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Motor Control Sensor Feedback Circuits

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INTRODUCTION

Sensors are a critical component in a motor control system. They are used to sense the current, position, speed and direction of the rotating motor. Recent advancements in sensor technology have improved the accuracy and reliability of sensors, while reducing the cost. Many sensors are now available that integrate the sensor and signal-conditioning circuitry into a single package.

In most motor control systems, several sensors are used to provide feedback information on the motor. These sensors are used in the control loop and to improve the reliability by detecting fault conditions that may damage the motor. As an example, Figure 1 provides a block diagram of a DC motor control system to show the sensor feedback provided for a typical motor control.

A list of the sensors that can be used to feedback information to a microcontroller are listed below:

- Current sensors
  - Shunt resistor
  - Current-sensing transformer
  - Hall effect current sensor
- Speed/position sensors
  - Quadrature encoder
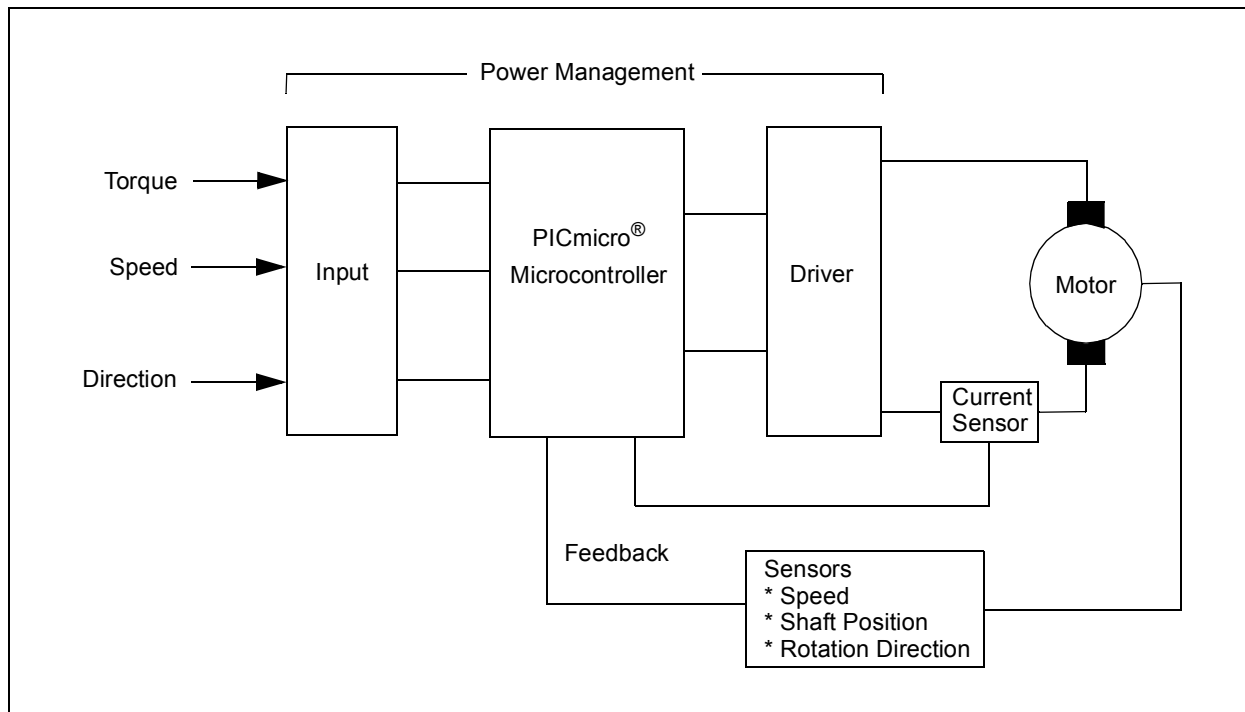 - Hall efect tachometer
- Back EMF/Sensorless control method

FIGURE 1: *Typical DC Motor Block Diagram.*

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CURRENT SENSORS

The three most popular current sensors in motor control applications are:

- Shunt resistors
- Hall effect sensors
- Current transformers

Shunt resistors are popular current sensors because they provide an accurate measurement at a low cost. Hall effect current sensors are widely used because they provide a non-intrusive measurement and are available in a small IC package that combines the sensor and signal-conditioning circuit. Current-sensing transformers are also a popular sensor technology, especially in high-current or AC line-monitoring applications. A summary of the advantages and disadvantages of each of the current sensors is provided in Table 1.

Figure 2 shows an example of an AC motor powered by a three-phase inverter bridge circuit. This example shows that the composite current of all three Insulated Gate Bipolar Transistor (IGBT) circuit legs can be measured with a single shunt resistor, or that the current in each individual leg can be determined with three shunt resistors. Figure 2 shows a system that uses shunt resistors. However, Hall effect and current-sensing transformers can also be used to provide the current measurement.

TABLE 1: COMPARISON OF CURRENT SENSING METHODS

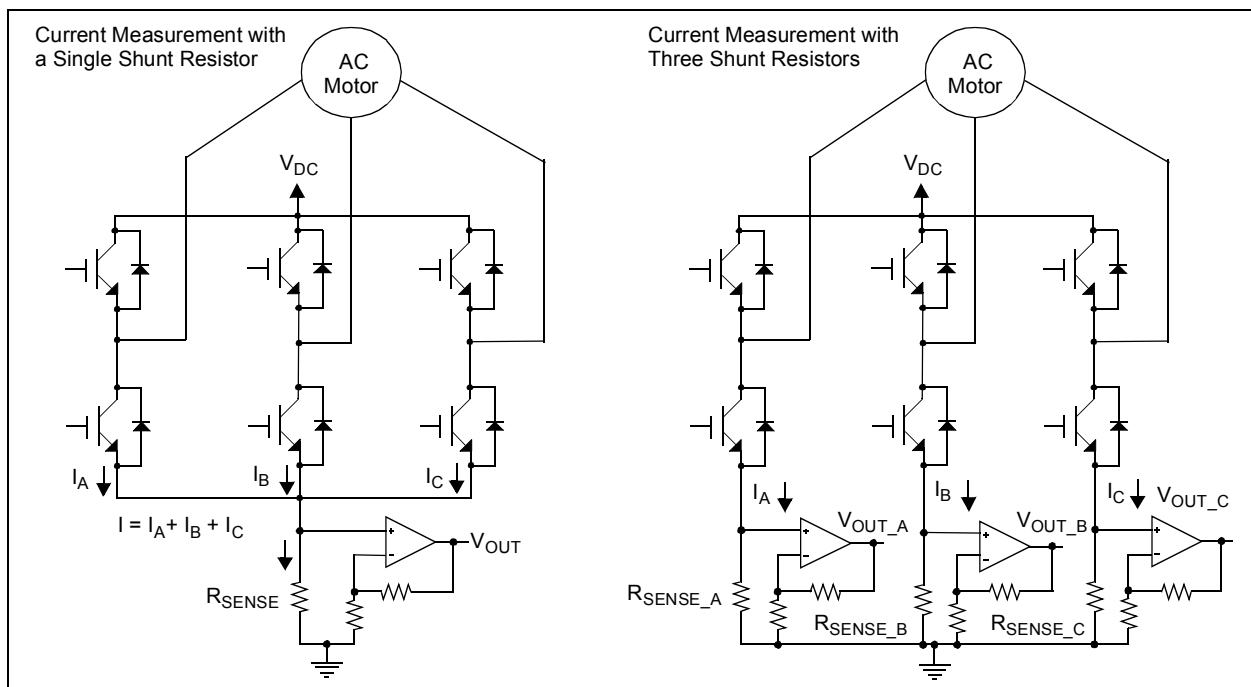| Current Sensing Method	Shunt Resistor	Hall Effect	Current Sensing Transformer
Accuracy	Good	Good	Medium
Accuracy vs.Temperature	Good	Poor	Good
Cost	Low	High	Medium
Isolation	No	Yes	Yes
High Current-Measuring Capability	Poor	Good	Good
DC Offset Problem	Yes	No	No
Saturation/Hysteresis Problem	No	Yes	Yes
Power Consumption	High	Low	Low
Intrusive Measurement	Yes	No	No
AC/DC Measurements	Both	Both	Only AC

FIGURE 2:   *AC Motor Current Measurement.*

Shunt Resistors

Shunt resistors are a popular current-sensing sensor because of their low cost and good accuracy. The voltage drop across a known low value resistor is monitored in order to determine the current flowing through the load. If the resistor is small in magnitude, the voltage drop will be small and the measurement will not have a major effect on the motor circuit. The power dissipation of the resistance makes current shunts impractical for measurements of more than approximately 20 amperes.

The selection criteria of a shunt current resistor requires the evaluation of several trade-offs, including:

• Increasing R_{SENSE} increases the V_{SENSE} voltage, which makes the voltage offset (V_{OS}) and input bias current offset (I_{OS}) amplifier errors less significant.

• A large R_{SENSE} value causes a voltage loss and a reduction in the power efficiency due to the I^2 x R loss of the resistor.

• A large R_{SENSE} value will cause a voltage offset to the load in a low-side measurement that may impact the EMI characteristics and noise sensitivity of the system.

