Chapter 4

Electrical Considerations

Introduction

To effectively apply Hall effect technology, it is necessary to understand the sensor, its input and its output. The previous two chapters covered the sensor and its input. This chapter covers electrical considerations as they relate to the output of a Hall effect sensor.

There are two types of Hall effect sensor outputs: analog and digital. They have different output characteristics and will be treated separately in this chapter. Analog sensors provide an analog output voltage which is proportional to the intensity of the magnetic field input. The output of a digital sensor is two discrete levels, 1 or 0 (ON or OFF), never in between. Output specifications, basic interfaces and interfaces to common devices will be examined for both sensor types.

Digital output sensors

The output of a digital Hall effect sensor is NPN (current sinking, open collector), as shown in Figure 4-1. The illustration shows the outputs in the actuated (ON) state.

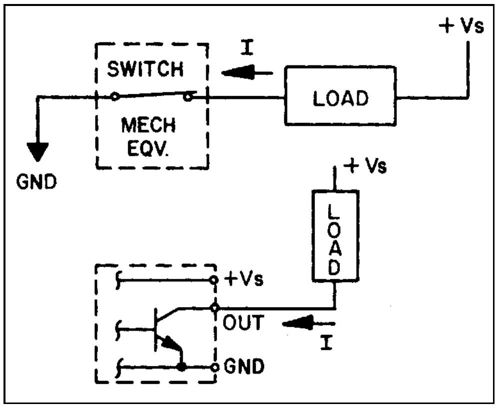

Figure 4-1 NPN output

Current sinking derives its name from the fact that it “sinks current from a load.” The current flows **from the load** into the sensor. Current sinking devices contain NPN integrated circuit chips. The physics of chip architecture and doping are beyond the scope of this book.

Like a mechanical switch, the digital sensor allows current to flow when turned ON, and blocks current flow when turned OFF. Unlike an ideal switch, a solid state sensor has a voltage drop when turned ON, and a small current (leakage) when turned OFF. The sensor will only switch low level DC voltage (30 VDC max.) at currents of 20 mA or less. In some applications, an output interface may be current sinking output, NPN.

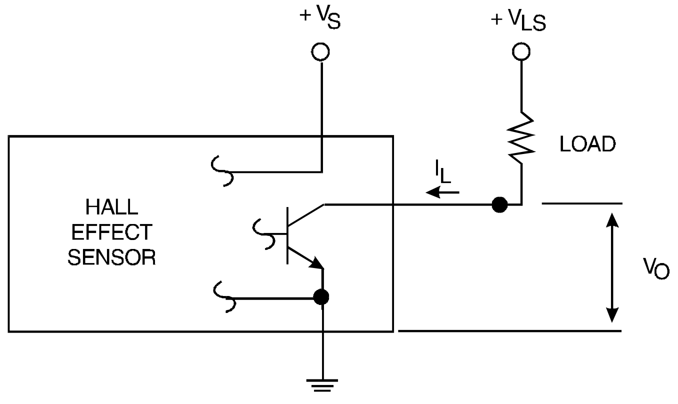

Figure 4-2 NPN output Hall effect sensor

Figure 4-2 represents an NPN (current sinking) sensor. In this circuit configuration, the load is generally connected between the supply voltage and the output terminal (collector) of the sensor. When the sensor is actuated, turned ON by a magnetic field, current flows through the load into the output transistor to ground. The sensor’s supply voltage (V_S) need not be the same value as the load supply (V_{LS}); however, it is usually convenient to use a single supply. The sensor’s output voltage is measured between the output terminal (collector) and ground (-). When the sensor is not actuated, current will not flow through the output transistor (except for the small leakage current). The output voltage, in this condition, will be equal to V_{LS} (neglecting the leakage current). When the sensor is actuated, the output voltage will drop to ground potential if the saturation voltage of the output transistor is neglected. In terms of the output voltage, an NPN sensor in the OFF condition is considered to be normally high.

Electrical specifications

An example of typical characteristics of an NPN (current sinking) sensor are shown in the tables in Figure 4-3. The characteristics are divided into Absolute Maximum Ratings and Electrical Characteristics.

Absolute maximum ratings are the extreme limits that the device will withstand without damage to the device. However, the electrical and mechanical characteristics are not guaranteed as the maximum limits (above recommended operating conditions) as approached, nor will the device necessarily operate at absolute maximum ratings.

Figure 4-3A Typical NPN sensor characteristics

Absolute Maximum Ratings

Supply Voltage (VS)	-1.0 to +30 VDC
Voltage externally applied to output	+25 VDC max. OFF only -0.5 VDC min. OFF or ON
Output Current	50 mA max.
Temperature	-40 to +150°C operating
Magnetic flux	No limit. Circuit cannot be damaged by magnetic overdrive

Absolute Maximum Ratings are the conditions if exceeded may cause permanent damage. Absolute Maximum Ratings are not continuous ratings, but an indication of the ability to withstand a transient condition without permanent damage. Function is not guaranteed. Rated operating parameters are listed under Electrical Characteristics.

Figure 4-3B Typical NPN sensor characteristics

Electrical Characteristics

Parameters	Min.	Typ.	Max.
Supply Voltage (VDC)	3.8		30
Supply current (mA)			10.0
Output voltage (operated) volts		0.15	0.40
Output current (operated) mA			20
Output leakage current (released) µA			10
Output switching time (sinking 10 mA)			
Rise time 10 to 90%			1.5 µs
Fall time 90 to 10%			1.5 µs

Specification definitions

Absolute Maximum Ratings

Supply voltage refers to the range of voltage which may be applied to the positive (+) terminal of a sensor without damage. The sensor may not, however, function properly over this entire range.

Voltage externally applied to output refers to the breakdown voltage of the output transistor between its collector and emitter when the transistor is turned OFF (BV_{CER}). Voltage measured at the output terminals of an inactivated sensor must never exceed 30 VDC or the device may be damaged. If the sensor is used in a single supply ($V_S = V_{LS}$) configuration, the 30 VDC maximum rating of the supply insures that this limit will never be exceeded.

Output Current specifies the maximum output current that may flow without damage when the sensor is actuated.

