9}$$

This will give us our required V_{SENSE} of 200mV. From Equation 5 (page 12) and noting that the ZXCT1008 has a G_T of 0.01S, we calculate the output current as

$$I_{out} = 0.01 \cdot 0.2 = 2mA \quad \text{Equation 10}$$

This only now requires choosing an appropriate value of R_G to obtain the required output, thus

$$R_G = \frac{1V}{2mA} = 500\Omega \quad \text{Equation 11}$$

With this design the supply voltage would only now lose 0.2V and the power loss in R_S would only be 1W. It should be pointed out that this major improvement is, by comparison, modest when compared with what can now be achieved with Zetex' latest range of current monitors which can give reasonable accuracy at sense voltages as low as 10mV.

VOCM

The gain for a VOCM is given on the datasheet and we therefore only need to determine R_S as per Equation 7 and Equation 8, decide what gain is required and pick a device with that gain.

Example 2

For example, consider a requirement for a 20A current to be sensed with a maximum of 500mW dissipated power within an accuracy of 3%.

$$\text{Power} = I^2 \times R$$

Therefore,

$$R_S = 0.5/400 = 1.25m\Omega$$

(4 x 5mΩ resistors in parallel could be used for instance).

$$V_{SENSE} \text{ at } 20A = 25mV$$

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In order to meet our requirement, the VO_{CM} must have a typical input offset of 3% at 25mV of less than 750µV. The ZXCT1021/22 were created to meet design requirements such as these. They are rated at ±3% at 10mV sense voltage. So, requirement is met.

The ZXCT1021 would give an output of $V_{SENSE} \times 10$ or 250mV, whilst the ZXCT1022 would give an output of $V_{SENSE} \times 100$ or 2.5V.

Example 3

10A is to yield a resulting output voltage of approximately 2.56V for an ADC input. R_S must be smaller than 10mΩ to minimize power loss.

We have the choice of gain of 10 or 100. Which would give the best value of V_{SENSE} ?

$$V_{SENSE} = V_{OUT} / \text{Gain}$$

$$V_{SENSE} = 2.56 / 10 = 256\text{mV or}$$

$$V_{SENSE} = 2.56 / 100 = 25.6\text{mV}$$

To obtain these two V_{SENSE} values at 10A, R_S must be:

$$R_S = 256\text{mV} / 10\text{A} = 25.6\text{m}\Omega \text{ or}$$

$$R_S = 25.6\text{mV} / 10\text{A} = 2.56\text{m}\Omega$$

Since R_S is to be less than 10mΩ, we choose a gain of 100 i.e. the ZXCT1022 with a 2.5mΩ sense resistor, which could be two 5mΩ resistors in parallel. This yields an output of 2.50V at 10A.

5.2 Transient protection

In some applications, especially those containing inductive elements, high voltage transients can be present. Because of this, it may be necessary to provide some protection for the device, its connected load or both. The following circuits are suggested ways of accomplishing this.

In Figure 8, the zener diode, Z1, is chosen such that any transient voltage that is greater than ($V_Z + V_{OUT}$) is commuted to the output, therefore protecting the ZXCT device from any harm. This scheme assumes that the load is tolerant of this transient or over-voltage event.

An alternative scheme that does not transfer the strain to the output as much is shown in Figure 9. Here, an additional resistor, R_{LIM} , is added in series with R_G to limit the transient output current. Any circuit connected to V_{OUT} will therefore be protected from input voltage transients. A zener diode can also be placed between V_{OUT} and ground as optional protection for the connected circuitry. In this case, ensure that the zener diode voltage is sufficiently higher than $V_{OUT(max)}$ so as not to interfere with normal operation.

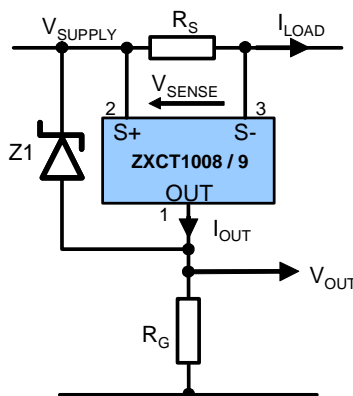


Figure 8 Transient protection for device

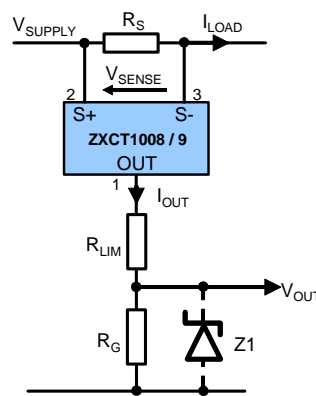


Figure 9 Transient protection for device and load

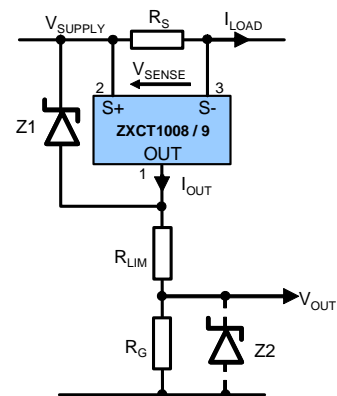


Figure 10 Better transient protection for device and load

The value of R_{LIM} will have to be carefully determined. At the lower end of its value, it is limited by the maximum current that can be supplied by the device, whilst at the higher end the limiting factor is the available circuit compliance. The two limits are determined as follows.

$$R_{LIM(min)} = \frac{V_{PK} - V_{MAX}}{I_{OUT(max)}} \quad \text{Equation 12}$$

$$R_{LIM(max)} = \frac{R_G (V_{SUPPLY(min)} - (V_{DO} + V_{OUT(max)}))}{V_{OUT(max)}} \quad \text{Equation 13}$$

Where,

V_{PK} = Peak transient voltage to be withstood

V_{MAX} = Maximum operating voltage (20V in most cases)

$I_{OUT(max)}$ = Max continuous output current (25mA)

$V_{SUPPLY(min)}$ = Minimum supply operating voltage,

V_{DO} = Drop-out voltage

$V_{OUT(max)}$ = Maximum required output voltage

For practical determination of R_{LIM} , since the value has to lie somewhere between these two limits, it is just as well to pick a value nearest mid-point between them. Therefore:

$$R_{LIM} = \frac{R_{LIM(min)} + R_{LIM(max)}}{2} \quad \text{Equation 14}$$

If the two values are very close together, then use either of the values. Note that the two values can converge and this is acceptable. If, as can sometimes happen, $R_{LIM(min)}$ is larger than $R_{LIM(max)}$, this would indicate that the maximum output voltage, $V_{OUT(max)}$, required from the circuit is too high for the set of circumstances. This can be corrected by doing any or all of the following.

- Reducing $V_{OUT(max)}$ which means lowering the value of R_G .
- Increasing minimum supply voltage $V_{SUPPLY(min)}$.
- Reducing I_{OUT} . Note that this can only be done by reducing R_S which will result in an increase in error which may not be desirable.

The solutions in Figure 8 and Figure 9 can be combined as in Figure 10 to get the best of both. Figure 8 and Figure 10 in particular and, to a lesser degree Figure 9, have the advantage of protecting the current monitor against any negative excursions of the supply voltage.

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5.3 Extended operating range

The ZXCT1009, for example, has a maximum operating voltage of 20V¹. Where higher voltages are required, the following circuits can be used to extend the operating voltage range of the current output current monitor.

5.3.1 Simplest circuit for $V_{SUPPLY} > V_{MAX}$

Figure 11 shows the simplest way to extend the working voltage range of a current monitor above its design value. The zener diode, Z1, is simply inserted in series with R_G.

The zener diode's value is chosen taking into consideration the range of the supply voltage and ensuring that the following conditions are met.

$$V_{SUPPLY(min)} \geq V_{DO} + V_{OUT(max)} + V_Z \quad \text{Equation 15}$$

$$V_{SUPPLY(max)} \leq V_{MAX} + V_Z \quad \text{Equation 16}$$

where, V_{DO} = device drop-out voltage, V_Z = zener voltage, $V_{OUT(max)}$ is the maximum output voltage, V_{MAX} = maximum working voltage.

In reality this scheme is not so much an "extension" of the working voltage range as a "lifting" of it by an amount equal in magnitude to the zener voltage. It nonetheless does allow the device to be used beyond its designed maximum working voltage.

It may be noticed that the circuit in Figure 11 is quite similar to Figure 9 with R_{LIM} being replaced with a zener diode. Indeed Figure 9 can be used as a simple supply voltage range extender where the supply range is lifted by an amount given by $I_{OUT} \times R_{LIM}$ instead of V_Z .