• Special-purpose, low inductance resistors are required if the current has a high-frequency content.

• The power rating of R_{SENSE} must be evaluated because the I^2 x R power dissipation can produce self heating and a change in the nominal resistance of the shunt.

Special-purpose, shunt current measurement resistors are available from a number of vendors. If standard resistors are used, it is recommended that metal-film resistors be used rather than wire-wound resistors that have a relatively large inductance.

A shunt resistor can also be created from the trace resistance on a PCB, as shown in Figure 3. PCB shunt resistors offer a low cost alternative to discrete resistors. However, their accuracy over a wide temperature range is poor when compared to a discrete resistor. The temperature coefficient of a copper PCB trace shunt resistor is equal to approximately +0.39%/°C. Further details on PCB trace resistors are given in reference (2).

Trace resistance is based on:
* Length (L)
* Thickness (t)
* Width (w)
* Resistivity (ρ)

* 1 oz. Copper (Cu) is defined to be a layer with 1 oz. of Cu per square foot.

$t \approx 1.37$ mil./oz. Copper
$\rho \approx 0.68$ µΩ-inch

$R_{\square} \approx (0.50$ mΩ / $\square$) x [(1 oz. Cu) / (# oz. Cu)]

Example: What is the resistance of the PCB shunt resistor using the parameters listed below?
Given: 1 oz Cu PCB
      w = 50 mils (0.050 in)
      L = 1 inch
      I = 5 ampere
L / w = number of squares ($\square$)
      = 1 in / 0.050 in
      = 20 squares
$R \approx (L / w)$ x $R_{\square}$
  $\approx$ (20 squares) x 0.50 mΩ/$\square$
  $\approx$ 10 mΩ
$P = I^2$ x R
  = $(5A)^2$ x (0.010Ω)
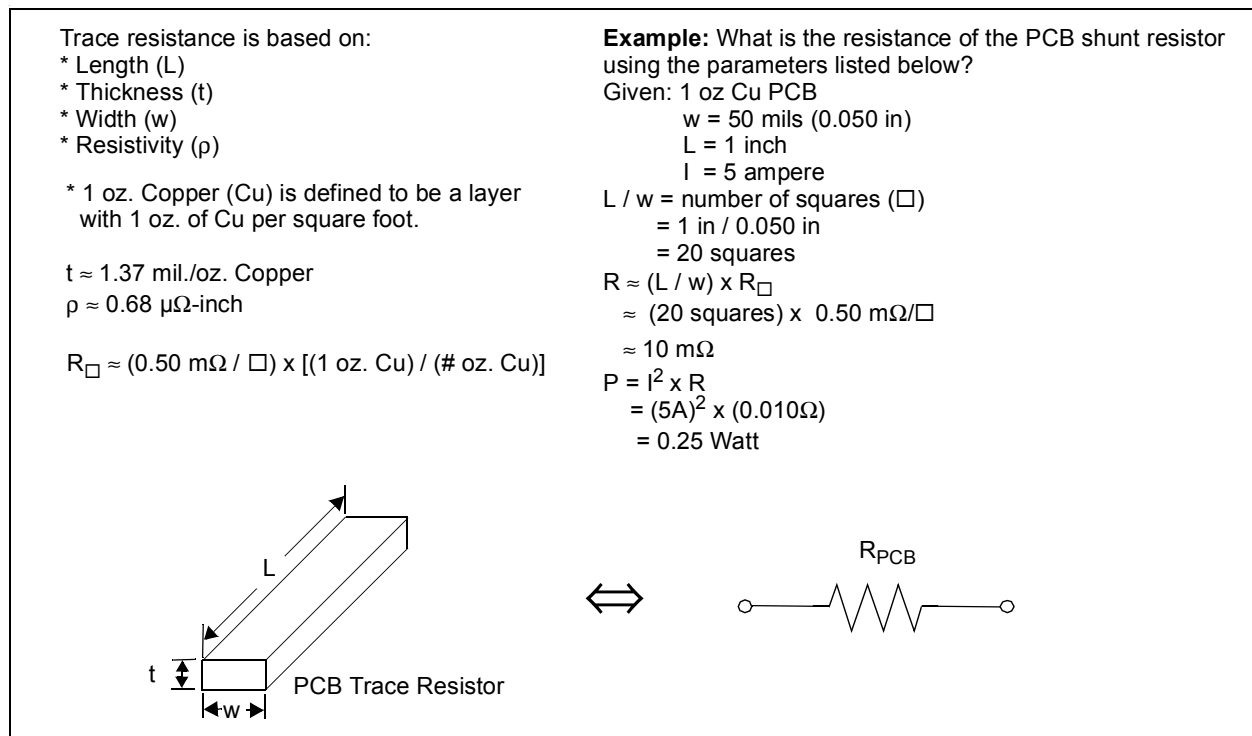 = 0.25 Watt

FIGURE 3: *PCB Shunt Resistor.*

High-Side vs. Low-Side Current Shunt Measurements

SYSTEM INTEGRATION ISSUES

Shunt resistors can provide either a high-side or low-side measurement of the current through the load, as shown in Figure 4. A high-side monitor has the resistor connected in series with the power source, while the low-side monitor locates the resistor between the load and the ground current return path. Both approaches pose a trade-off to the designer. The attributes of the two methods, along with the typical monitor circuits, will be shown in the following sections. Reference (3) provides more details on high-side and low-side shunts.

High-side current measurements are the preferred method from a system-integration standpoint because they are less intrusive than low-side measurements. The trade-off with the high-side measurement is that the circuitry is more complex than the low-side method.

High-side resistive shunt measurements will not have a significant impact on the system if the sensing resistor is small and the resulting voltage drop across the shunt is small compared to the supply voltage. In contrast, low-side monitoring disrupts the ground path of the load, which can cause noise and EMI problems in the system.

Low-side current measurements are often chosen because low voltage op amps can be used to sense the voltage across the shunt resistor. Note that low-side monitoring is not possible in some applications because the ground connection is made via the mechanical mounting of the motor on the chassis or metal frame. For systems powered via a single wire connection, it may not be practical to insert a shunt resistor between the device and the chassis that functions as the ground wire.
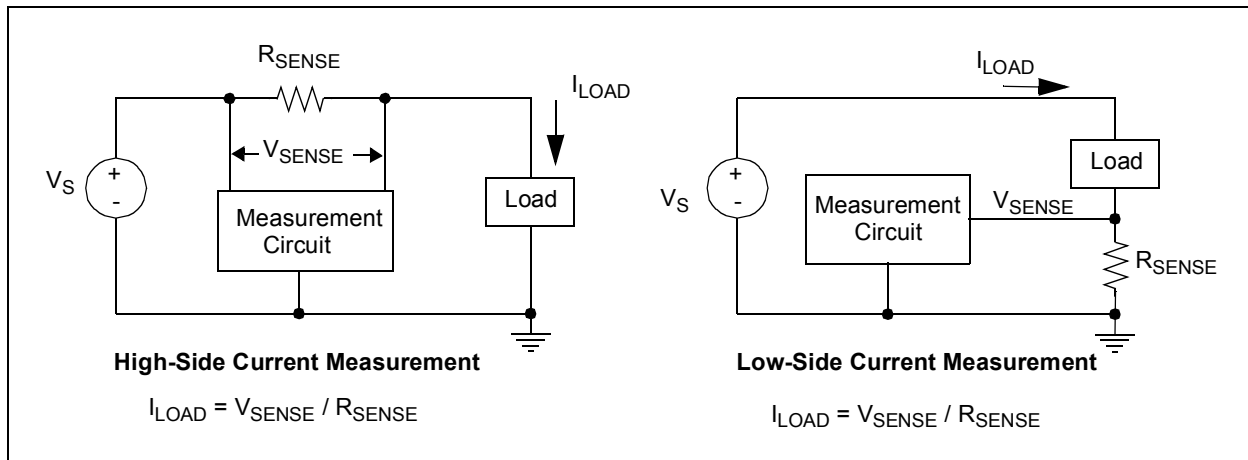

High-Side Current Measurement

$I_{LOAD} = V_{SENSE} / R_{SENSE}$

Low-Side Current Measurement

$I_{LOAD} = V_{SENSE} / R_{SENSE}$

FIGURE 4: *High-Side and Low-Side Resistive Current Shunts.*

HIGH-SIDE CURRENT SHUNT MEASUREMENTS

High-side current measurements can be implemented with a differential amplifier circuit that produces an output voltage that is proportional to V_{SENSE} or the current flowing through the load. Figure 5 provides an example of a high-side shunt circuit. The differential amplifier circuit can be implemented with an op amp and discrete resistors or with an integrated IC device. Integrated differential amplifier ICs are available from a number of semiconductor vendors and offer a convenient solution because the amplifier and well-matched resistors are combined in a single device.

The attributes of high-side monitoring are listed below:

Advantages:

• Less intrusive than low-side monitors and will not affect the EMI characteristics of the system.

• Can detect overcurrent faults that can occur by short circuits or inadvertent ground paths that can increase the load current to a dangerous level.

• A differential amplifier circuit will filter undesirable noise via the common-mode-rejection-ratio (CMRR) of the amplifier.