Temperature refers to the temperature range that the sensor may be operated within without damage. This temperature range is distinguished from the rated temperature range over which the sensor will meet specific operational characteristics.

Magnetic flux – a Hall effect sensor cannot be damaged by excessively large magnetic field densities.

Rated Electrical Characteristics

Supply voltage refers to the voltage range over which the sensor is guaranteed to operate within performance specifications.

Supply current corresponds to the current drain on the V_S terminal. The supply current is dependent on the supply voltage.

Output voltage (operated) refers to the saturation voltage (V_{SAT}) of the output transistor. This is the voltage that appears at the output due to the inherent voltage drop of the output transistor in the ON condition.

Output current (operated) refers to the maximum output current at which the sensor is guaranteed to operate within performance specifications.

Output leakage current is the maximum allowable current that remains flowing in the output transistor after it is turned OFF.

Output switching time refers to the time necessary for the output transistor to change from one logic state to another after a change in actuating field. This specification only applies to conditions specified on product drawings.

Basic interfaces

When the electrical characteristics are known, it is possible to design interfaces that are compatible with NPN (current sinking) output Hall effect sensors. The current sink configuration produces a logic “0” condition when a magnetic field of sufficient magnitude is applied to the sensor.

Current sinking sensors may be operated with a dual supply; one for the sensor and a separate supply for the load.

Certain conditions must be met for interfacing with sinking output sensors:

- the interface must appear as a load that is compatible with the output
- the interface must provide the combination of current and voltage required in the application

Pull-up resistors

It is common practice to use a pull-up resistor for current sinking. This resistor minimizes the effect of small leakage currents from the sensor output or from the interfaced electronics. In addition, they provide better noise immunity along with faster rise and fall times.

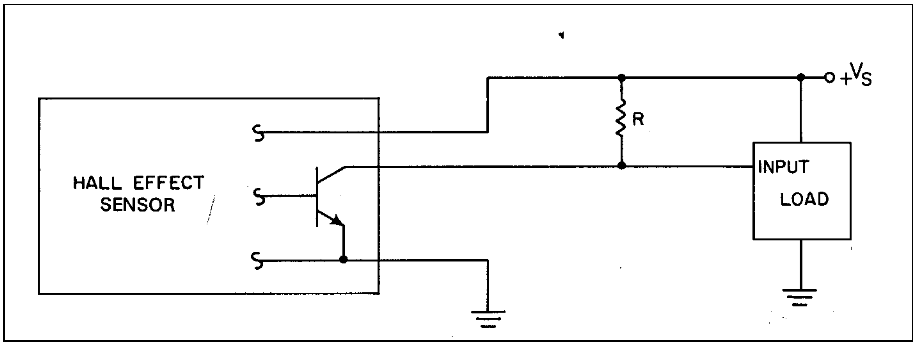

Figure 4-4 Pull-up resistor interface

The current sinking output is an open collector. The output is floating, so the pull-up resistor helps establish a solid quiescent voltage level. When selecting the pull-up resistor, it must be determined if the interface will tolerate a resistance in parallel with it. If there is a parallel resistance, the total resistance and load current should be calculated to make sure that the Hall effect sensor’s output current will not be exceeded.

The basic interface for a digital Hall effect sensor is a single resistor. When a resistor is used in conjunction with a current sinking sensor, it is normally tied between the output and the plus power supply and is referred to as a pull-up resistor. Figure 4-4 illustrates pull-up resistor (R) connected between the sensor and its load. When the sensor is actuated, the input to the load falls to near ground potential, independent of the pull-up resistor.

When the device is de-actuated, the input to the load is **pulled-up** to near V_S. If the pull-up resistor were not present, the input to the load could be left floating, neither at ground nor V_S potential.

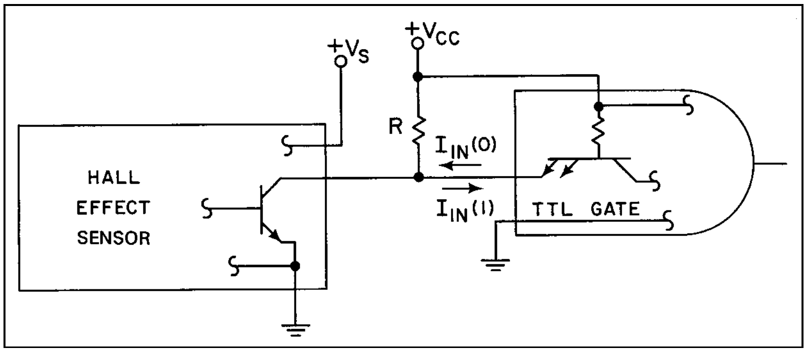

Figure 4-5 NPN sensor interfaced with TTL gate

Logic gate interfaces

Digital sensors are commonly interfaced to logic gates. In most cases, the interface consists of a single pull-up or pull-down resistor on the input of the logic gate. Figure 4-5 illustrates an example of the interface to a TTL gate.

Transistor interfaces

To further illustrate how input and output specifications are related, consider an interface with the requirement for a higher load current that the sensor's rated output current. Figure 4-6 illustrates one of the four possible high current interfaces. The interface consists of a Hall effect sensor driving an auxiliary transistor. The transistor must have sufficient current gain, adequate collector breakdown voltage, and power dissipation characteristics capable of meeting the load requirements.

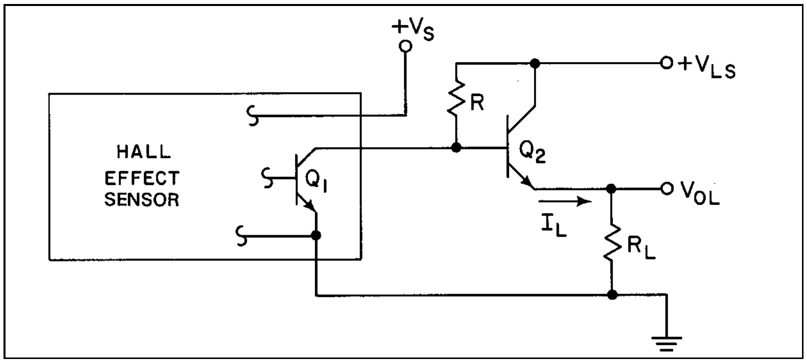

Figure 4-6 High load current interface

The rated output current of the sensor will determine the minimum value of (R). The resistor must also bias the transistor ON when the sensor is not actuated. The current required to adequately drive the transistor will determine the maximum value of (R). Since the bias voltage appears across the sensor output, it is important that the bias be less than the sensor's breakdown voltage.