¹ 20V is used as an example in most cases as many of the ZXCT range work at this maximum supply voltage, although the range has now expanded to include 40V and 60V devices. The same principle will still apply to these other devices.

5.3.2 Improved circuit for $V_{SUPPLY} > V_{MAX}$

A true extension of the supply voltage range is provided by Figure 12. This circuit has the advantage of also offering very good transient protection.

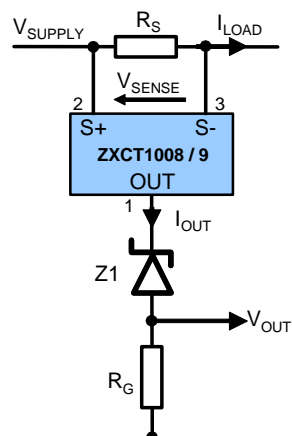


Figure 11 Simplest supply range extension

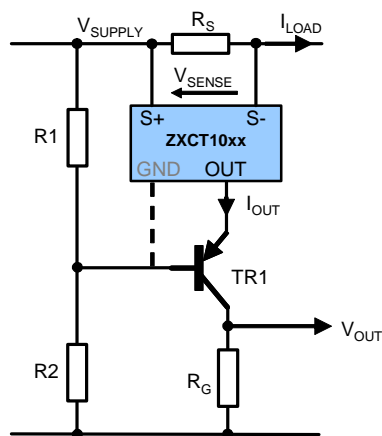


Figure 12 Improved supply range extension

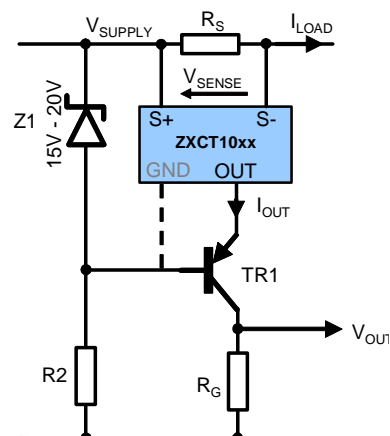


Figure 13 Best supply range extension

Suitable devices: All COCM's.

Note that the ZXCT1050 has a V_{CC} pin which needs to be at least 2V above V_{SUPPLY} . Whilst this is not impossible it might present a challenge in some situations. In that case the circuit shown in Figure 28 (page 28) and Figure 32 (page 31) is recommended instead especially for short circuit measurement. Also, the common mode range of these circuits does not include ground, the more reason why Figure 32 should be used for the ZXCT1050 if low side sensing is required.

TR1 is used in the common base configuration and is used to drop most of the supply voltage between collector and emitter. When the current gain is reasonably high (>100), $I_C \approx I_E$ and I_{OUT} still flows through R_G and hence V_{OUT} can still be calculated in the normal way.

Ideally, R1 must be chosen to preserve the ZXCT's normal supply range, large enough in value to provide the minimum operating voltage to the device at the lowest supply voltage but not too large that the maximum device operating voltage is exceeded at the highest input voltage.

Procedure 1 - Design steps for Figure 12

1. Determine or estimate I_{OUT} (it doesn't need to be precise at this stage)
2. Determine the required minimum supply voltage, $V_{SUPPLY(min)}$.
3. Determine device's maximum working voltage, V_{MAX} .

4. Calculate transistor bias current I_B from
$$I_B = \frac{I_{OUT}}{h_{FE(min)}}$$

5. Calculate bias resistor R_B from

$$R_B = \frac{(V_{SUPPLY(min)} - V_{DO} - V_{eb})}{I_B} = \frac{(V_{SUPPLY(min)} - V_{DO} - V_{eb}) \cdot h_{FE(min)}}{I_{OUT}} = \frac{R1 \cdot R2}{R1 + R2}$$

6. Calculate R1 from
$$R1 = \left(\frac{V_{SUPPLY(max)}}{V_{SUPPLY(max)} - V_{MAX}} \right) \cdot R_B$$

7. Calculate R2 from
$$R2 = \left(\frac{V_{SUPPLY(max)}}{V_{MAX}} \right) \cdot R_B$$

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In a situation where a higher supply voltage is required or where the supply voltage varies over a wide range, the scheme in Figure 13 could be used where resistor R1 in Figure 12 is replaced with a zener diode rated within the maximum working voltage of the COCM. The design steps are similar to those in Procedure 1 but slightly simpler.

Procedure 2 - Design steps for Figure 13

1. Determine or estimate I_{OUT} (it doesn't need to be precise at this stage)
2. Determine device's maximum working voltage, V_{MAX} .
3. Chose the value of Z1 to be within V_{MAX} e.g. $V_Z=15V$ for a $20V_{MAX}$ device. In general, make sure $(V_{DO} + V_{be}) < V_Z \leq V_{MAX}$.
4. Determine the required minimum supply voltage, $V_{SUPPLY(min)}$.
5. Calculate transistor bias current I_B from $I_B = \frac{I_{OUT}}{h_{FE(min)}}$
6. Calculate resistor R2 from

$$R2 = \frac{(V_{SUPPLY(min)} - V_Z)}{I_B} = \frac{(V_{SUPPLY(min)} - V_Z) \cdot h_{FE(min)}}{I_{OUT}}$$

5.4 Bi-directional current sensing

Two COCM's can be connected in anti-parallel fashion to provide bi-directional current monitoring as shown in Figure 14 below.

It will be noticed from Figure 14 below that only amplitude information is available, which is acceptable if all that is needed is amplitude data as is often the case in many applications. However, sometimes it may also be required to preserve polarity information after rectification. The arrangement in Figure 14 does not have this feature. Zetex has produced the ZXCT1041 to fulfil this role. The ZXCT1041 is a VOCCM and not only converts bi-directional current into a unipolar output voltage but also has an output flag which indicates the current polarity.

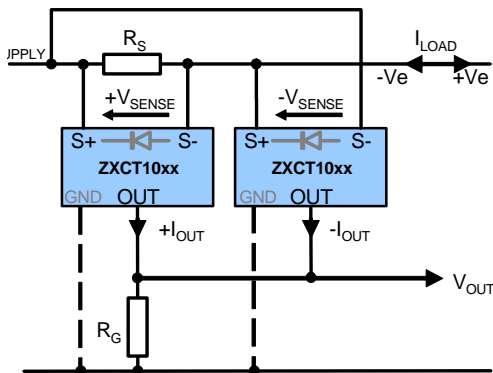


Figure 14 Bi-directional current monitoring

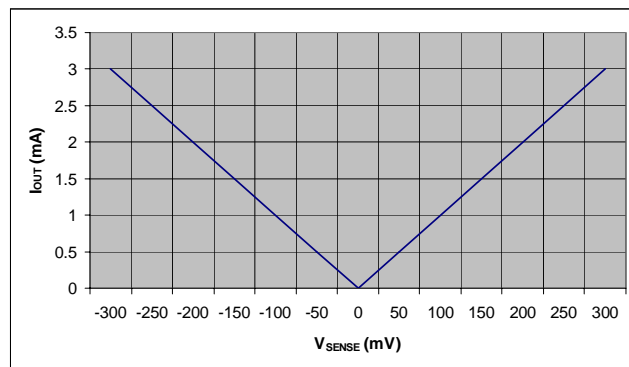


Figure 15 Output response for bi-directional COCM

Suitable devices: ZXCT1008, 1009, 1010, 1012, 1020

Note that some VOCCM's (e.g. 1021, 1022) can also be used but the outputs need to be kept separate. This in fact means that both amplitude and direction information can now be captured.

Some points are worth noting regarding Figure 14.

- If the ZXCT1008 or ZXCT1009 are used, the quiescent current offset error will be doubled. For this reason, the ZXCT1010 and 1012 may be preferable as they have separate ground pin which diverts the quiescent current away from the output.
- All current monitors have an internal reverse diode across the S+ and S- pins (shown in-laid on diagram). Thus, in the anti-parallel mode example given above, it is important to make sure that V_{SENSE} is kept below $\pm 500\text{mV}$ so that these diodes do not become forward biased. This is not a problem as it is in any case advisable to keep V_{SENSE} well below this level for other reasons.
- While one half of the devices is active, the other device' internal output stages are driven into a saturation mode from which it will take a finite time for them to recover. It will therefore be found that this application will not be suitable for very fast (sub-milliseconds) circuits. Again the ZXCT1041 has kept this delay to a minimum, less than $5\mu\text{s}$.