• A resistive network can be used to reduce the voltage at the amplifier's input terminals. For example, if $R_{IN} = R^*$, the input voltage will be reduced in half and the amplifier will be biased at $V_S/2$. Note that the amplifier gain will be equal to one and that a second amplifier may be needed to increase the sensor's output voltage.

Disadvantages:

• The V_{SENSE} voltage is approximately equal to the supply voltage, which may be beyond the maximum input voltage range of the operational amplifier.

• A differential amplifier's CMRR will be degraded by mismatches in the amplifier resistors.

• The input impedance of the differential circuit is relatively low and is asymmetrical. The input impedance at the amplifier's non-inverting input is equal to $R_{IN} + R^*$, while the impedance at the inverting terminal is equal to R_{IN}.

• May require rail-to-rail-input op amps because of the high voltage level of the input signal.

The high-side shunt circuit requires a high-voltage amplifier that can withstand a high common mode voltage. In addition, the key amplifier specifications are a high CMRR and a low V_{OS} because of the relatively small magnitude of V_{SENSE}. High voltage op amps and integrated differential amplifier ICs are available for systems that have a maximum voltage of approximately 60V. For voltage requirements beyond 60V, a current mirror circuit can be used to sense the current. A current mirror can be implemented with readily available, high-voltage transistors. References (1) and (5) provide examples of high-voltage, high-side current monitor circuits.

Table 2 provides a list of the recommended Microchip op amps that can be used in a high-side circuit.
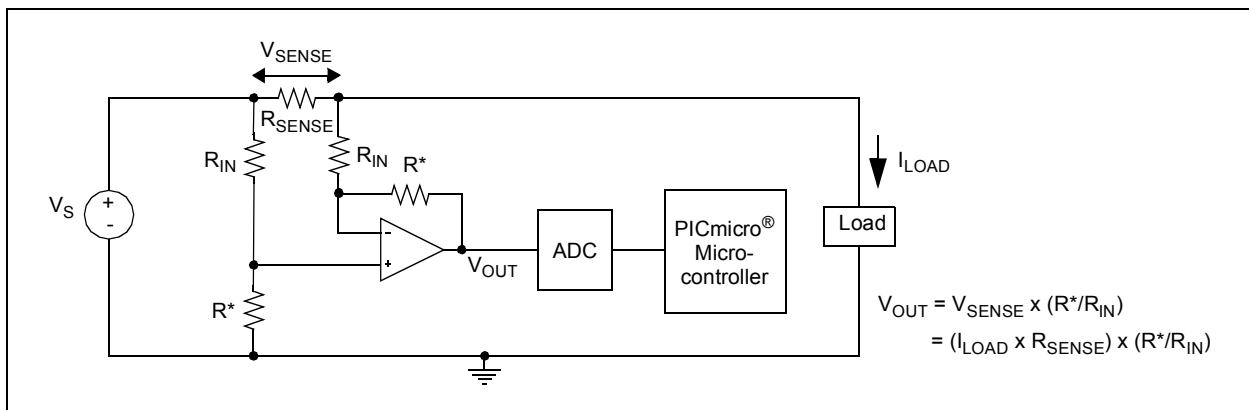

FIGURE 5: *High-Side Resistive Current Measurement Circuit.*

$$V_{OUT} = V_{SENSE} \times (R^*/R_{IN})$$
$$= (I_{LOAD} \times R_{SENSE}) \times (R^*/R_{IN})$$

TABLE 2: RECOMMENDED MICROCHIP OP AMPS FOR HIGH-SIDE CURRENT SHUNTS

Product	Operating Voltage	CMRR (Typ.)	V_{OS} (Max.)	Features
TC7652	6.5 to 16V	140 dB	10 µV	• Low Noise • Chopper Stabilized
TC913A	6.5 to 16V	116 dB	15 µV	• Auto-zeroed Op Amp
TC913B	6.5 to 16V	110 dB	30 µV	• Auto-zeroed Op Amp

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LOW-SIDE CURRENT MEASUREMENT

Low-side current measurements offer the advantage that the circuitry can be implemented with a low voltage op amp because the measurement is referenced to ground. The low-side measurement circuit can use a non-inverting amplifier, as shown in Figure 6.

The low-side current monitor can also be implemented with a differential amplifier. The advantages of differential amplification are limited because R_{SENSE} is connected to ground and the common mode voltage is very small. Note that integrated IC low-side monitors that combine the op amp and resistors are not readily available because of the simplicity of the circuit that can be implemented with a few discrete resistors and low voltage op amp.

The attributes of low-side monitoring are:

Advantages

• V_{SENSE} is referenced to ground. Therefore, a low voltage amplifier can be used.

• A non-inverting amplifier can be used and the input impedance of the circuit will be equal to the large input impedance of the amplifier.

Disadvantages

• The low-side resistor disrupts the ground path and the added resistance to the grounding system produces an offset voltage which can cause EMI noise problems.

• Low-side current monitors are unable to detect a fault where the load is accidently connected to ground via an alternative ground path.

Table 3 provides a list of the recommended Microchip op amps that can be used in a low-side circuit. The key op amp specifications for selecting a low-side amplifier are rail-to-rail input and a low offset voltage (V_{OS}).
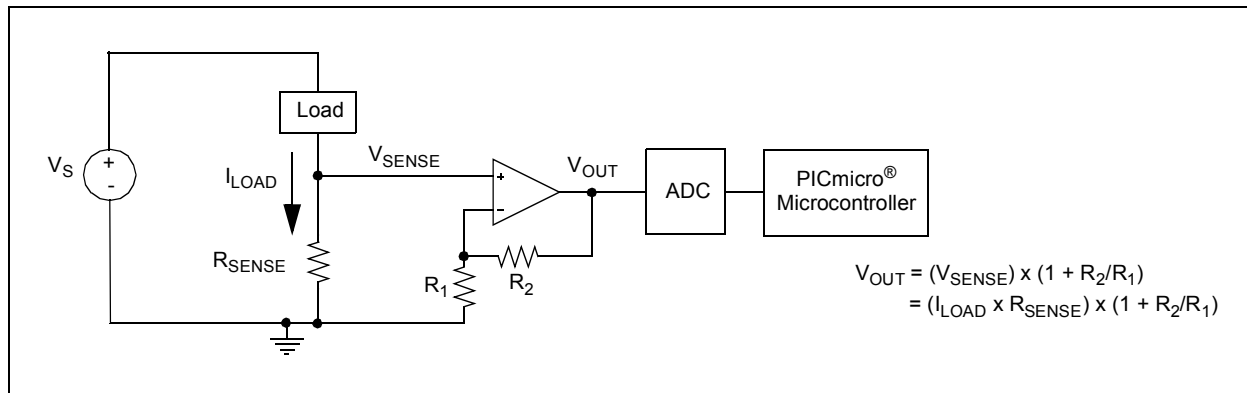

$$V_{OUT} = (V_{SENSE}) \times (1 + R_2/R_1)$$
$$= (I_{LOAD} \times R_{SENSE}) \times (1 + R_2/R_1)$$

FIGURE 6: *Low-Side Resistive Current Measurement Circuit.*

TABLE 3: **RECOMMENDED MICROCHIP OP AMPS FOR LOW-SIDE CURRENT SHUNTS**

Product	Operating Voltage	CMRR (Typ.)	V_{OS} (Max.)	Features
TC913A	6.5 to 16V	116 dB	15 µV	• Auto-zeroed Op Amp
TC913B	6.5 to 16V	110 dB	30 µV	• Auto-zeroed Op Amp
MCP606	2.5 to 5.5V	91 dB	250 µV	• Rail-to-Rail Output • Low Operating Current
MCP616	2.3 to 5.5V	100 dB	150 µV	• Rail-to-Rail Output • Low Operating Current

SHUNT OFFSET ADJUSTMENT CIRCUIT

The circuit shown in Figure 7 can be used to provide an offset to the amplification of the V_{SENSE} signal. Resistor R_1 is used to prevent the offset voltage provided by resistors R_4 and R_5 from changing the value of V_{SENSE}. The offset can be used to center the amplifier's output to the midpoint of the voltage supply ($V_{DD}/2$). The V_{SENSE} signal is typically only 10 to 100 mV above ground and the offset often is needed if the amplifier is connected to an ADC.
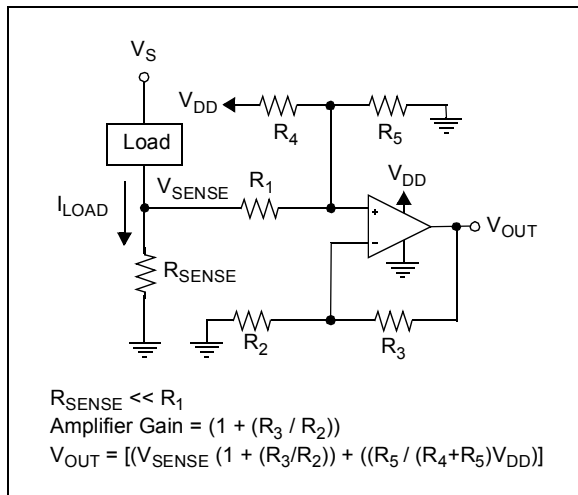

$R_{SENSE} \ll R_1$
Amplifier Gain = $(1 + (R_3 / R_2))$
$V_{OUT} = [(V_{SENSE} (1 + (R_3/R_2)) + ((R_5 / (R_4+R_5))V_{DD})]$

FIGURE 7: *Shunt Offset Adjustment Circuit.*

Providing an offset to the shunt resistor circuit can also improve the linearity of the amplification, especially if standard op amps are used. The linearity, accuracy and power consumption of a standard single power supply op amp is typically degraded when the output signal is at, or near, the power supply rails. Thus, the offset circuit can be used to avoid this problem. The preferred op amps to use in a shunt circuit have a small offset voltage (V_{OS}) and a rail-to-rail, input-output specification.