Four additional combinations of transistor interfaces can be realized with current sourcing and current sinking sensors. These are:

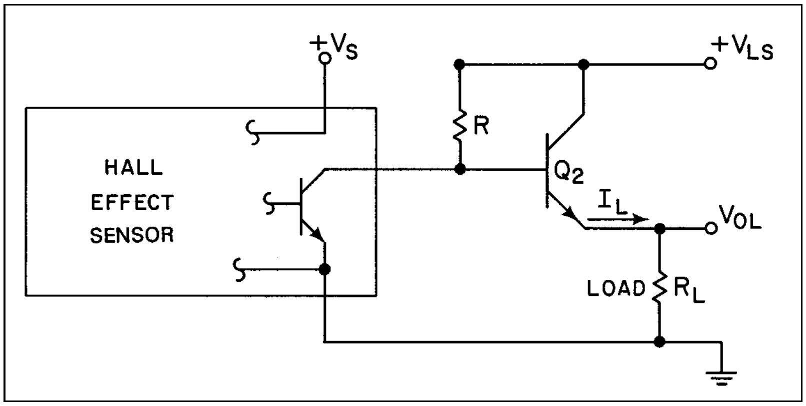

Figure 4-7 Sinking sensor - sourcing output

- Current sinking sensor with a current sourcing drive
- Current sinking sensor with a current sinking drive
- Current sourcing sensor with a current sinking drive
- Current sourcing sensor with a current sourcing drive

The design equations necessary to choose the correct bias resistors and drive transistors for the first two are shown in Figures 4-7 and 4-8. The current sourcing sensor interfaces will not be discussed any further due to lack of widespread use. The symbols used in the sensor interface design equations are defined in Figure 4-9.

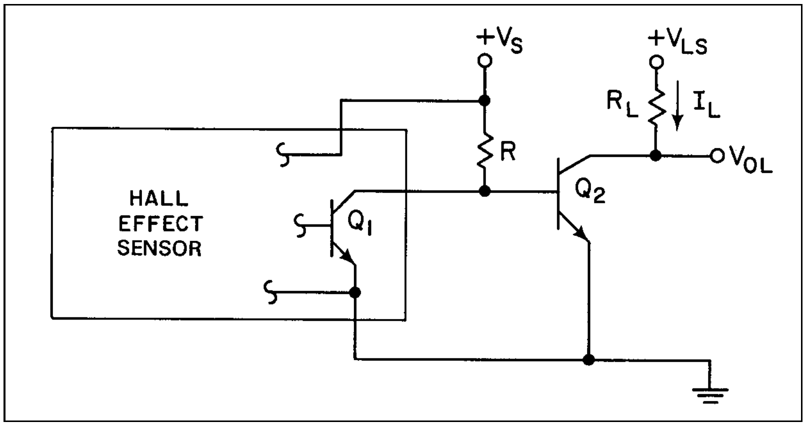

Figure 4-8 Sinking sensor - sinking output

R for a given sensor:

$$R_{min} = \frac{V_{LS} - V_{CE(Q1)}}{I_{ON}}$$

R for adequate load current:

$$R_{max} = \frac{(\beta_{min} + 1)(V_{LS} - R_L I_{L(max)}) - B_{BE(ON)}}{I_{L(max)}}$$

If $R_{max} \leq R_{min}$ then use either a transistor with a higher β or a second amplifier stage.

β_{min} for given R:

$$\beta_{min} = \frac{R I_{L(max)}}{V_{LS} - R_L I_{L(max)} - V_{BE(ON)}}$$

Output voltage:

$$V_{OL} = \frac{V_{LS} - V_{BE(ON)}}{1 + \frac{R}{R_L\beta + R_L}}$$

Transistor output requirements:

$$I_{L(max)} < I_{C(max)}$$

$$V_{LS} < BV_{CER}$$

Transistor power dissipation:

$$P_D = I_L(V_{LS} - V_{OL}) = \frac{\frac{R V_{LS}}{R_L\beta + R_L + V_{BE(ON)}}}{1 + \frac{R}{R_L\beta + R_L}}$$

R for given sensor:

$$R_{min} = \frac{V_S - V_{CE(Q1)}}{I_{(ON)}}$$

R for adequate load current:

$$R_{max} = \frac{\beta_{min}(V_S - V_{BE(ON)})}{V_S - V_{BE(ON)}}$$

If $R_{max} \leq R_{min}$ then use either a transistor with a high β or a second amplifier stage.

β_{min} for a given R:

$$\beta_{min} = \frac{R I_{L(max)}}{V_S - V_{BE(ON)}}$$

Output voltage:

$V_{OL} = V_{CE(SAT)Q2}$ for I_L

A minimum β of 10 is recommended for good saturation voltage.

Transistor output requirements:	Transistor power dissipation:
$I_{L(max)} < I_{C(max)}$	$P_D = V_{OL} \bullet I_L$
$V_{LS} < BV_{CER}$	

Symbols for design calculations

BV_{CEO} =	Collector-to-emitter breakdown voltage with base open
BV_{CER} =	Collector-to-emitter breakdown voltage with resistor from base-to-emitter
BV_{EBO} =	Emitter-to-base breakdown voltage, junction reverse biased, collector open circuited
$I_{C(max)}$ =	Maximum collector current rating
$I_{L(max)}$ =	Maximum load current
$I_{(ON)}$ =	Sensor rated output current
$V_{CE(Q2)}$ =	Driver transistor voltage drop
R_L =	Load resistance
$V_{BE(ON)}$ =	Base-emitter forward voltage drop when transistor is ON (typically 0.7 V)
V_{LS} =	Load power supply voltage
V_S =	Sensor supply voltage
β =	DC current gain of drive transistor
I_{CBO} =	Collector-to-base leakage current
I_L =	Load current
$I_{(OFF)}$ =	Sensor output transistor leakage current
$V_{CE(Q1)}$ =	Sensor output transistor voltage drop
P_D =	Drive transistor power dissipation
$V_{BE(OFF)}$ =	Forward base-emitter voltage drop when transistor is OFF (typically 0.4 V)
V_{OL} =	Output voltage
I_S =	Sensor supply current in ON condition