5.5 Driving an H bridge

5.5.1 With two independent current monitors

A very common application of bi-directional current monitoring is in a full or H bridge circuit. If there is access to the supply rails to the bridge, the optimum way to measure the load current is to use either low or high side sensing as depicted by RX and RY in Figure 16. However there are situations when this may not be possible (if for example there is no access to the supply rails) or the right thing to do. For example, it may be required to know which direction the load current is flowing. Measuring with RX and RY will not necessarily indicate this as the current through them is always unidirectional regardless of the direction of the load current. However this is only true if the load is resistive. The situation gets even more complicated if the load is inductive as is the case with driving a motor. In this case, the current in RX or RY will change direction when commutating the FET switches whilst the current through the inductive load is still flowing in the same direction! For these three different reasons, the most reliable way, therefore, to monitor the load current is at the load.

Since the current is bidirectional, the designer may be tempted to use the simple two device arrangement illustrated in Figure 14 above. This however would not work due to the fact that both devices would need to have a common mode input range which includes ground. Therefore the only effective way to measure the bidirectional current in this bridge would be as shown in Figure 16.

Two separate COCM's (VOCM's are also possible) are used to alternately monitor the load current depending on the direction. Whilst one device is active, the other is inactive due to it being biased off, hence the two devices together provide both amplitude and polarity information.

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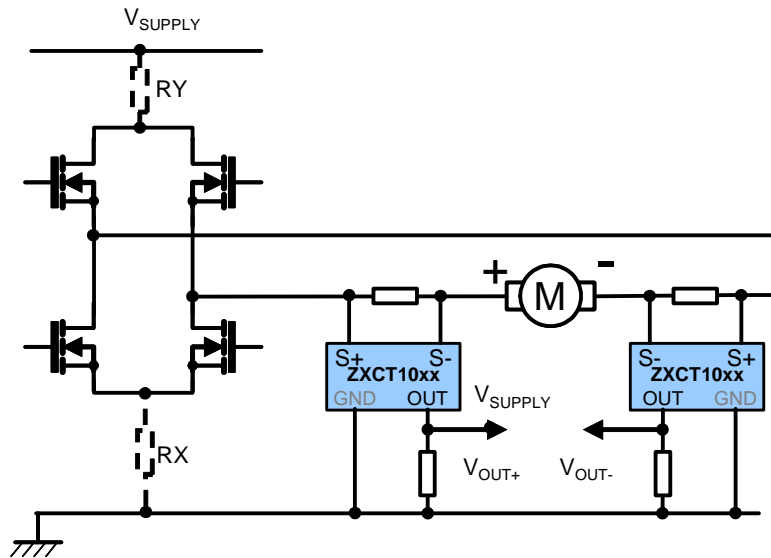


Figure 16 Measuring bidirectional motor current in a full bridge driver

5.5.2 With anti-parallel current monitors

It has been argued above that the circuit of Figure 14 would not be suitable for the H-bridge application in Figure 16. Whilst this is true, some of the latest devices, the ZXCT1050, ZXCT1051, which can also work in the low-side mode can indeed be configured for anti-parallel operation in this application. However, doing this only results in saving one sense resistor and a separate V_{CC} supply would have to be provided. The user needs to make a judgement whether this is acceptable or not.

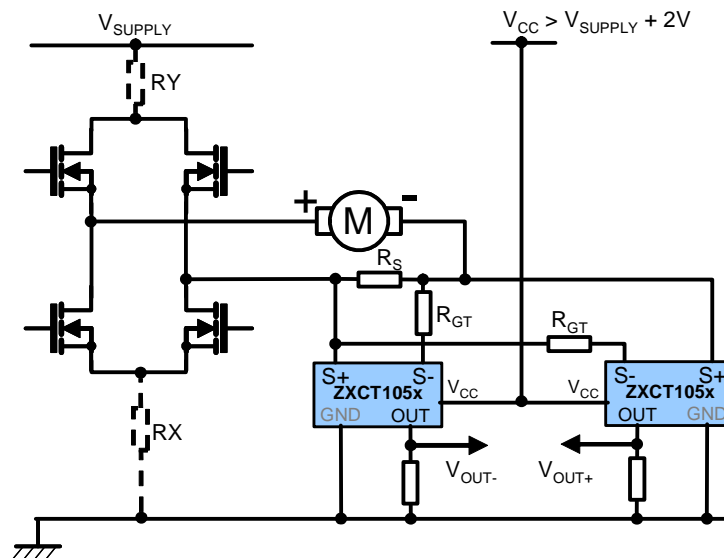


Figure 17 Measuring bidirectional motor current with anti-parallel current monitors

5.6 Short circuit protection/over-current protection applications

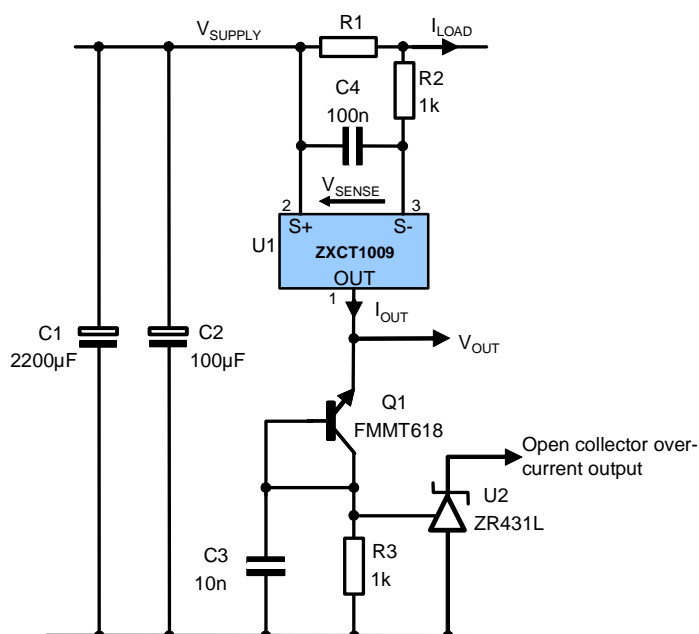


Figure 18 Over-current protection circuit

Transistor Q1 serves to reduce the voltage seen by U1 and operates as a zener diode in its reverse V_{be} breakdown mode. Q1 is not needed when operating with supplies below the device's V_{MAX} .

The voltage developed across R3 is then fed to U2 (ZR431L) which is a programmable voltage reference used as a comparator. When the voltage on the Vref pin exceeds 1.24 volts, the device conducts, pulling the open collector output low. The required pull-up resistor can be connected to any supply rail of choice up to 20V. The advantage of using the ZR431L as a level detector in preference to a transistor V_{be} or a FET V_{Gth} is that the voltage sense level is virtually independent of temperature and varies less from device to device.

The sensitivity of the current limit can be increased or reduced by adjusting the value of R3 to develop the required 1.24 volts at different currents. C3 provides a time delay to prevent false triggering.

The value of current that causes the output to switch can be calculated by rearranging the datasheet formula:

$$V_{OUT} = V_{ref} = 0.01 \times V_{SENSE} \times R_G \quad (V_{ref} = 1.24V, R_G = R3 \text{ and } V_{SENSE} = I_{LOAD} \times R1)$$

Hence, the trip current will be:

$$I_{trip} = \frac{1.24}{0.01 \cdot R1 \cdot R3}$$

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For the example in Figure 18 $I_{trip} = 5.6A$

When monitoring an inductive load where voltage transients may be present, R2 and C4 provide filtering to ensure correct operation. If the load is purely resistive these components can be omitted.

For a more integrated solution for over-current applications see the ZXCT1030 with internal comparator and reference.

5.7 Latching over-current protection

Figure 19 below shows how any standard COCM may be used to implement a latching over-current protection circuit. This particular circuit is aimed at low power applications but can easily be adapted for a higher power one by suitably substituting Q5 with a high power p-channel MOSFET. With a little modification, it can also be adapted for use with a VOVM. The circuit consists of three distinct stages.

Stage **A** is easily recognised as a compliance-boostered current monitor as previously discussed in Figure 13 with a slight modification of including a grounded second zener diode, Z2, to generate a reference supply.

Stage **B** is a comparator consisting of Q2 and Q3. It compares the current monitor's output at R3 with a reference, V_{REF} derived from Z2. Once this is reached, the comparator turns on Q4 which turns off the series pass transistor, Q5, thus removing power from the load. Q4 and Q5 form Stage **C**.

Q5 at the same time provides a positive feedback via R10 to the current monitor forcing it into an over-drive mode that will eventually saturate it. The circuit will remain locked in this state until both power and the overload are removed.