NOISE REDUCTION TECHNIQUES

The combination of a differential amplifier with a high CMRR and discrete RC filters can be used to minimize the effect of EMI noise. The effect of EMI on a measurement typically results in poor DC performance and a large DC offset at the output of the op amp. Figure 8 provides an example of a circuit that can be used in a motor application to reduce noise.

The addition of the common mode filters formed by the RC combinations of R_1C_1 and R_2C_2 are used to reduce the noise that is imposed on the two input lines of the amplifier. Discrete RC networks lower the voltage level of the noise signal by functioning as a low pass filter. However, an EMI filter, such as a TVS zener diode, is required to ensure that the input noise is clamped to a safe voltage level that will not damage the amplifier.

The common mode resistors and capacitors should be matched as close as possible. The resistors should have a tolerance of 1% or better, while the capacitors should have a tolerance of 5% or better. Capacitor C_3 is used to add a RC differential filter that compensates for any mismatch of R_1C_1 and R_2C_2. Any difference in the RC combinations will result in a degradation of the amplifier's CMRR. The differential filter formed by R_1C_3 and R_2C_3 will attenuate the differential signal at the amplifier caused by the tolerances of the common mode filters.

$R_{SENSE} \ll R_1$ and R_2
$R_1 = R_2$
$C_1 = C_2$
$C_3 \gg C_1$ and $C_3 \gg C_2$

Common Mode Filter
$f_{-3dB} = 1 / (2\pi R_1 C_1)$
$\quad\quad = 1 / (2\pi R_2 C_2)$

Differential Mode Filter
$f_{-3dB} = 1/ [2\pi (R_1+R_2) (((C_1 \times C_2)/(C_1+C_2)) + C_3)]$
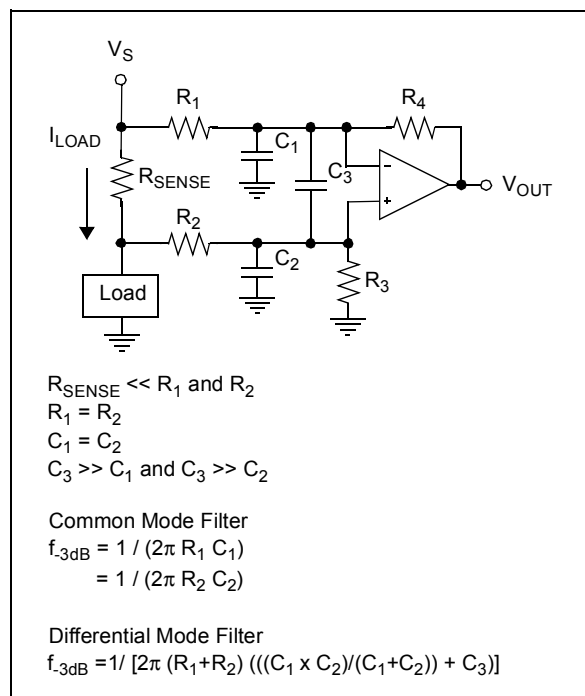
FIGURE 8: *RC Noise Reduction Circuit.*

Figure 9 provides an example of a shunt amplifier circuit that combines the filtering of the shunt current signal with an offset adjustment. The RC components R_1C_1, R_2C_2 and C_3 are used to provide EMI and ESD protection to the amplifier. The RC feedback networks of R_7C_5 and R_6C_4 are selected to provide a low pass filter response to the differential amplifier.

A trade-off with discrete filter networks is that the frequency response of the filter is dependent on the source and load impedance. The filter equations shown are only an approximation. A more detailed analysis or SPICE simulation may be required to accurately model the filter response of the circuit.
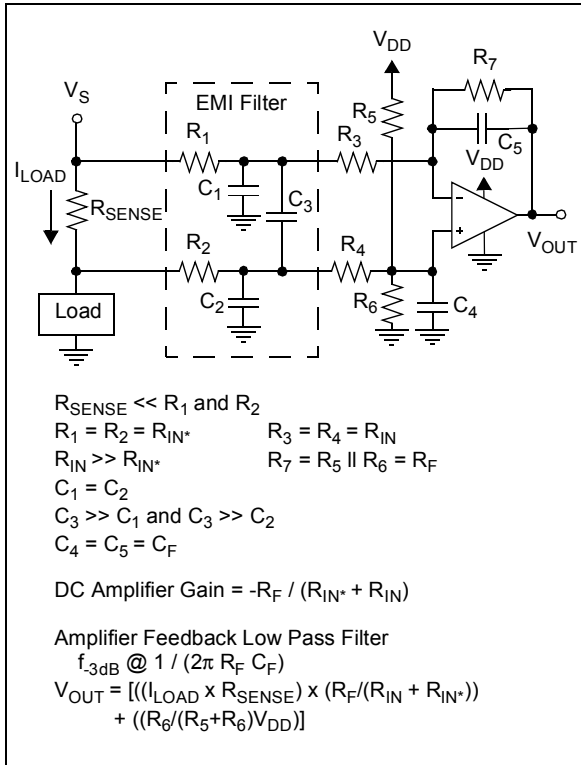

$R_{SENSE} \ll R_1$ and R_2
$R_1 = R_2 = R_{IN*}$ $R_3 = R_4 = R_{IN}$
$R_{IN} \gg R_{IN*}$ $R_7 = R_5 \| R_6 = R_F$
$C_1 = C_2$
$C_3 \gg C_1$ and $C_3 \gg C_2$
$C_4 = C_5 = C_F$

DC Amplifier Gain = $-R_F / (R_{IN*} + R_{IN})$

Amplifier Feedback Low Pass Filter
    f_{-3dB} @ $1 / (2\pi R_F C_F)$
$V_{OUT} = [((I_{LOAD} \times R_{SENSE}) \times (R_F/(R_{IN} + R_{IN*}))$
        $+ ((R_6/(R_5+R_6)V_{DD})]$

FIGURE 9:   *Combining the Offset and Noise Reduction Circuit.*

Integrated EMI filters can be used to simplify the circuit shown in Figure 9 and reduce the number of discrete components. Integrated Passive Device (IPD) EMI filters that consist of resistors and transient suppression (TVS) zener diodes are available from a number of IC venders. IPD filters integrate the discrete components in a small IC package, while providing transient voltage protection.

TVS devices offer the advantage that the input signal is clamped to a safe value that is equal to the breakdown voltage of a zener diode. The zener diode functions as a capacitor when the voltage is below the breakdown voltage. Thus, the IPD filter is equivalent to a RC filter when the input voltage is small. Further details on IPD EMI filters and ESD protection devices are provided in reference (8).

Hall Effect Current Sensors

Hall effect sensors are a current-measuring sensor that can be easily integrated into an embedded application. Several vendors offer devices that combine the magnetic sensor and conditioning circuit in a small IC package. These IC sensors typically produce an analog output voltage that can be input directly into the microcontroller's ADC. The main disadvantages of Hall effect current sensors are that they are expensive and their accuracy varies with temperature.

The Hall effect is based on the principle that a voltage (V_H) is created when current (I_C) flows in a direction perpendicular to a magnetic field (B), as shown in Figure 10. Hall effect current sensors are available in either an open-loop or closed-loop implementation. The closed-loop Hall effect sensors offer the advantage that their output linearity is better than an open-loop sensor over a wider current measurement range. Further details on Hall effect sensors are available in references (4), (7) and (12).
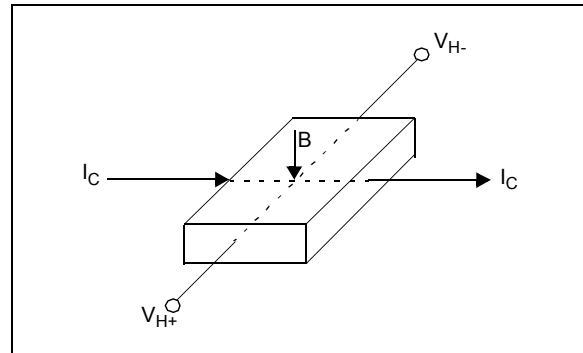

FIGURE 10:   *Hall Effect Principle.*

The Hall effect current sensor can be placed on the PCB directly over the current trace that will be monitored. The sensor functions by measuring the magnetic flux that is created by the current flowing through the trace. Figure 11 provides an example of a PCB mounted Hall effect sensor that measures the current through a wire placed on the top of the IC. Hall effect current sensors are also available in a package that is mounted on the PCB, with the current-carrying wire passing through a hole in the sensor.
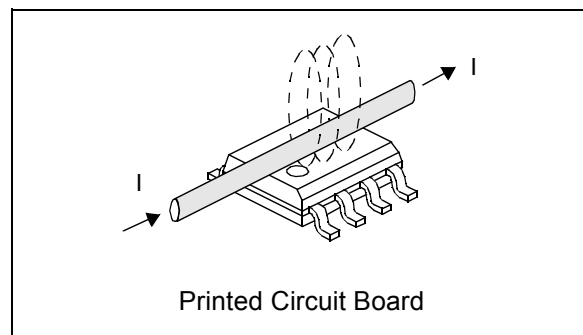

Printed Circuit Board

FIGURE 11:   *Hall Effect Current Sensor.*

Current-Sensing Transformers

Current-sensing transformers offer an alternative to shunt resistors and Hall effect sensors to measure current. These sensors use the principle of a transformer, where the ratio of the primary current to the secondary current is a function of the turns ratio. The main advantage of current transformers is that they provide galvanic isolation and can be used in high-current applications. The main disadvantage of current transformers is that an AC input signal is required to prevent the transformer from saturating.