Figure 4-9 Design calculation symbols

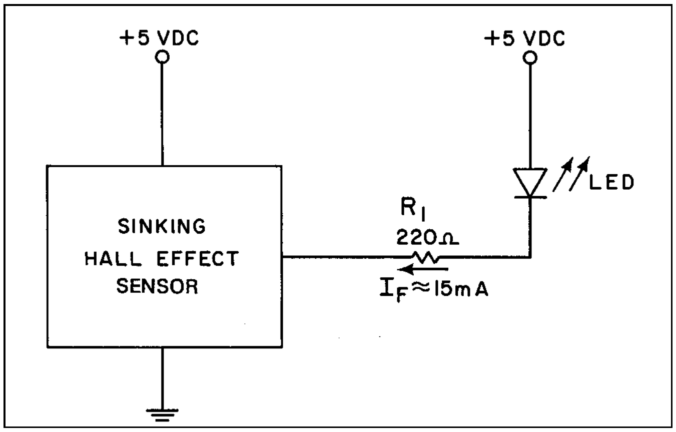

Figure 4-10 Sinking sensor interfaced to normally OFF LED

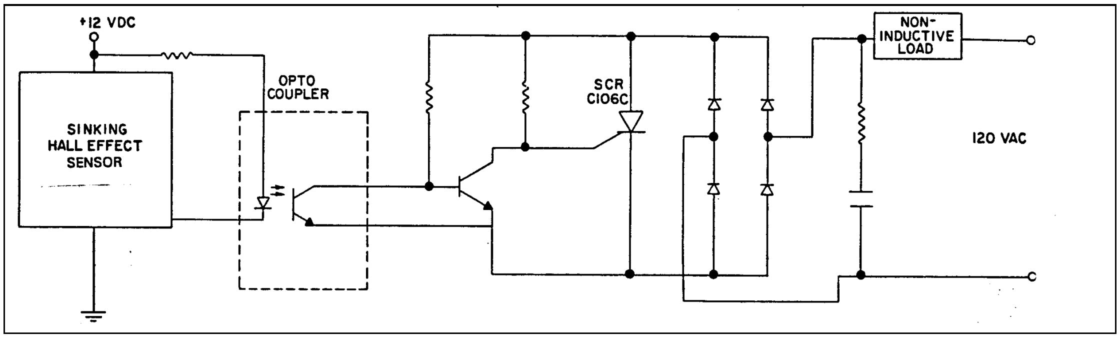

Figure 4-11 Sinking sensor interfaced to normally OFF SCR

For C106C: Breakdown voltage = 300 VDC

Current rating = 4 amperes

Sensor: $I_{(ON)}$ = 20 mA

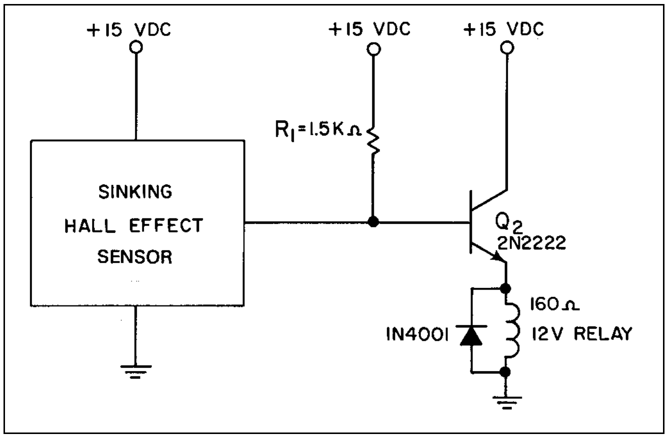

Figure 4-12 Sinking sensor interfaced to normally ON relay

For 2N2222: $V_{BE(ON)} = 0.7$ V

$\beta_{min} = 75$

Sensor: $V_{CE(SAT)Q1} = 0.15$ V $I_{ON} = 20$ mA

For load: $I_{L(max)} = 81$ mA

For design equations, see Figure 4-7.

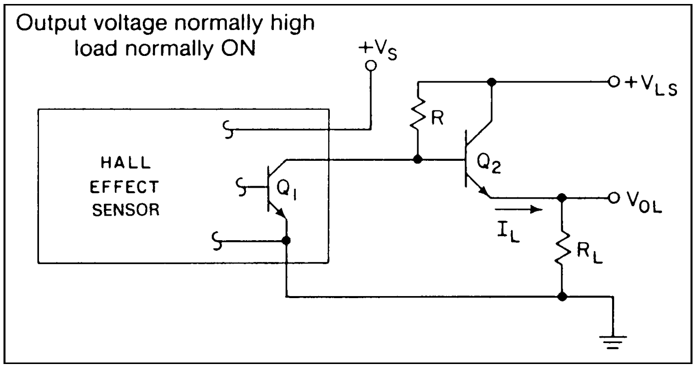

Figure 4-13 Sinking sensor interfaced to normally ON solenoid

For 2N3715: $\beta_{min} = 50$

Sensor: $V_{CE(SAT)Q1} = 0.15$ V

For load $I_{L(max)} = 911$ mA

$V_{BE(ON)} = 0.7$ V

$I_{ON} = 20$ mA

For design equations, see Figure 4-8.