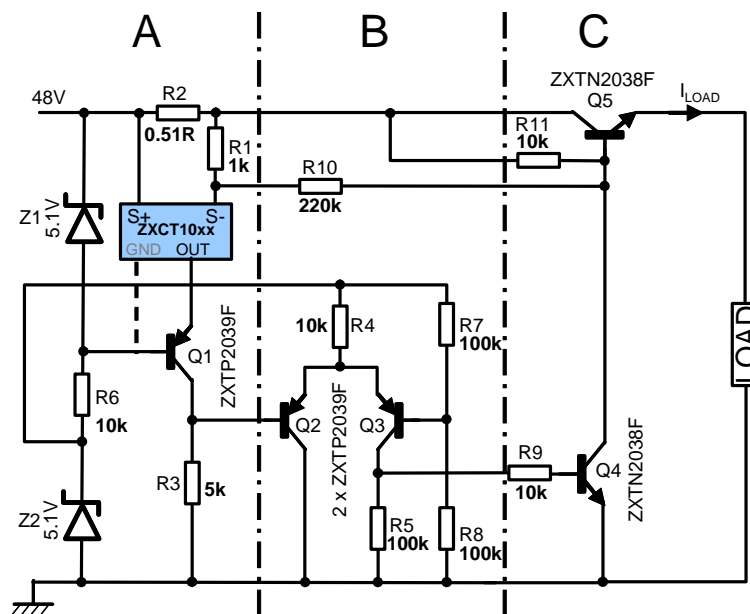


Figure 19 Latching over-current protection

The transfer function of this circuit (i.e. the current at which the circuit trips) is deduced and is given by:

$$I_{trip} = \frac{V_{Z2}}{G_T} \left(\frac{R8}{R2 \cdot R3(R7 + R8)} \right) = 100 \cdot V_{Z2} \left(\frac{R8}{R2 \cdot R3(R7 + R8)} \right) \quad \text{Equation 17}$$

With the values shown in Figure 19, the circuit would trip out at around 100mA. This trip current value can be extended up to 2A by substituting transistor Q5 with the two transistor network as shown below in Figure 20. Also, this simplified circuit (when compared with an op-amp implementation instead of the ZXCT COCM) can be further much simplified when implemented using one of Zetex' later addition to the range, the ZXCT1030 (see "ZXCT1030 application" below).

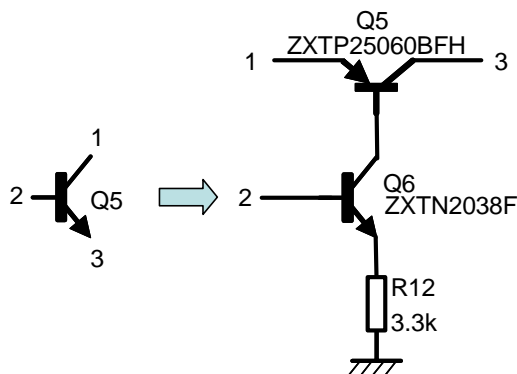


Figure 20 Replace Q5 in Figure 19 above with this network to extend the trip current range up to 2A

5.8 ZXCT1030 application

The ZXCT1030, with its integrated bandgap reference and comparator, expands the functionality of the Zetex current monitors range. It is essentially a VOVM with a fixed gain of 10 and housed in an SO8 package. It is also classed as a special function current monitor (SFCM) because of the additional in-built features.

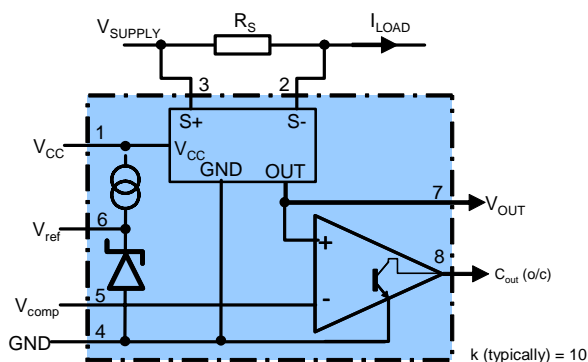


Figure 21 The ZXCT1030 VOVM with comparator and bandgap reference

The ZXCT1030 has all of the basic functions of a VOVM and can be used to implement the latching current monitor of Figure 19.

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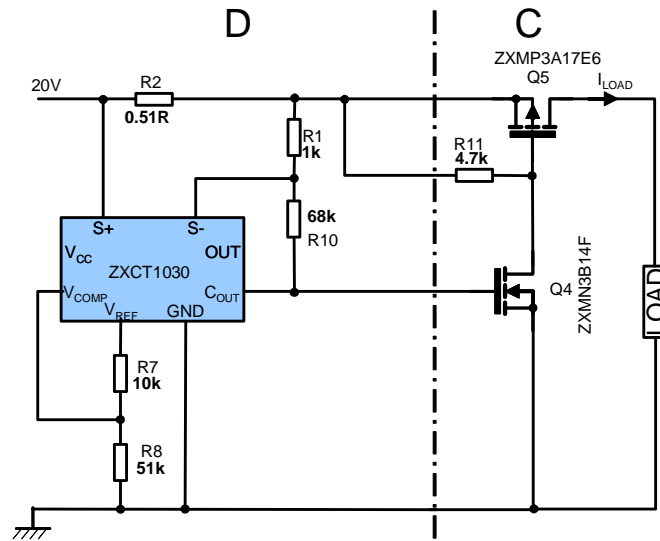


Figure 22 A much reduced version of Figure 19 using the ZXCT1030

It can be seen from above that the entire A and B section in Figure 19 (13 components) has been replaced by just section D in Figure 22 (5 components).

The transfer function, i.e. the trip current, of this simplified circuit can be shown to be

$$I_{trip} = \frac{1.24 \cdot R8}{10 \cdot R2(R7 + R8)} \quad \text{Equation 18}$$

Both Figure 23 and Figure 24 show the ZXCT1030 being used in motor drive applications.

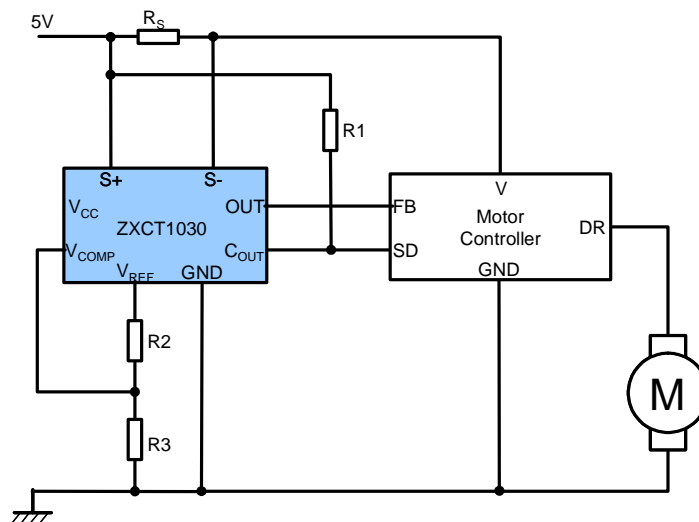


Figure 23 ZXCT1030 in a motor control application

In Figure 23 the ZXCT1030 monitors the motor current and feeds it output into a generic dedicated motor controller which is able to modulate the motor based on the current information received from the ZXCT1030. The comparator's output in this circuit is used to determine the maximum current at which to send a shut-down signal to the SD (shut down) input of the controller.

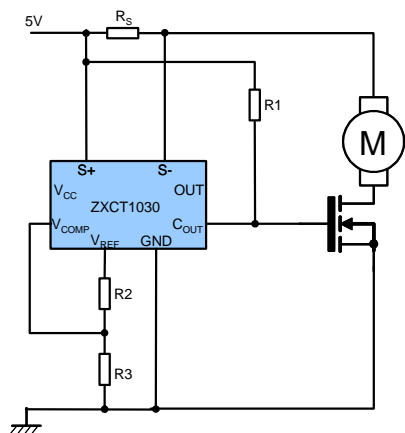


Figure 24 Motor current limit

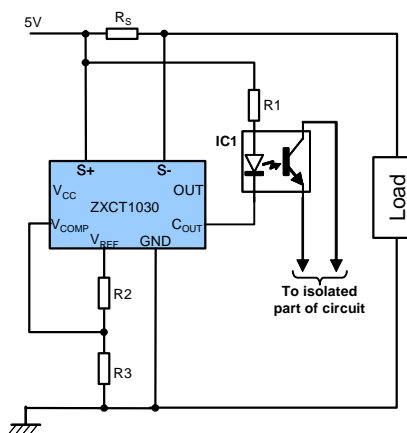


Figure 25 Driving optocoupler for isolated application

Figure 24 is a bit simpler and relies entirely on the ZXCT1030 and an external MOSFET to control the motor. The motor is simply powered on by the device. If the motor current, due to loading, ever rises to the reference level set by R2 and R3, it shuts down the MOSFET which then removes power from the motor. When the overload is removed, the motor automatically restarts.