Figure 12 provides schematics of a single turn and a multi-turn primary current-sensing transformers. The single-turn primary transformer offers the advantage that the measurement is non-intrusive and the current-carrying wire can be passed directly through a hole in the transformer. The multi-turn transformer offers the advantages of improved magnetic coupling, since many turns of the primary wire can be provided.
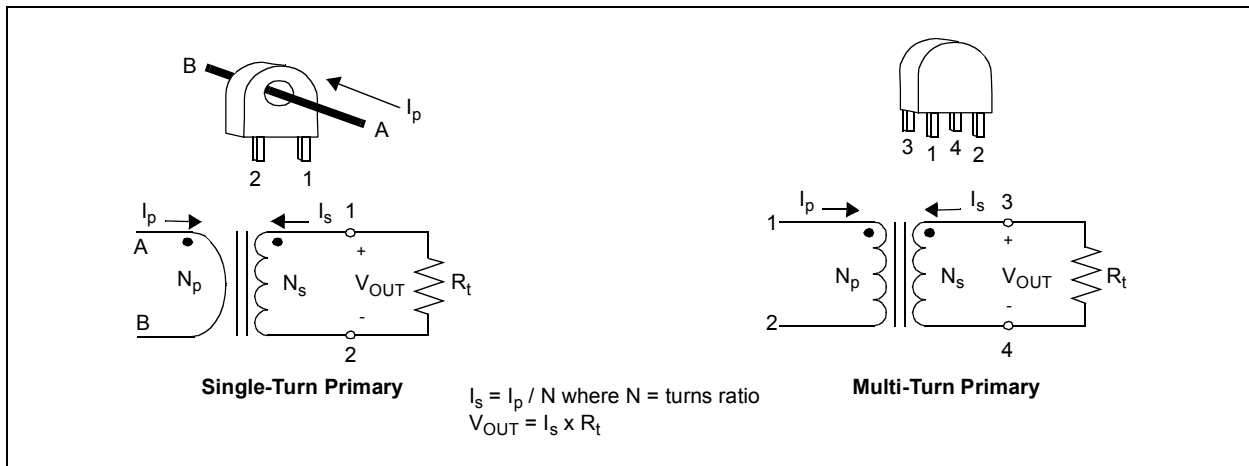
$$I_s = I_p / N \text{ where } N = \text{turns ratio}$$
$$V_{OUT} = I_s \times R_t$$

FIGURE 12:   *Current-Sensing Transformers.*

BACK EMF CONTROL METHOD

The back electro-magnetic-force (EMF) or sensorless motor control method obtains the speed and position of the motor directly from the voltage at the motor windings. This method is typically used in brushless DC motors to provide commutation. The back EMF control method eliminates the requirement for relatively expensive sensors, such as Hall effect devices. The back EMF voltage produces a sine or trapezoidal waveform that is sensed at the motor's winding and typically is converted into a digital square wave by a zero-crossing comparator circuit. The comparator signal is inputted to the microcontroller, which calculates the commutation sequence and motor position from the phase relationship of the square wave representation of the back EMF signals.

The back EMF is created when the motor's armature turns, which creates a electrical kickback or EMF that is sensed as a voltage through a resistor. The amplitude of the EMF signal increases with the speed of the armature rotation. A limitation of the back EMF method is that the amplitude of the signal is very small at low shaft RPMs.

The zero-crossing circuit can be constructed from either discrete comparator ICs or comparators that are located inside the PICmicro® microcontroller. Figure 13 provides a block diagram of a sensorless control for a Brushless Direct Current (BLDC) motor that uses discrete comparator circuits.
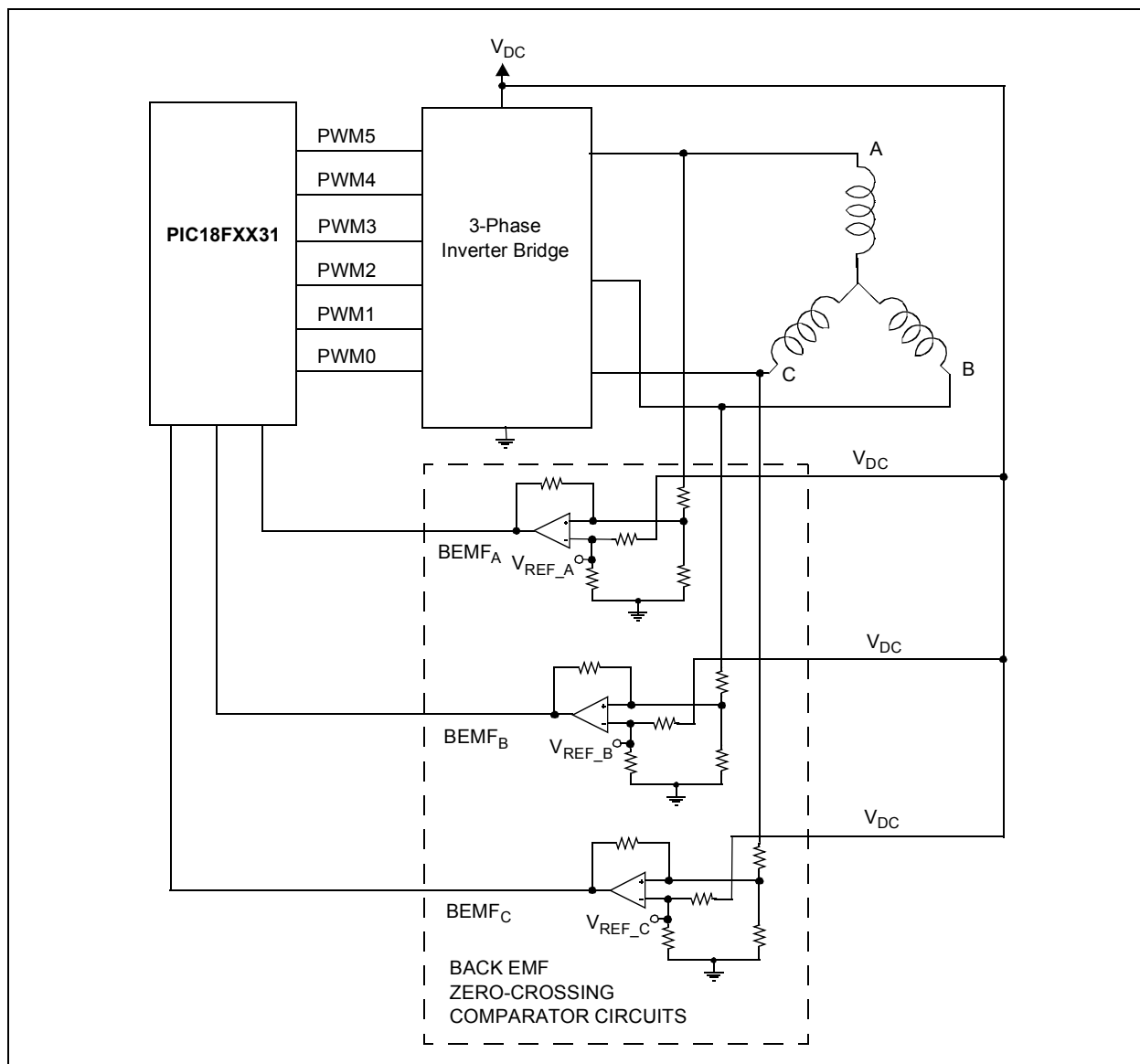
FIGURE 13:   *Block Diagram of a Sensorless BLDC Motor Control.*

SELECTING A COMPARATOR

A comparator is designed to provide a logic-level output signal that indicates whether the voltage at the non-inverting input is larger or smaller than the voltage at the inverting input. Figures 14 and 15 show the circuit topology and design equations for a non-inverting and inverting comparator, respectively. The non-inverting circuit's output is in phase with the sinewave input, while the inverting circuit that has an output $180°$ out of phase from the input signal. Reference (6) provides further details on the comparator voltage transition and hysteresis equations.