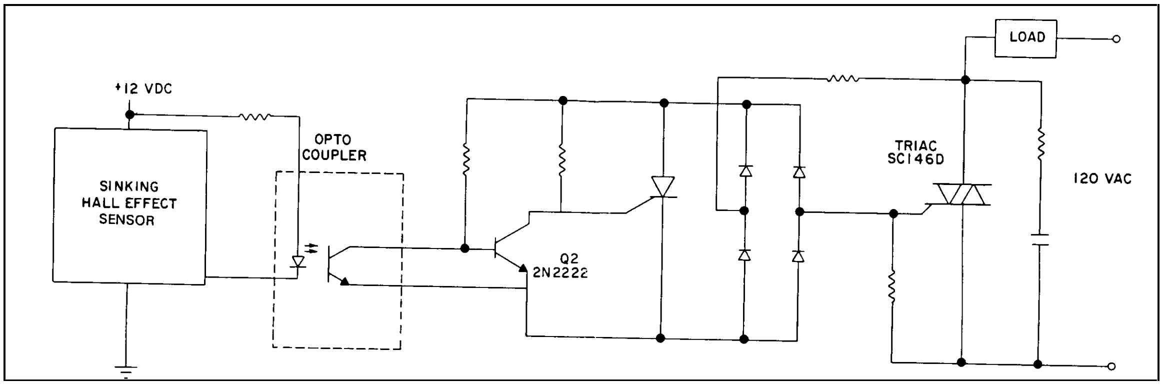

Figure 4-14 Sinking sensor interfaced to normally OFF triac

For SC146D: Breakdown voltage = 400 V

Current rating = 10 A

For 2N2222: $V_{BE(ON)}$ = 0.5 V

β_{min} = 75 V

Sensor: $V_{CE(Q1)}$ = 0.15 V

Input voltage = 2.5 V

Input current = 50 mA

I_{CBO} = 10 µA

$I_{(ON)}$ = 10 mA

Other digital output sensor interface circuits can provide the functions of counting, latching, and the control of low level AC signals. Figures 4-15 through 4-17 demonstrate how these functions can be achieved.

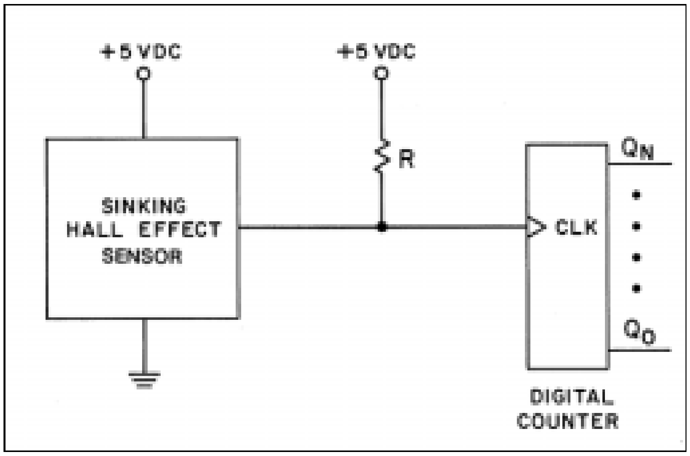

Figure 4-15 Sinking sensor interfaced to digital counter

Counter output is a binary representation of the number of times the sensor has been actuated.

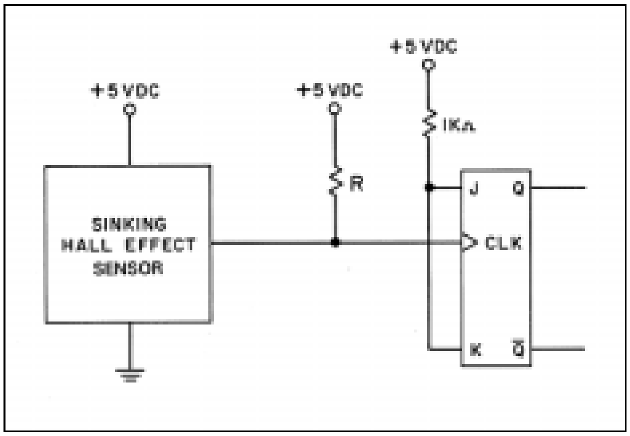

Figure 4-16 Sinking sensor interfaced to a divide by 2 counter

Latch output remains in the same state until sensor is actuated a second time.

Three additional interface circuits which extend the capabilities of digital output Hall effect sensors are shown in Figures 4-18 through 4-20. Figure 4-18 demonstrates how more than one Hall effect sensor may be connected in parallel. This configuration is known as **wired OR** since a logic 0 will be provided to the input of the TTL gate if any combination of sensors is actuated. It is important to note that only current sinking sensors may tied in parallel.

$$R_{min} = \frac{V_{CC} - V_{O(0)}}{I_{(ON)} - nI_{IN(0)}}$$

$$R_{max} = \frac{V_{CC} - V_{IN(1)}}{nI_{(OFF)} - nI_{IN(1)}}$$

Where:

N = number of sensors in parallel

$V_{IN(1)}$ = Minimum input voltage to insure logic 0

$V_{O(0)}$ = Maximum output voltage of sensor for logic 0

$I_{IN(0)}$ = Maximum input current per unit load at $V_{O(0)}$

$I_{IN(1)}$ = Maximum input current per unit load at $V_{IN(1)}$

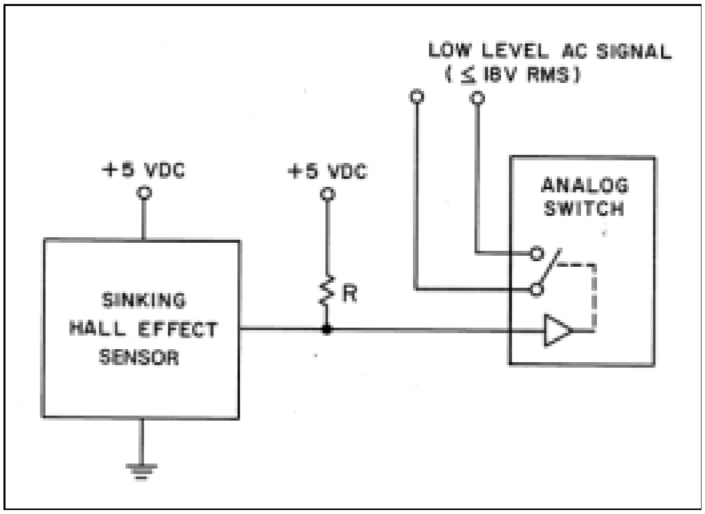

Figure 4-17 Sinking sensor interfaced to analog switch

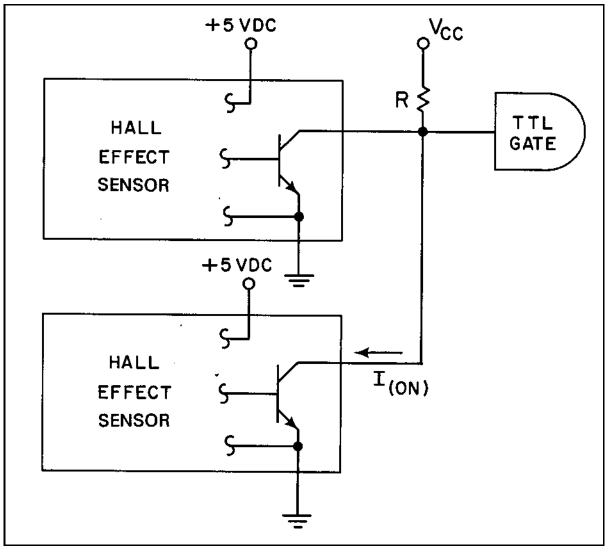

Figure 4-18 Wired OR interface

When a Hall effect sensor is placed in a remote location, it may be desirable to convert its three terminals to a two-wire current loop as shown in Figure 4-19. When the sensor is not actuated, the current in the loop will be equal to the sensor supply current plus leakage current. Conversely, when the sensor is actuated, the loop current will increase to equal the supply current plus the current flow in the output transistor. The difference in loop current will cause a voltage change across the sense resistor R_2 that in turn, reflects the state (ON or OFF) of the sensor. The comparator will then detect this change by comparing it against a fixed reference. Since this changing voltage (V_1) is also the sensor supply voltage, the sensor must also have internal regulator. The value of R_2 must also be chosen so that when the sensor is actuated, V_1 does not fall below the minimum supply rating of the Hall effect sensor.

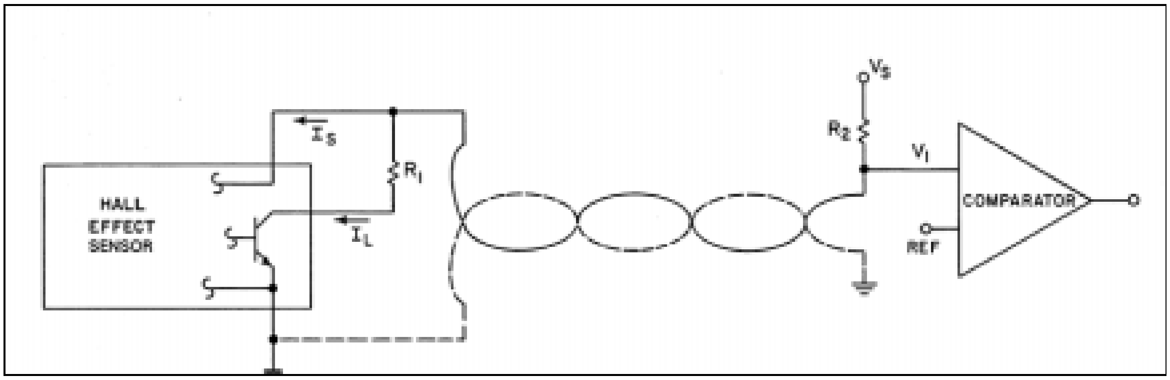

Figure 4-19 Two-wire current loop interface

$$\frac{V_S - V_{OL} - R_2 I_{S(ON)}}{R_1 + R_2} \leq I_{L\,max}$$

$$V_{1(ON)} = \frac{V_S - I_{S(ON)} + R_2/R_1 V_{OL}}{1 + R_2/R_1}$$

$$V_{1(OFF)} = V_S - I_{S(OFF)} R_2$$

Two digital output Hall effect devices may be used in combination to determine the direction of rotation of a ring magnet, as shown in Figure 4-20. The sensors are located close together along the circumference of the ring magnet. If the magnet is rotating in the direction shown (counter-clockwise) the time for the south pole of the magnet to pass from sensor T_2 to T_1 will be shorter than the time to complete one revolution. If the ring magnet's direction is reversed, the time it takes the south pole to pass from T_2 to T_1 will be almost as long as the time for an entire revolution. By comparing the time between actuations of sensors T_2 and T_1 with the time for an entire revolution (successive actuations of T_2), the direction can be determined.

A method by which these two times can be compared is also shown in Figure 4-20. An oscillator is used to generate timing pulses. The counter adds these pulses (counts up) starting when sensor T_2 is actuated and stopping when sensor T_1 is actuated. The counter then subtracts pulses (counts down) for the remainder of the revolution. The shorter time interval between T_2 and T_1 actuation will result in fewer pulses being added than subtracted, thus actuating the counter's BR (borrow) output. When the time between T_2 and T_1 is longer, more pulses are added than subtracted and the BR output is not actuated. For the configuration shown, there will be no output for clockwise motion and a pulse output for each revolution for counterclockwise motion.

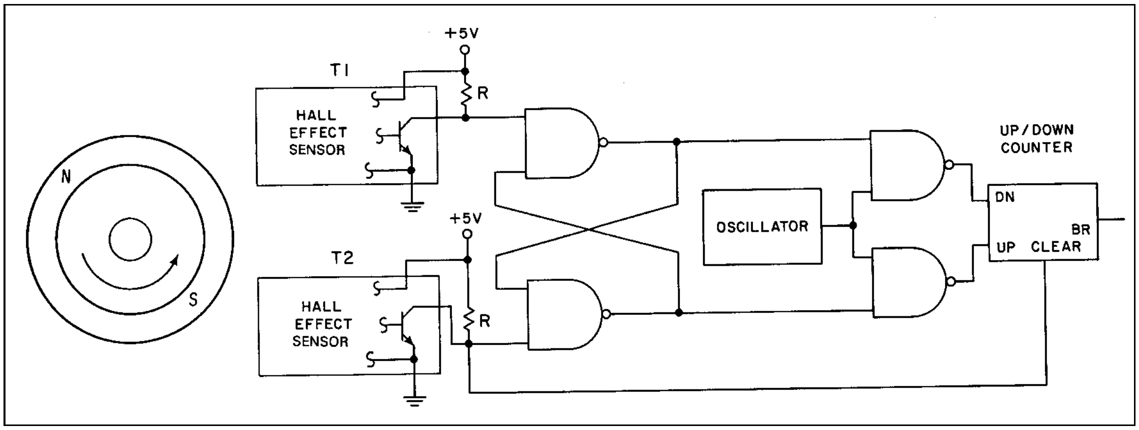

Figure 4-20 Digital output sensor direction sensor

In addition to the interface design concepts covered in this section, there are many other possible ways to utilize the output of digital Hall effect sensors. For example, the output could be coupled to a tone encoder in speed detection applications or a one-shot in current sensing applications. To a large extent, the interface used is dependent on the application and the number of possible interface circuits is as large as the number of applications.