5.9 Short circuit detection and continued operation (ZXCT1050, 1051)

Most Zetex current monitors are line powered. The ZXCT1050 and ZXCT1051 have a separate supply rail (VCC) enabling them to continue operating even if the rail being sensed is shorted to ground. Both devices have a common mode range that includes ground which means they can be used for either low or high side current monitoring.

The ZXCT1050 is a COCM with an external transconductance setting resistor (offering greater versatility) whilst the ZXCT1051 is a VOCM with a fixed gain of 10 (offering economy of component count and board space).

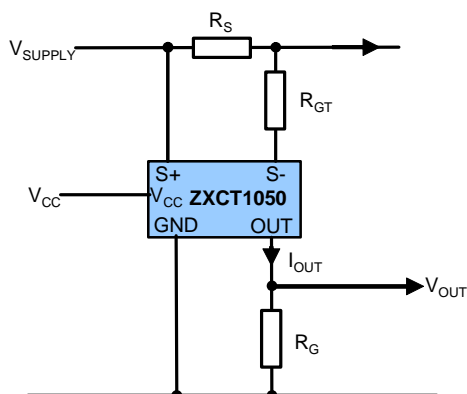


Figure 26 Basic ZXCT1050 configuration

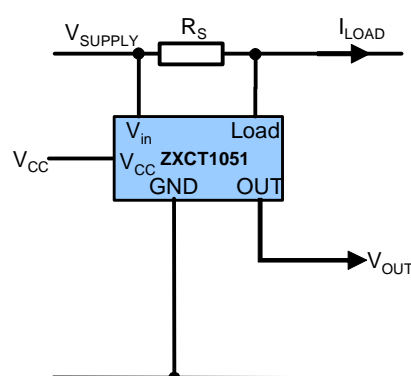


Figure 27 Basic ZXCT1051 configuration

$$V_{OUT} = R_G \cdot G_T \cdot R_S \cdot I_{LOAD}$$

Equation 19

where $GT = 20/RGT$.

$$V_{OUT} = 10 \cdot R_S \cdot I_{LOAD}$$

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Although R_{GT} can be freely chosen, it is recommended that its value be kept at 7.5k or similar since the internal design of the ZXCT1050 has been optimised for this value. Any other value may impact on linearity and accuracy.

V_{SUPPLY} which is effectively the common mode input voltage can vary between 0 and $V_{CC}-2V$. A very useful circuit to extend this common mode input range to V_{CC} and beyond is given in Figure 28 below.

5.9.1 Extending the common mode input range of the ZXCT1050 beyond V_{CC} - using a higher voltage than V_{MAX}

In some situations, it may be advantageous to operate the ZXCT1050 with a supply range in excess of V_{CC} . Happily this is something that can be easily realised with just three additional resistors as shown in Figure 28 below.

A resistor, R_3 , is connected from the S- pin to ground so as to form a potential divider with the transconductance resistor, R_{GT} . The S+ pin is similarly connected to another potential divider formed by R_1 , R_2 . It must be strictly ensured that the ratios (not necessarily absolute values) of the two potential dividers are exact. In other words, R_1/R_2 must be equal to R_{GT}/R_3 . Failure to observe this rule will result in massive common mode error that would render the scheme practically useless. In addition, the resistors themselves need to be very closely matched to better than 1%. In a practical implementation of this circuit (Figure 29), 0.1% tolerance resistors were used and the performance shown in Figure 30 was obtained. It will be noticed that there is virtually no common mode error in this example.

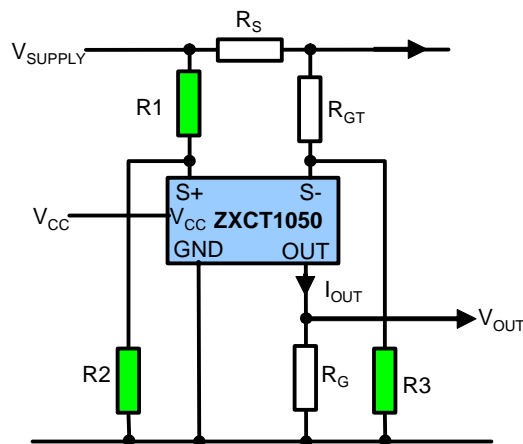


Figure 28 Extending the CM range of the ZXCT1050

Extending CM range for ZXCT1050

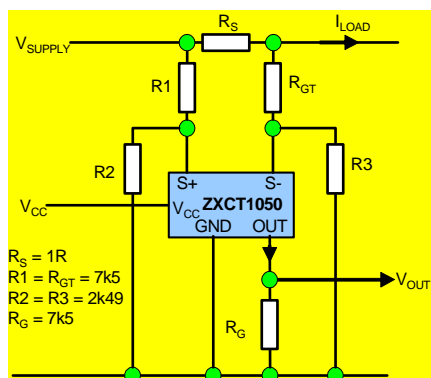


Figure 29 Test circuit

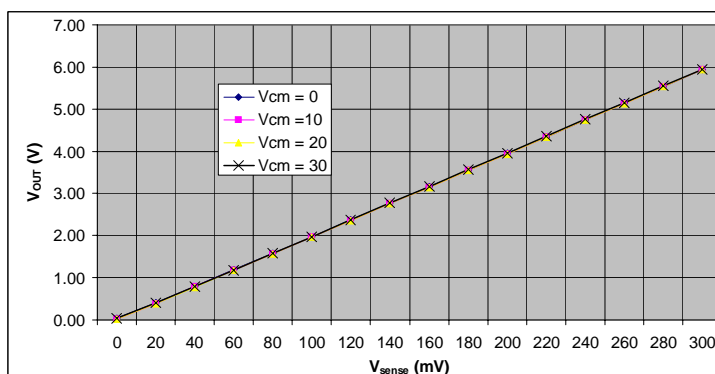


Figure 30 Output response

With the values shown, it can be seen that the circuit has a gain of 20.

An analysis of Figure 28 will readily show that the transfer function of the ZXCT is not affected by the addition of R1, R2 and R3 and remains that given by Equation 19 in Figure 26.

It will be noticed from Figure 30 above that there is virtually no common mode error in this circuit for a CM input ranging from zero to 30V

5.9.2 Cost of precision resistors

Although readily available, precision resistors cost a lot more than standard tolerance ones. That fact may make this proposed solution less desirable for some low-volume low-cost applications. However there is a way round the problem. Remember that what is important is the relative ratios of the two potential dividers and not their absolute values.

Hence, one resistor could be replaced by a trimmable resistor to balance both legs. This way, less than precise values could be used to start with as shown in Figure 31. Here, R2 has been replaced by the combination of a fixed and a variable resistor¹. Now, the resistors do not have to be low tolerance ones and standard 1% or even 2% resistors can be used. What is more important is stability. So, in any case, always make sure that high stability resistors are used. Metal film resistors are generally very good in this regard.

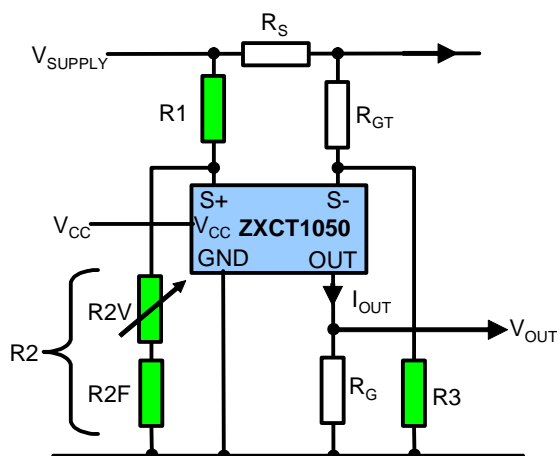


Figure 31 Using non-precision resistors to extend CM range

¹Note that it is not recommended to make all of R2 variable as this would result in very low resolution, increased potential for long term drift and make the circuit more susceptible to thermal and mechanical shock effects.

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It needs to be kept in mind that there is a very small error associated with the scheme in Figure 31 (and Figure 28) due to the small quiescent current that now flows in R_{GT} and R_3 . This error is quantified by the following expression.

$$I_{Error} = \left(\frac{V_{SUPPLY}}{R_{GT} + R_2 + R_S} \right) \cdot \frac{R_S}{R_{GT}} \quad \text{Equation 20}$$

In most cases, this error current will be quite small and negligible but it should be verified that this is so in all cases.