For example, the output voltage of a single voltage supply, non-inverting comparator will be analyzed. The output will be the same for a push-pull or an open-drain output device that is connected to voltage V_{DD} through a pull-up resistor. If the voltage at the non-inverting (+) terminal is larger than the voltage at the inverting (-) terminal, the output will be equal to approximately V_{DD}. In contrast, if the voltage at the (+) terminal is less than the voltage at the (-) terminal, the output will be equal to approximately V_{SS} or ground.

Though op amps can be used as a comparator, the designer must consider the trade-offs of using an amplifier in a non-linear mode. Op amps are designed to linearly amplify a small signal and use negative feedback to function in the linear region. By contrast, comparators are designed to function in the non-linear region and use positive feedback to force the output to have a fast transition to the saturation region where the output is at either the high or low power supply rail.

Though op amps can function as a comparator by using positive feedback, the switching speed of the circuit is typically poor. The propagation delay of an op amp comparator is large in comparison with a typical comparator. In addition, the current consumption of an op amp comparator usually is much larger than a standard comparator.

Table 4 provides a list of recommended Microchip comparators. A key specification for motor control applications is the propagation delay of the comparator.

TABLE 4:   RECOMMENDED MICROCHIP COMPARATORS

Product	Operating Voltage	I_Q (Typ.)	Propagation Delay (typ.)	Features
TC1025	1.8 to 5.5V	8 µA	4 µs	• Rail-to-rail input and output
TC1027 **TC1028**	1.8 to 5.5V 1.8 to 5.5V	18 µA 10 µA	4 µs 4 µs	• On-board V_{REF} • Shutdown pin (TC1028)
TC1031	1.8 to 5.5V	6 µA	4 µs	• Prog. Hysteresis • Shutdown pin • On-board V_{REF}
TC1037 **TC1038** **TC1039**	1.8 to 5.5V 1.8 to 5.5V 1.8 to 5.5V	4 µA 4 µA 6 µA	4 µs 4 µs 4 µs	• Shutdown pin (TC1038) • On-board V_{REF} (TC1039)
TC1040 **TC1041**	1.8 to 5.5V 1.8 to 5.5V	10 µA 10 µA	4 µs 4 µs	• On-board V_{REF} • Prog. Hysteresis (TC1041)
MCP6541/2/3/4	1.6 to 5.5V	0.6 µA per comparator	4 µs	• Low I_Q • Push-pull output
MCP6546/7/8/9	1.6 to 5.5V	0.6 µA per comparator	4 µs	• Low I_Q • Open-drain output

Assume: $V_{OH} = V_{DD}$, $V_{OL} = 0$, $R_3 \gg R_1$ and $R_3 \gg R_{PULL-UP}$

$$V_{IN} = \left(\frac{R_{1B}}{R_{1A} + R_{1B}}\right) \times V_M \qquad R_1 = R_{1A} \| R_{1B}$$

$$V_{REF} = V_{DD} \times \left(\frac{R_4}{R_2 + R_4}\right)$$

$$V_{TL} \cong \frac{(R_1 + R_3)V_{REF} - (R_1 \times V_{DD})}{R_3}$$

$$V_{TH} \cong \frac{(R_1 + R_3)V_{REF}}{R_3}$$

$$V_{HYS} = V_{TH} - V_{TL}$$

$$V_{HYS} \cong \left(\frac{R_1}{R_3}\right) \times V_{DD}$$

Design Procedure:
1. Select V_{REF}, the "zero-crossing" voltage
2. Select V_{HYS} to be equal to 10 to 100 mV
3. Select $R_3 \gg R_1$

Note: $R_{PULL-UP}$ is required for open drain outputs, but is not required for push-pull output comparators.
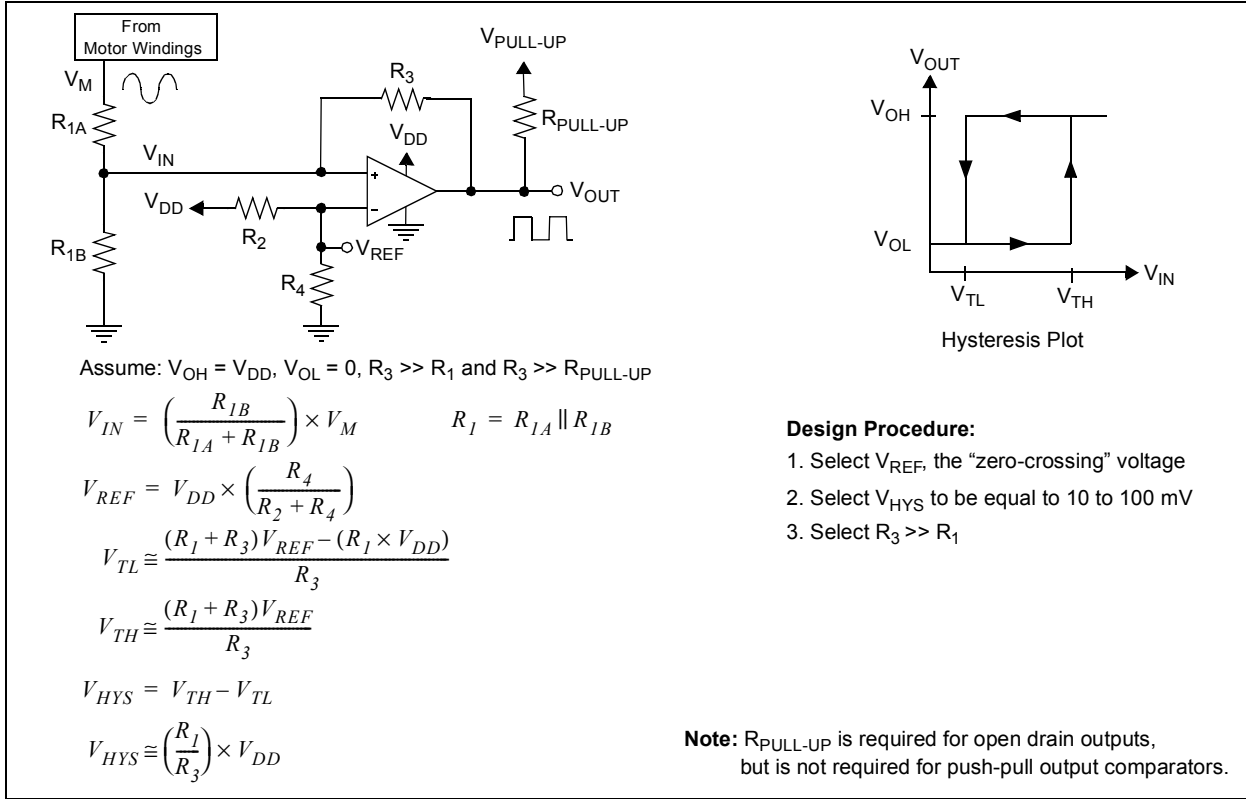
FIGURE 14: *Single Supply Non-Inverting Comparator Circuit.*

Assume: $V_{OH} = V_{DD}$, $V_{OL} = 0$, $R_3 \gg R_1 \| R_2$ and $R_3 \gg R_{PULL-UP}$

$$V_{IN} = \left(\frac{R_{1B}}{R_{1A} + R_{1B}}\right) \times V_M \qquad R_1 = R_{1A} \| R_{1B}$$

$$V_{REF} \cong V_{DD} \times \left(\frac{R_1}{R_1 + R_2}\right)$$

$$V_{TL} \cong \left(\frac{R_1}{R_1 + R_2}\right) \times V_{DD}$$

$$V_{TH} \cong \left(\left(\frac{R_1}{R_1 + R_2}\right) \times V_{DD}\right) + \left(\frac{(R_1 \| R_2) \times V_{DD}}{R_3}\right)$$

$$V_{HYS} = V_{TH} - V_{TL}$$

$$V_{HYS} \cong \frac{(R_1 \| R_2) \times V_{DD}}{R_3}$$

Design Procedure:
1. Select V_{REF}, the "zero-crossing" voltage
2. Select V_{HYS} to be equal to 10 to 100 mV
3. Select $R_3 \gg R_1 \| R_2$