Analog output sensors

The output of an analog Hall effect sensor is an open emitter (current sourcing) configuration intended for use as an emitter follower. Figure 4-21 illustrates the output stage of a typical analog output Hall effect sensor. The output transistor provides current to the load resistor R_{LOAD} producing an analog voltage proportional to the magnetic field at the sensing surface of the sensor. The load in Figure 4-21 is indicated as a resistor, but in practice may consist of other components or networks.

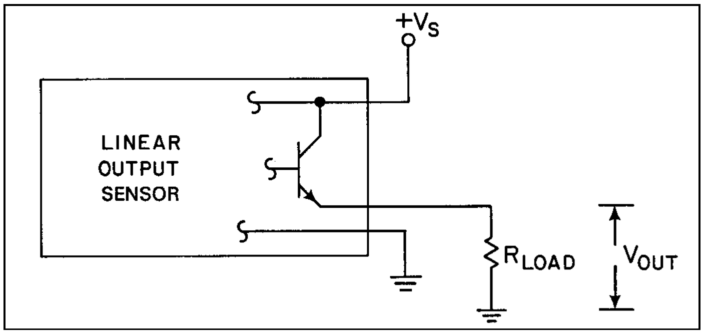

Figure 4-21 Analog output Hall effect sensor

Electrical specifications

Typical characteristics of an analog output Hall effect sensor are shown in Figure 4-22. These characteristics, like those of digital devices, are divided into Absolute Maximum Ratings and Electrical Characteristics. The parameters listed under Absolute Maximum Ratings are defined in the same manner as digital sensors. With the exception of output voltage at 0 gauss (null offset), span and sensitivity, the electrical characteristics are also defined the same as those for digital devices. Span, output voltage at 0 gauss or null offset, and sensitivity are transfer function characteristics that were defined in Chapter 2.

Figure 4-22 Analog output characteristics

Absolute Maximum Ratings

Supply voltage (V_s)	-1.2 and +18 VDC
Output current	10 mA
Temperature	-40 to +150°C operating
Magnetic flux	No limit. Circuit cannot be damaged by magnetic over-drive

Electrical Characteristics

	Min.	Typ.	Max.	Conditions
Supply voltage, V	5.0		16.0	
Supply current, mA			20	Vs = 12 V @ 24 ± 2°C
Output current, mA			10	Vs = 12 V
Output voltage @ 0 gauss, V	5.4	6.0	6.6	@ 24 ± 2°C
Span (-400 to +400 gauss), V	5.84	6.0	6.16	@ 24 ± 2°C
Sensitivity, mV/G	7.3	7.5	7.7	@ 24 ± 2°C

Basic interfaces

When interfacing with analog output sensors, it is important to consider the effect of the load. The load must:

- provide a path to ground
- limit the current through the output transistor to the rated output current for all operating conditions.

Figure 4-23 illustrates a typical load configuration. The parallel combination of the pull-down resistor (R) and the load resistance R_L must be greater that the minimum load resistance which the sensor can drive. In general, this parallel combination should be at least 2200 ohms.

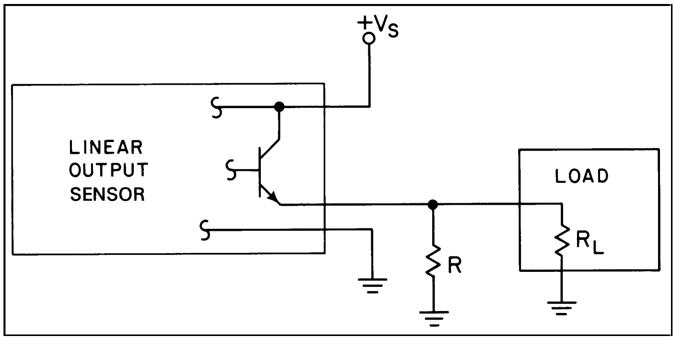

Figure 4-23 Typical load . . . Analog output sensor

In many cases, the output of an analog sensor is connected to a component such as a comparator or operational amplifier, with an external pull-down resistor, as illustrated in Figure 4-24. This resistor should be selected so that the current rating of the analog output sensor is not exceeded. Depending on the comparator used and the electrical noise, this resistor may not be required.

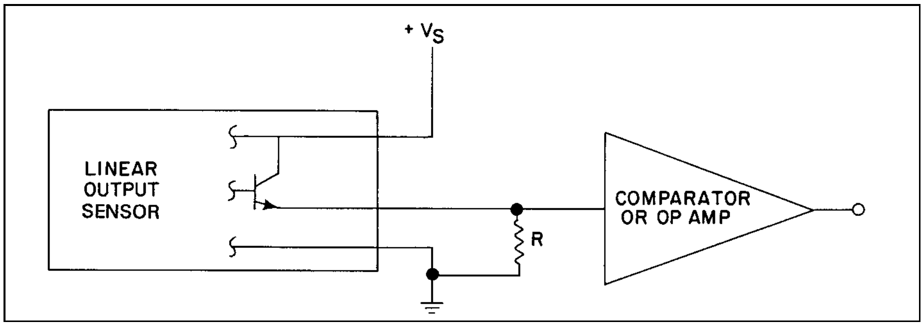

Figure 4-24 Analog sensor interfaced with comparator

Interfaces to common components

The basic concepts needed to design simple interfaces to analog sensors have been presented. Using these basic techniques, more sophisticated interface circuits can be implemented. The interface circuits shown in Figures 4-25 through 4-27 demonstrate how analog Hall effect sensors can be used with standard components.