Procedure 3 - Design steps for extending CM range Figure 28 and Figure 31

1. Determine the maximum required supply voltage, $V_{S(max)}$.
2. Calculate R_3 from

$$R_3 = \frac{R_{GT}}{\left(\frac{V_{S(max)}}{V_{CC} - 2} \right) - 1}$$

3. Make R_3 the nearest lower preferred value. E.g. if the result of 2 above were 69.35k, choose 68k as the nearest lower preferred value.
4. Next, determine R_1 and R_2 from $\frac{R_1}{R_2} = \frac{R_{GT}}{R_3}$.

The easiest thing to do is to simply make $R_1=R_{GT}$ and $R_2=R_3$ but you may also make $R_1=nR_{GT}$ and $R_2=nR_3$ where n is any number preferably not less than 1. The advantage of making n greater than 1 is that the current down the potential divider network formed by R_1, R_2 can be kept to a minimum. Be careful however not to make n too high as it then begins to introduce offset errors into the circuit. A value of n between 1 and 10 is quite reasonable.

This is all that is required as far as using high precision resistors is concerned (Figure 28). In order to use standard resistors however (Figure 31) the following steps are required as well.

5. Determine the tolerance, Tol, of resistors being used, e.g. 1%.
6. Calculate R_{2V} from $R_{2V} \geq \frac{8 \cdot Tol}{100} \cdot R_2$ and select the nearest higher preferred value.
7. Calculate R_{2F} from $R_{2F} \leq \left(1 - \frac{4 \cdot Tol}{100} \right) \cdot R_2$ and select the nearest lower preferred value.

Make sure that R_{2V} is a good quality variable resistor (e.g. cermet type). If the circuit is going to be subjected to a wide temperature range, it would also be advisable to make sure that the temperature coefficient of R_{2V} is comparable to that of the fixed resistors.

Worked example:

It is required to measure the current of a load which is powered from a maximum supply of 30V. Design the monitoring circuit around the ZXCT1050 using a VCC supply of 12V. Assume R_{GT} to be 7.5k.

Solution;

$$R3 = \frac{R_{GT}}{\left(\frac{V_{S(\max)}}{V_{CC} - 2}\right) - 1} = \frac{7.5}{\left(\frac{30}{12 - 2}\right) - 1} = 3.75k\Omega$$

Therefore,

$R3 = 3.6k$ - picking the lower nearest preferred value in the E24 series.

Hence,

$$\begin{aligned} R1 &= R_{GT} = 7.5k, \text{ and} \\ R2 &= R3 = 3.6k \end{aligned}$$

5.9.3 Using ZXCT1050 at high voltages

The technique discussed above provides a very convenient way to use the ZXCT1050 at a higher operating voltage than its normal V_{MAX} of 20V would allow.

An example to extend the operating voltage to 60V is shown in Figure 32 below. Note that the 12V V_{CC} is derived from V_{SUPPLY} which has a maximum value of 60V. At this voltage, the voltage on the S+ and S- pins is 10V which is 2V less than V_{CC} . Thus operational requirement will be met. Because V_{CC} is dependent on V_{SUPPLY} , this circuit's common mode range will not include ground. This can be changed by simply supplying V_{CC} from a different source.

There is no theoretical limit to how high V_{SUPPLY} (hence common mode input changes) can be as long as the resistor values are scaled accordingly. However the higher the common mode input voltage, the more accurate the resistors will have to be and, if the circuit in Figure 31 is used, the more difficult it will be to trim out common mode errors.

There is also the limit imposed by power dissipation requirement of the resistors especially the zener bias resistor which needs to drop most of the excess voltage and still supply the operating current of the current monitor.

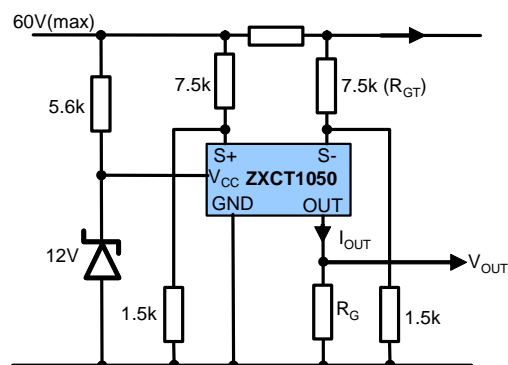


Figure 32 Using the ZXCT1050 at a higher voltage (alternative to using the schemes in Figure 12 and Figure 13)

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5.10 High speed and reverse transient considerations of ZXCT series

The ZXCT series have very good bandwidth and good high speed performance even though they are aimed primarily at low speed applications. For example, the bandwidth of the ZXCT1009 operating with a V_{SENSE} of 100mV is 2MHz.

However in cases where the current is bi-directional or where there is a lot of high frequency noise resulting in the device being exposed (even momentarily) to negative V_{SENSE} , the ZXCT device can be dramatically slowed down. This is because it ceases to operate in the linear part of its range and takes considerable time (several microseconds) to recover. This can sometimes result in a big part of the output being suppressed or even "disappearing" altogether. Therefore if quick response is required, it is recommended to ensure that the device is never exposed to a negative V_{SENSE} . The magnitude of reverse voltage to cause this need not be large at all (2mV or less) due to the very high internal gain stages in the device.

An example of where this can happen is where an inductive load is being driven and the load current is monitored on the high (or low) side as shown in Figure 35 later. During the dead-band between one pair of transistors switching off and the other switching on, the stored energy in the inductive load causes current to continue to flow. This current reverses direction in RS and is dumped into the power supply. Thus a negative sense voltage is developed across the inputs of the current monitor. Since this is real current that is flowing in the reverse direction, merely protecting the input of the current monitor will not have much effect except to slow down the device generally. This will also happen when current flows in the forward direction.

One solution that has been found to work fine is to bias the device so that it never sees a negative voltage across its input even when current flows in the reverse direction. Figure 36 to Figure 38 show the effects that negative V_{SENSE} has on the speed of a current monitor. In contrast to these Figure 40 shows what a dramatic improvement is obtained when biasing is applied to the S- pin as shown in Figure 39.

This method of applying a compensating offset will only work provided the negative current flow is consistent, which it usually is. In this case we only need to determine the current and from it decide the required bias voltage as follows:

$$V_{BIAS} = I_{REVERSE} \cdot R_S \quad \text{Equation 21} \\ \text{(Determining bias voltage)}$$

We need a reference voltage, V_{REF} , from which to obtain the required V_{bias} . With reference to Figure 39 for example, where V_{REF} is 1.24V (ZTLV341)¹, we can see that

$$V_{BIAS} = \frac{V_{REF} \cdot R1}{R1 + R2} \quad \text{Equation 22} \\ \text{(Obtaining bias voltage from } V_{REF}\text{)}$$

Combining Equation 21 and Equation 22 and transposing results in

$$\frac{R2}{R1} = \left(\frac{V_{REF}}{I_{REVERSE} \cdot R_S} \right) - 1 \quad \text{Equation 23} \\ \text{(Determining R1 and R2)}$$

Since all in the RHS are known quantities, we can fix R1 and calculate R2 or vice versa. The simplest thing to do is perhaps determine R1 as follows.

1. Determine bias current I_{REF} for the reference and compute R3 from $R3 = \frac{V_{SUPPLY} - V_{REF}}{I_{REF}}$.
2. Calculate R1 from $R1 = \frac{k \cdot V_{BIAS}}{I_{REF}}$ where k should be chosen between 2 and 10 to ensure that the bias current is only a fraction (1/k) of I_{REF} . The value of k you choose will be dependent on how stable V_{SUPPLY} is.
3. Finally calculate R2 from $R2 = R1 \left(\left(\frac{V_{REF}}{I_{REVERSE} \cdot R_S} \right) - 1 \right)$

In the final analysis, as in most designs, a one-time tweak of V_{BIAS} may be required for the design.

5.11 Reverse transient

If the reverse current is of a relatively short duration compared to the signal of interest, it can be considered to be a transient. In that case it may be possible instead to use an RC network to filter out this transient and thus prevent it from interacting with the current monitor's operation as shown in Figure 33 and Figure 34 below. This method could be used for any of the current monitors and these two examples demonstrate that specifically for the ZXCT1050 and generically for all others.