Note: $R_{PULL-UP}$ is required for open drain outputs, but is not required for push-pull output comparators.
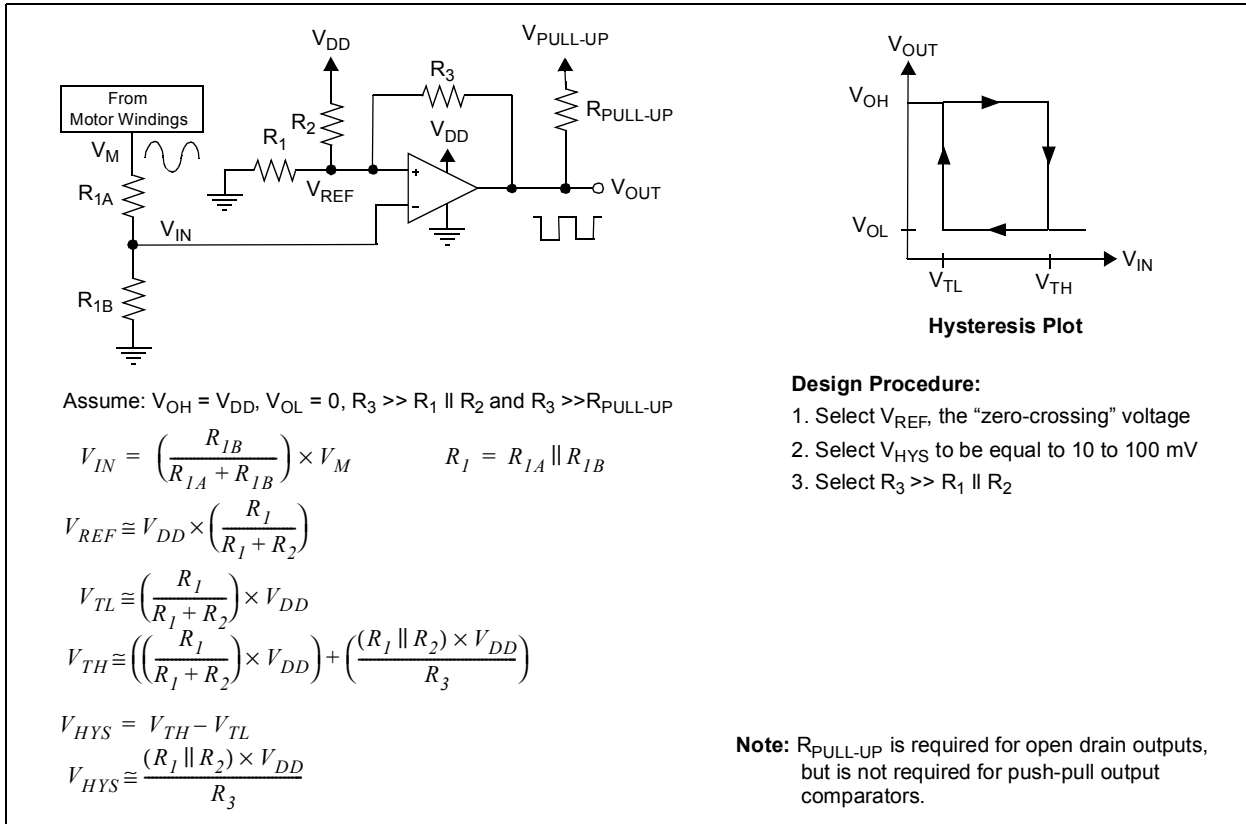
FIGURE 15: *Single-Supply Inverting Comparator Circuit.*

COMPARATOR REFERENCE VOLTAGE

In single supply comparators, a reference voltage must be created. The circuits create V_{REF} by using a resistor voltage divider. The offset voltage of V_{REF} enables the circuit to function as a zero-crossing detector without requiring a dual voltage power supply. The back EMF voltage produces a sine or trapazoidal waveform that swings above and below power ground. The back EMF voltage can be sensed as a sine or trapazoidal waveform offset by a DC voltage if the comparator circuit is either referenced to center point of the motor windings, or if a resistor network is used. The resistor network can either pull-up the floating signal to V_{DD} or pull-down the signal to ground. Further details on the back EMF comparator circuit used in a brushless DC motor controller are provided in reference (11).

HYSTERESIS

Hysteresis can be used to provide noise reduction and prevent oscillation when the comparator switches output states. A comparator provides hysteresis by feeding back a small fraction of the output signal to the positive input terminal. This additional voltage provides for a polarity sensitive offset voltage, which either increases or decreases the threshold value of the switching voltage. Hysteresis produces two different switching points that result in a transition voltage that is dependent on whether the input voltage is rising or falling in amplitude.

Frequency-dependent hysteresis can be provided by placing a capacitor in the positive feedback network, as shown in Figure 16. The capacitor adds an additional pole that changes the amount of hysteresis as a function of frequency. At frequencies below f_p, the hysteresis will be a constant voltage determined by resistors R_1 and R_3. However, at frequencies above the pole f_p, the hysteresis will be increased as a function of the frequency, as shown in the equations provided in Figure 16.
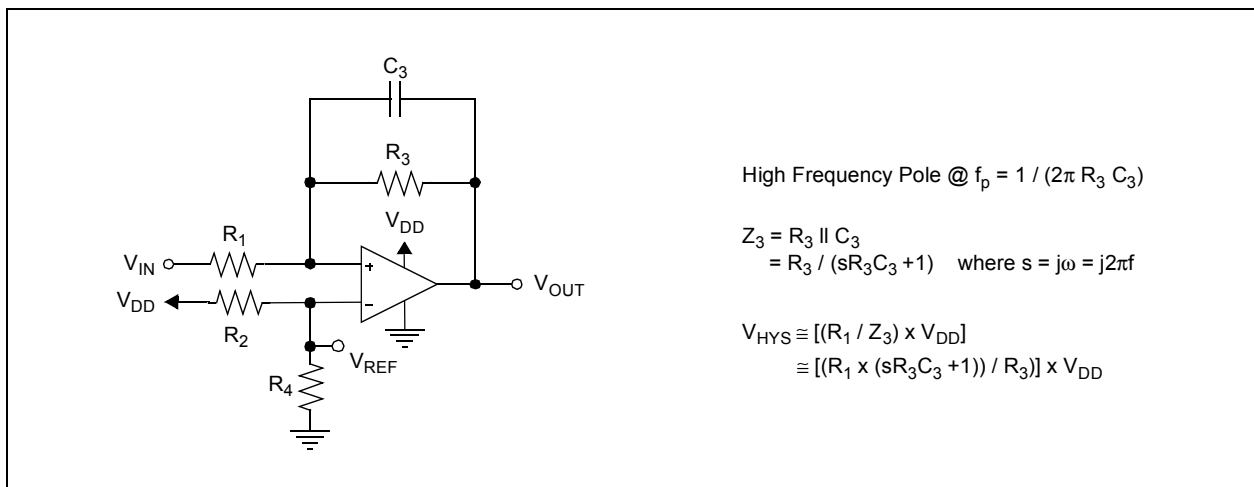

High Frequency Pole @ $f_p = 1 / (2\pi R_3 C_3)$

$Z_3 = R_3 \| C_3$
$\quad = R_3 / (sR_3C_3 +1)$ where $s = j\omega = j2\pi f$

$V_{HYS} \cong [(R_1 / Z_3) \times V_{DD}]$
$\quad\quad \cong [(R_1 \times (sR_3C_3 +1)) / R_3)] \times V_{DD}$

FIGURE 16:   *Frequency Dependent Hysteresis for a Comparator.*

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QUADRATURE ENCODER

A quadrature encoder can be used to provide the speed, direction and shaft position of a rotating motor. A simplified block diagram of an optical quadrature encoder is shown in Figure 17. The typical quadrature encoder is packaged inside the motor assembly and provides three logic-level signals that can be directly connected to the microcontroller.

Motor speed is determined by the frequency of the Channel A and B signals. Note that the counts-per-revolution (CPR) depends on the location of the encoder and whether motor-gearing is used. The phase relationship between Channel A and B can be used to determine if the motor is turning in either a forward or reverse direction. The Index signal provides the position of the motor and, typically, a single pulse is generated for every 360 degrees of shaft rotation.