An analog sensor can be used with an operation amplifier to adjust the sensor's null offset (to zero if desired). Figure 4-25 illustrates one method of accomplishing this using an inverting operational amplifier stage.

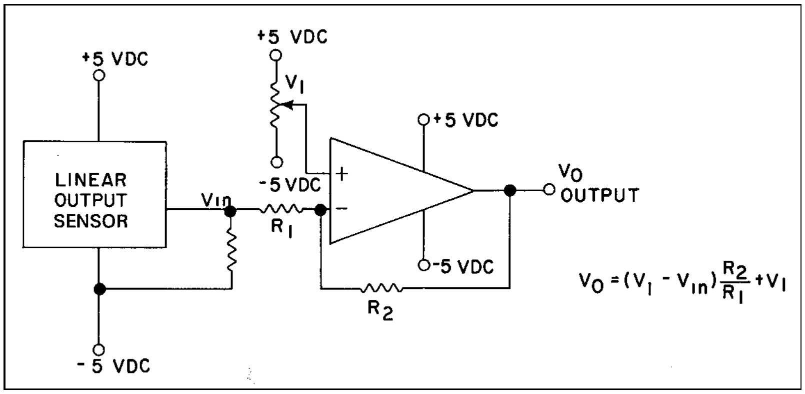

Figure 4-25 Null offset cancellation circuit

When an analog sensor is interfaced to a comparator (level detector), a digital output system results. Figure 4-26 illustrates a system consisting of an analog output sensor and comparator circuit with no hysteresis. The comparator output will remain in the OFF state until the magnetic field reaches the trigger level. The trigger level corresponds to a voltage output from the sensor equal to the reference on the minus input of the comparator. When the magnetic field is above the trigger level, the comparator's output will be ON. This circuit provides a trigger level that can be electronically controlled by adjusting R_2. Hysteresis can also be added to the circuit with the addition of a feedback resistor (dotted) between the comparator's output and positive input.

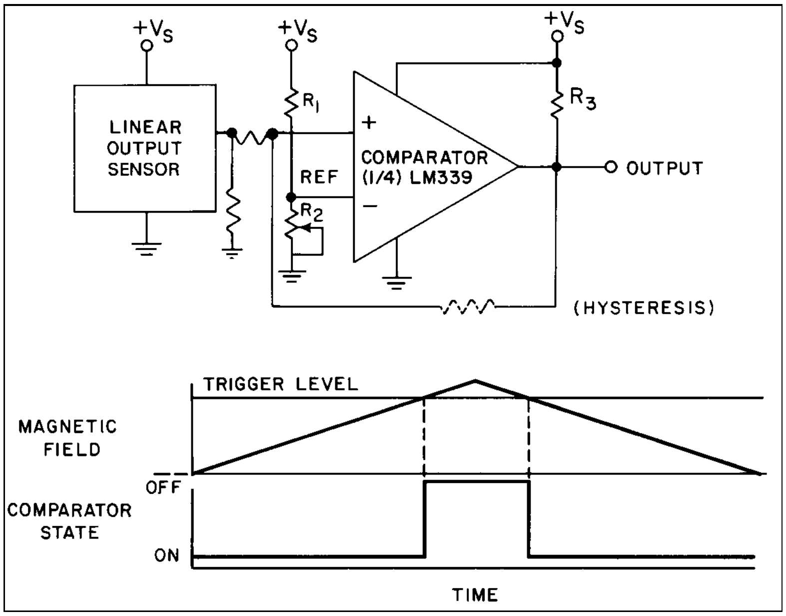

Figure 4-26 Digital system with analog sensor

When an analog output sensor is interfaced with two comparators, as shown in Figure 4-27, a window detector results. The output of the comparators will be ON only when the magnetic field is between trigger level 1 and trigger level 2. As in Figure 4-26, the trigger levels correspond to a sensor output voltage which is equal to reference voltages 1 and 2. This circuit is useful in applications where a band of magnetic fields needs to be developed.

Summary

In this chapter, the concepts and techniques necessary to interface Hall effect sensors have been explored. In conjunction with the preceding two chapters, the foundation necessary to design with Hall effect sensors has been established. The remainder of this book is devoted to putting these concepts to work in the design of Hall effect based sensing systems.

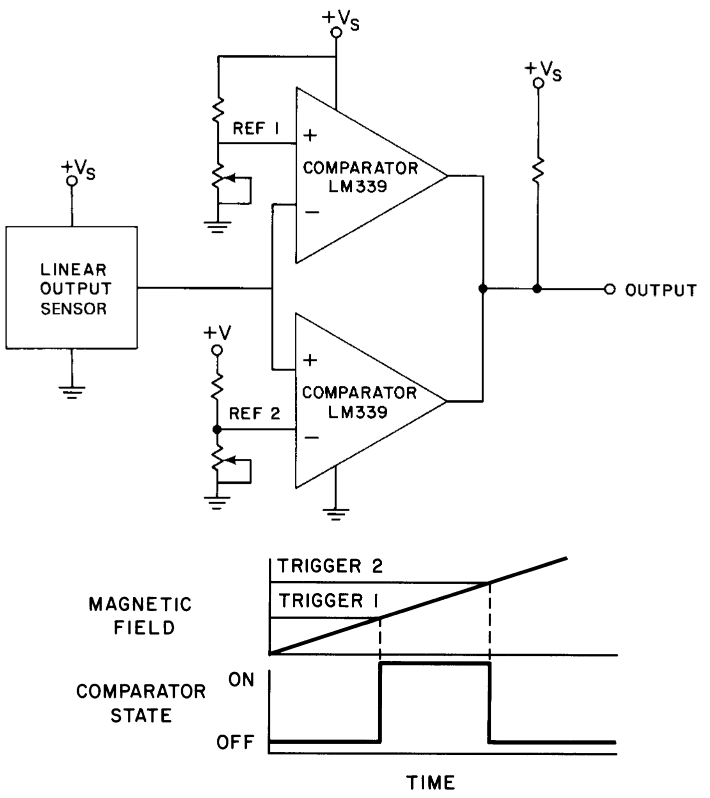

Figure 4-27 Window detector