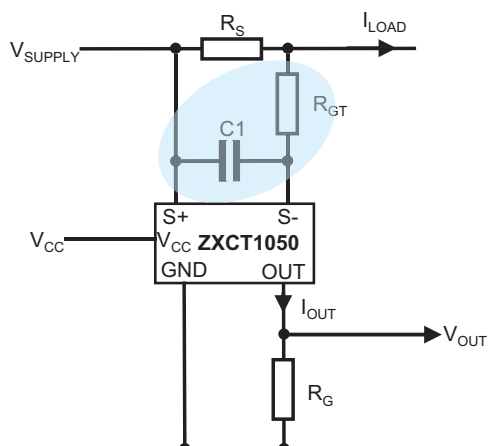


Figure 33 RC noise suppression for ZXCT1050

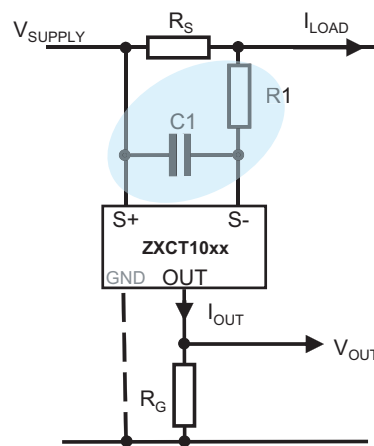


Figure 34 RC noise suppression for a generic current monitor

Notice in Figure 33 that the transconductance resistor is also used as the snubber resistor whilst in most other cases this would be an additional component.

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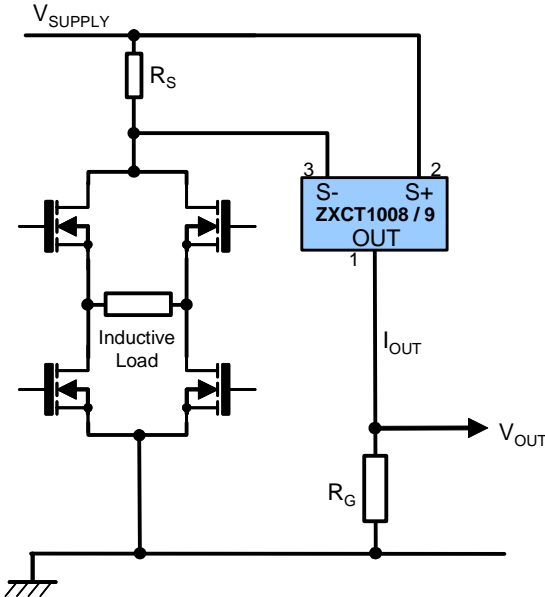


Figure 35 Example of reverse V_{SENSE} in a current monitor

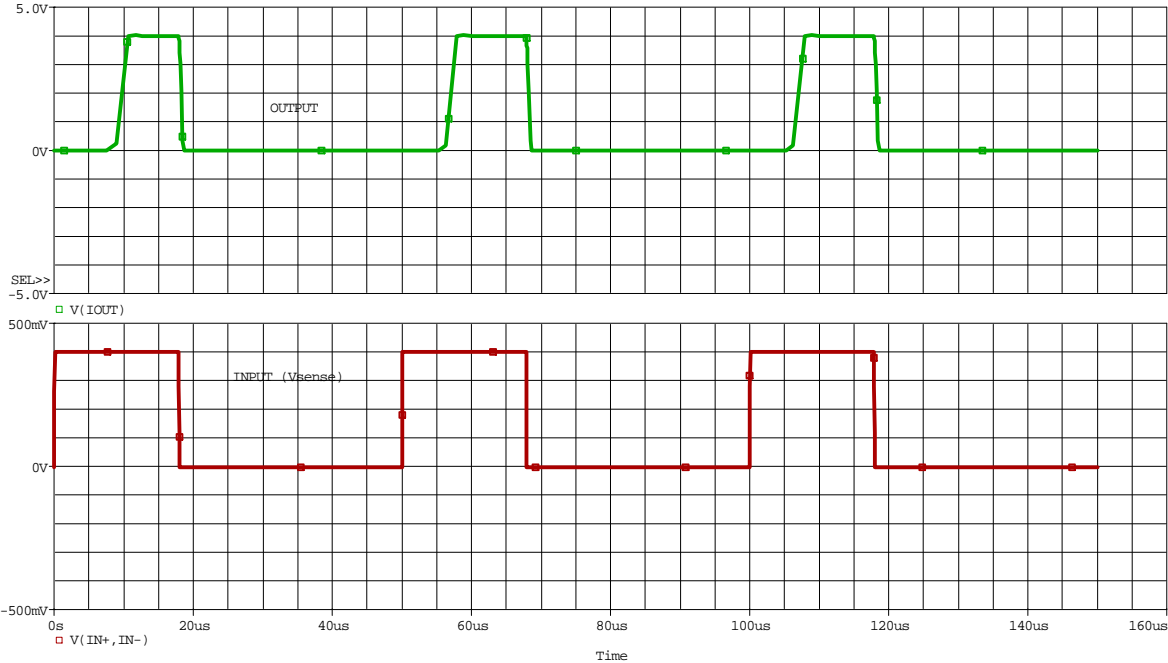


Figure 36 Response with only a 2.5mV of reverse sense voltage
 Bottom trace = V_{SENSE} ; Top trace = Output; freq = 20kHz

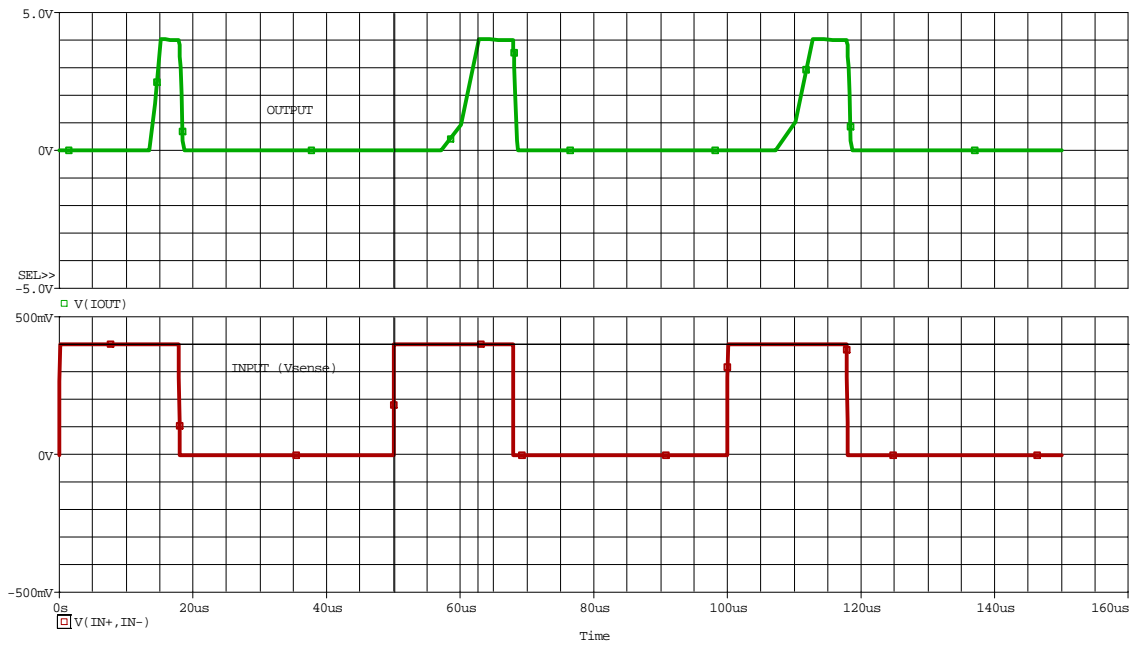


Figure 37 Response with a 5mV reverse sense voltage
 Bottom trace = V_{SENSE} ; Top trace = Output; freq = 20kHz