The quadrature encoder's speed and direction information can be determined either with discrete logic, a quadrature encoder logic IC or a PICmicro® microcontroller. Vendors, such as LSI Computer Systems, offer an IC that converts the three encoder signals to a signal that represents the velocity, position and distance that the motor has moved. Alternatively, the encoder information can be obtained from the hardware registers and software logic inside a PICmicro microcontroller. For example, the PIC18FXX31 dsPIC® MCUs have a Quadrature Encoder Interface logic integrated into the processor.
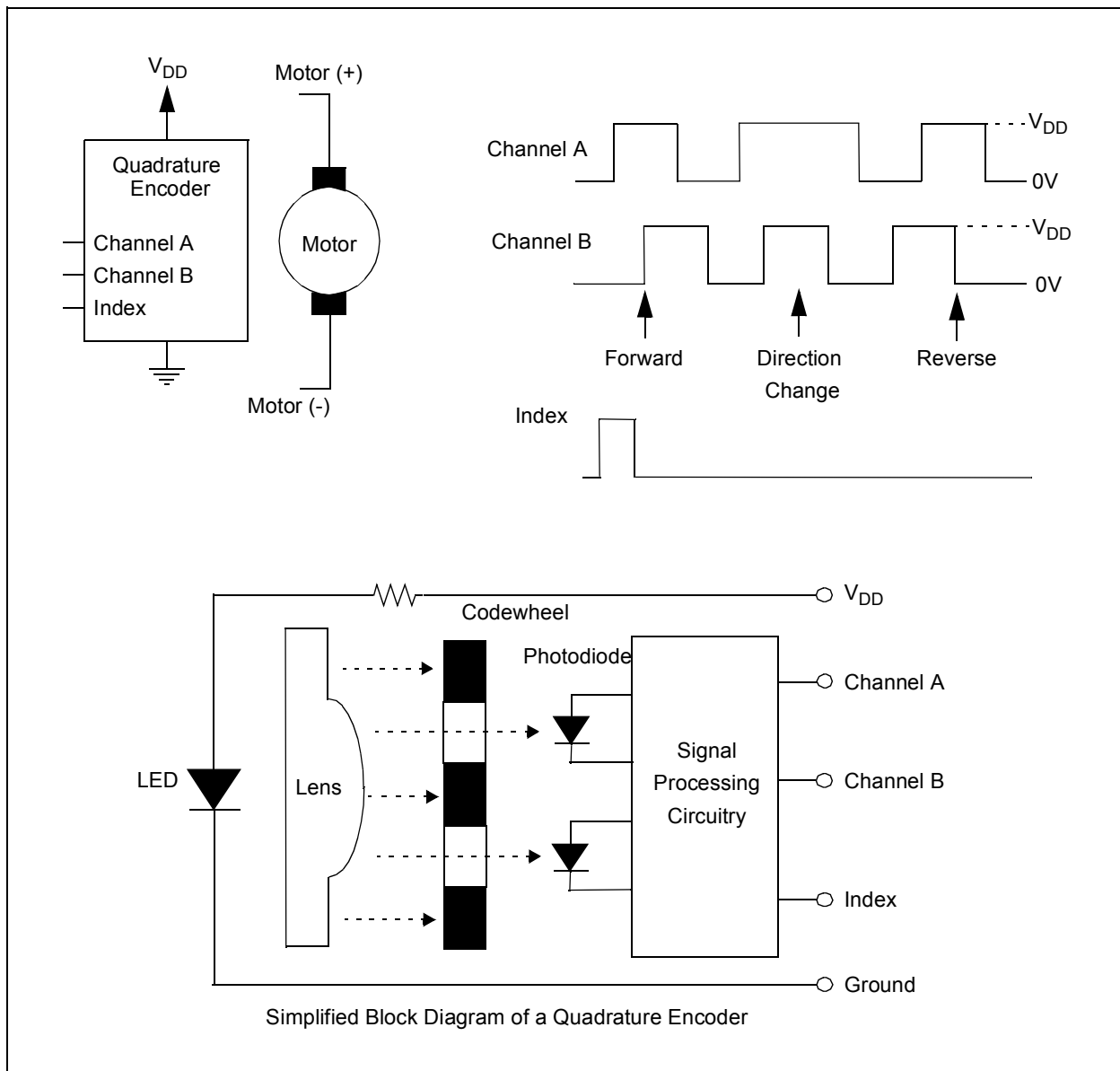

FIGURE 17: *Quadrature Encoder.*

HALL EFFECT TACHOMETERS

Hall effect sensors can be used to sense the speed and position of a rotating motor. Further information on Hall effect tachometer sensors are provided in references (4) and (12). These sensors are based on using the Hall element to sense the change influx in the air gap between a magnet and a notch in a rotating shaft or a passing ferrous gear tooth. The main advantage of Hall effect tachometers is that they are a non-contact sensor that is not limited by mechanical wear. Hall effect tachometers that integrate the sensor and sensor-conditioning circuit in a small IC package are available from a number of vendors. The circuitry inside the sensor typically consists of a comparator or Schmitt trigger to provide a digital output signal that can be directly connected to the microcontroller.

An example of a Hall effect rotary interrupt switch is provided in Figure 18. A notch is placed in the rotating shaft that provides a magnetic field to the sensor when the notch is positioned directly in-line with the magnet and the Hall effect sensor, turning the switch "ON". When the solid portion of the disk is between the Hall effect sensor and the magnet, the magnetic field is interrupted and the switch is in the "OFF" position.

Hall effect tachometers can also be used as a geartooth sensor. A Hall effect geartooth sensor, shown in Figure 19, senses the variation in the flux in the air gap between the passing ferrous geartooth and the magnet. Geartooth sensors typically provide a digital output that can be directly connected to the I/O port of the microcontroller. In addition to detecting the speed of the rotation, some Hall effect tachometers also detect the direction of the turning gears.
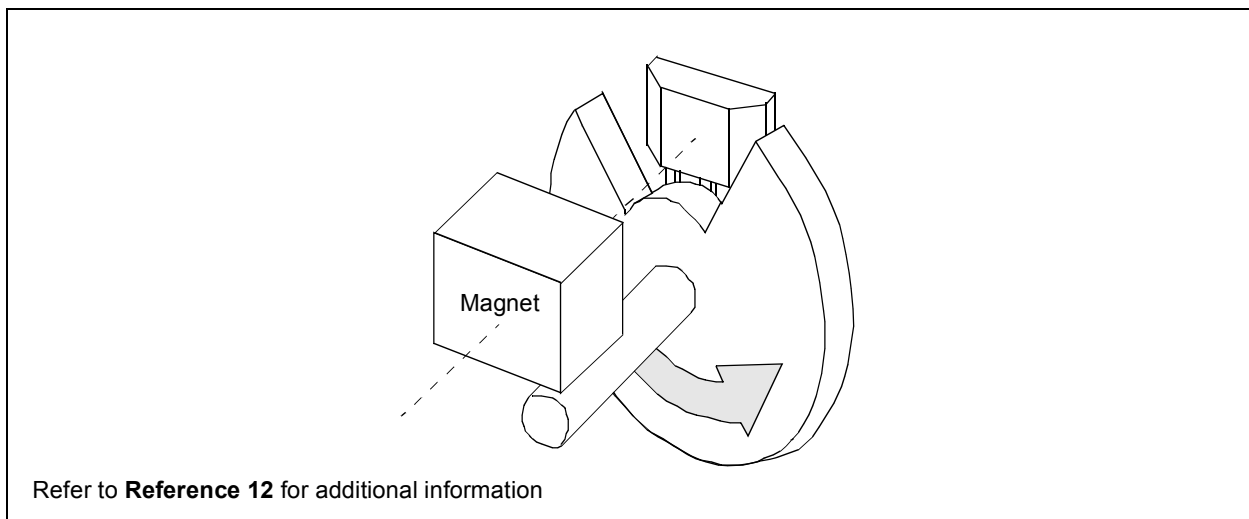

Refer to **Reference 12** for additional information

FIGURE 18: *Hall Effect Rotary Interrupt Switch Tachometer.*

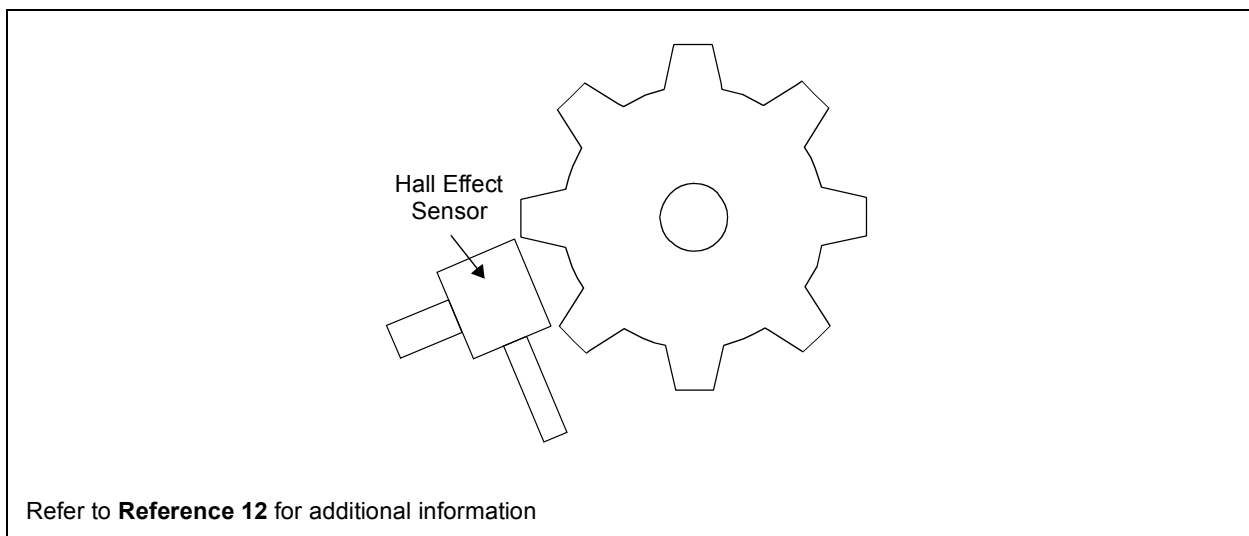Refer to **Reference 12** for additional information

FIGURE 19: *Hall Effect Geartooth Tachometer.*

CONCLUSION

Feedback sensors serve a critical role in a motor control system. These sensors provide information on the current, position, speed and direction of a rotating motor. In addition, the sensors improve the reliability of the motor by detecting fault conditions that may damage the motor.

The four major feedback sensors discussed in this document are: current sensors, back EMF or sensorless control, quadrature encoders and Hall effect tachometers. Each of these sensors offer advantages and disadvantages that the designer must evaluate in order to provide a stable, reliable and cost-effective control system.

Further details on motor control circuits and sensors are provided in several books, including "Motor Control Electronics" (10). In addition, please review Microchip's web site (www.microchip.com) for reference designs and applications notes on motor control systems. References (9) and (11) are just two of the many documents available that demonstrate how Microchip's PICmicro microntrollers and analog products can be used in a motor control system.

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