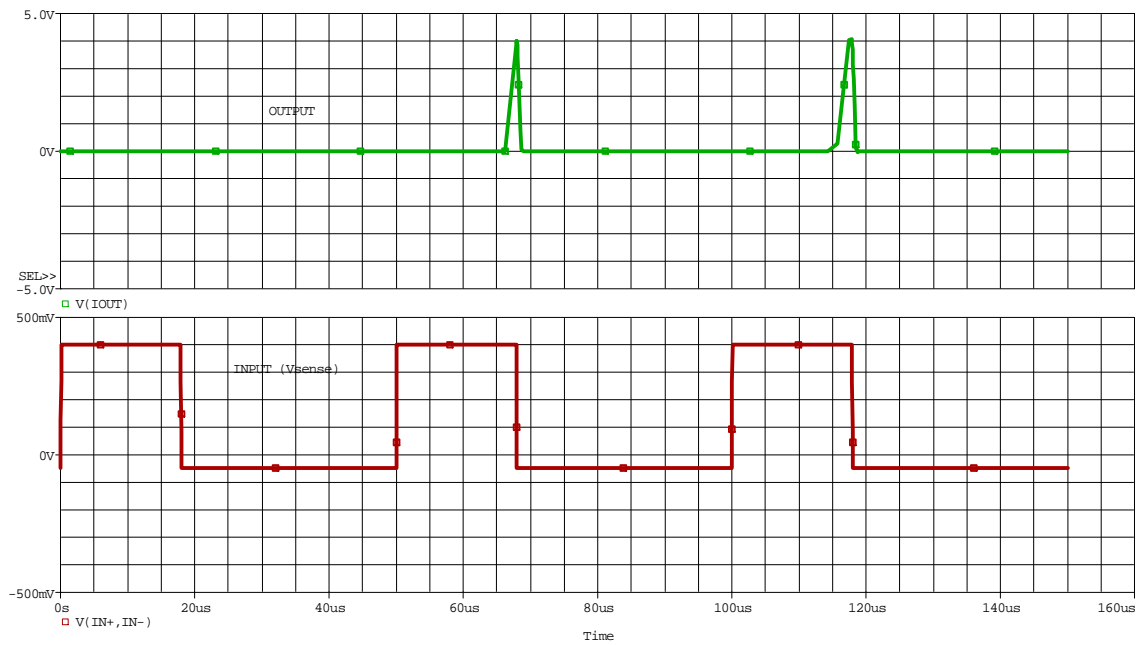


Figure 38 Response with a 50mV reverse sense voltage
 Bottom trace = V_{SENSE} ; Top trace = Output; freq = 20kHz

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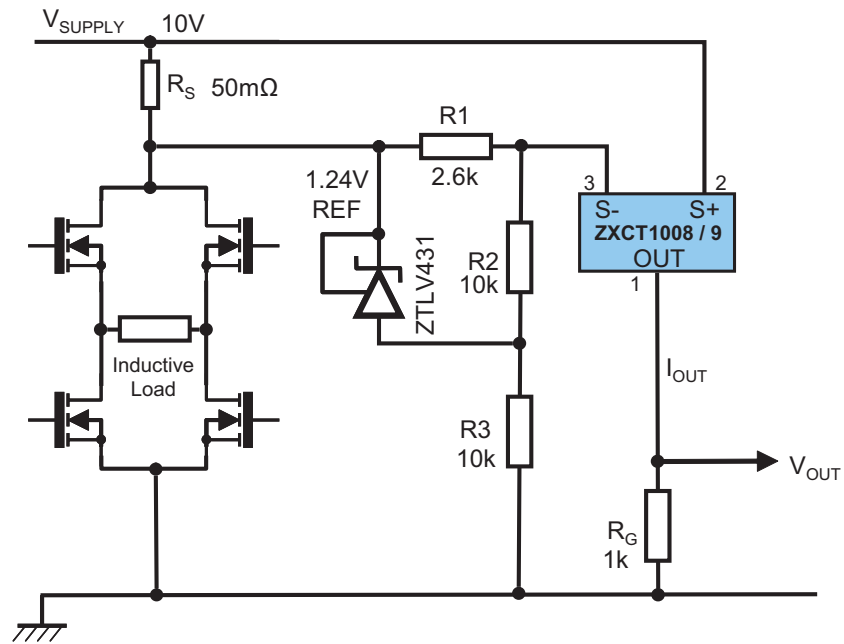


Figure 39 Bias applied to S- pin to prevent negative V_{SENSE}

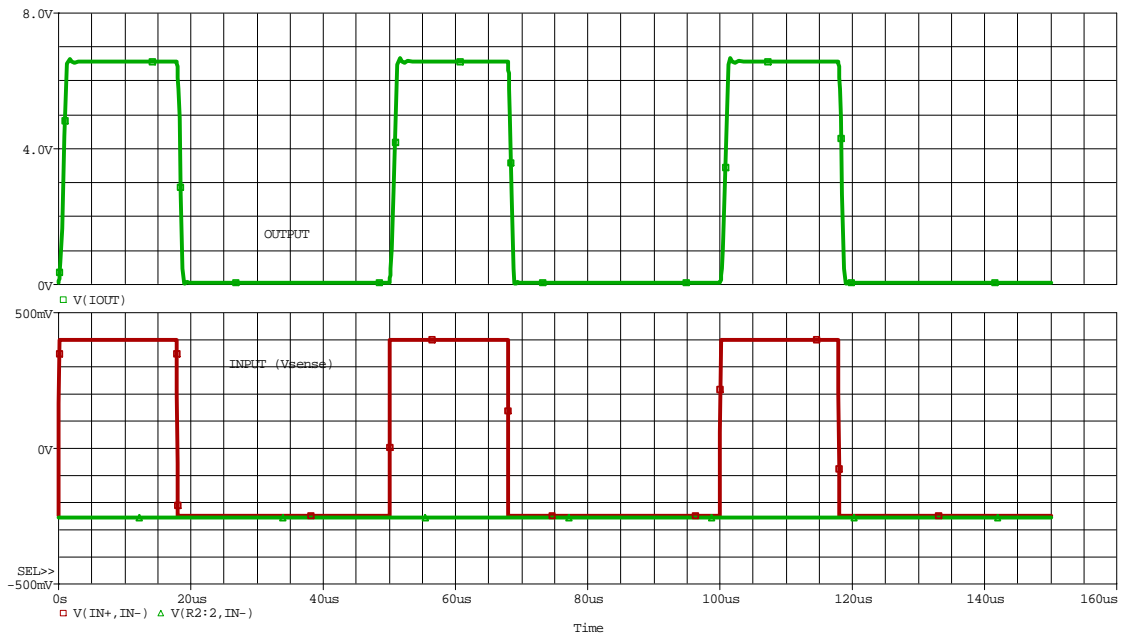


Figure 40 A much improved response by introducing an offset voltage onto the S- pin.

Bottom trace = V_{SENSE} ; Top trace = Output; freq = 20kHz

Notice the additional superimposed straight line trace on the bottom plot representing the offset voltage on pin S- with respect to S+.

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6 Appendix - Current monitor summary chart

Table 2 Current monitor summary/selection chart

Monitor	Output type		Sensing rail ¹		External Resistors	Special feature	Target application	Package	
	Current	Voltage gain ²		LS					HS
		x10	x100						
ZXCT1008	•				•	1	Simplest COCM ³ + Extended temperature range	General	SOT23
ZXCT1009	•				•	1	Simplest COCM	General	SOT23 or SM8
ZXCT1010	•				•	1	Ground pin ⁴	Battery discharge/ General	SOT23-5
ZXCT1011	•				•	2	Ground pin ⁴ + External transconductance resistor + Extended temperature range	General	SOT23-5
ZXCT1012	•				•	1	Ground pin ⁴	Battery discharge/ General	TSOT23-5 TDFN3-5
ZXCT1020	•				•	2	Ground pin ⁴ + External transconductance resistor + Extended temperature range	General	SOT23-5
ZXCT1021		•			•	0	Simplest VOVM ⁵	General	SOT23-5
ZXCT1022			•		•	0	Simplest VOVM	General	SOT23-5
ZXCT1030		•			•	0	High speed + Bandgap reference + OC Comparator	General	SO8
ZXCT1032					•	2	Series transistor drive + Programmable threshold + Output flag	In-rush or over-current protection	SO8

Monitor	Output type		Sensing rail ¹		External Resistors	Special feature	Target application	Package	
	Current	Voltage gain ²		LS					HS
		x10	x100						
ZXCT1041		•			•	0	Bidirectional + Output flag	General	SOT23-5
ZXCT1050	•			•	•	2	Separate V _{CC} pin + current gain (x20) + Short circuit operation	General	SOT23-5
ZXCT1051		•		•	•	0	Separate V _{CC} pin + Extended temperature + Short circuit operation	General	SOT23-5
ZXCT1080		•				0	Separate V _{CC} pin + 60V CM + Extended temperature	Automotive	SOT23-5
ZXCT1081		•			•	0	Separate V _{CC} pin + 40V CM + Extended temperature		SOT23-5

NOTES;

¹ LS = Low Side Sensing, HS = High Side Sensing.

² Output/V_{SENSE}.

³ Current Output Current Monitor.

⁴ Eliminates quiescent current error.

⁵ Voltage Output Current Monitor

7 Recommended further reading

1. AN45 - High voltage current monitoring using the ZXCT series in power supplies
2. DN77 - Transient and noise protection for current monitors

8 Glossary of terms

COCM	Current-Output Current Monitor
SFCM	Special Function Current Monitor
VOCM	Voltage-Output Current Monitor
RHS	Right Hand Side

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