<div align="right"># Chapter 2</div>

Hall Effect Sensors

Introduction

The Hall effect was discovered by Dr. Edwin Hall in 1879 while he was a doctoral candidate at Johns Hopkins University in Baltimore. Hall was attempting to verify the theory of electron flow proposed by Kelvin some 30 years earlier. Dr. Hall found when a magnet was placed so that its field was perpendicular to one face of a thin rectangle of gold through which current was flowing, a difference in potential appeared at the opposite edges. He found that this voltage was proportional to the current flowing through the conductor, and the flux density or magnetic induction perpendicular to the conductor. Although Hall's experiments were successful and well received at the time, no applications outside of the realm of theoretical physics were found for over 70 years.

With the advent of semiconducting materials in the 1950s, the Hall effect found its first applications. However, these were severely limited by cost. In 1965, Everett Vorthmann and Joe Maupin, MICRO SWITCH Sensing and Control senior development engineers, teamed up to find a practical, low-cost solid state sensor. Many different concepts were examined, but they chose the Hall effect for one basic reason: it could be entirely integrated on a single silicon chip. This breakthrough resulted in the first low-cost, high-volume application of the Hall effect, truly solid state keyboards. MICRO SWITCH Sensing and Control has produced and delivered nearly a billion Hall effect devices in keyboards and sensor products.

Theory of the Hall Effect

When a current-carrying conductor is placed into a magnetic field, a voltage will be generated perpendicular to both the current and the field. This principle is known as the Hall effect.

Figure 2-1 illustrates the basic principle of the Hall effect. It shows a thin sheet of semiconducting material (Hall element) through which a current is passed. The output connections are perpendicular to the direction of current. When no magnetic field is present (Figure 2-1), current distribution is uniform and no potential difference is seen across the output.

Figure 2-1 Hall effect principle, no magnetic field

When a perpendicular magnetic field is present, as shown in Figure 2-2, a Lorentz force is exerted on the current. This force disturbs the current distribution, resulting in a potential difference (voltage) across the output. This voltage is the Hall voltage (V_H). The interaction of the magnetic field and the current is shown in equation form as equation 2-1.

$$V_H \propto \mathbf{I} \times \mathbf{B} \qquad \textbf{Formula (2-1)}$$

Hall effect sensors can be applied in many types of sensing devices. If the quantity (parameter) to be sensed incorporates or can incorporate a magnetic field, a Hall sensor will perform the task.
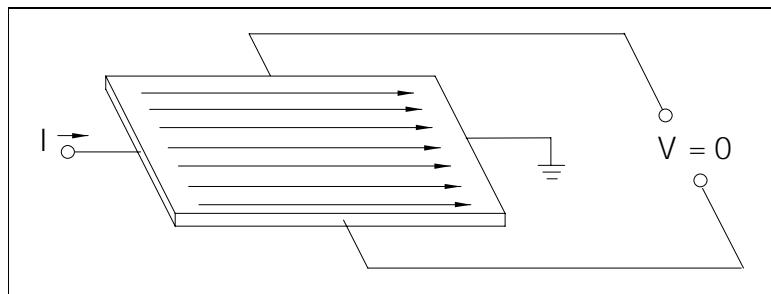
The Hall voltage is proportional to the vector cross product of the current (I) and the magnetic field (B). It is on the order of 7 $\mu v/V_s$/gauss in silicon and thus requires amplification for practical applications.

Silicon exhibits the piezoresistance effect, a change in electrical resistance proportional to strain. It is desirable to minimize this effect in a Hall sensor. This is accomplished by orienting the Hall element on the IC to minimize the effect of stress and by using multiple Hall elements. Figure 2-3 shows two Hall elements located in close proximity on an IC. They are positioned in this manner so that they may both experience the same packaging stress, represented by ΔR. The first Hall element has its excitation applied along the vertical axis and the second along the horizontal axis. Summing the two outputs eliminates the signal due to stress. MICRO SWITCH Hall ICs use two or four elements.
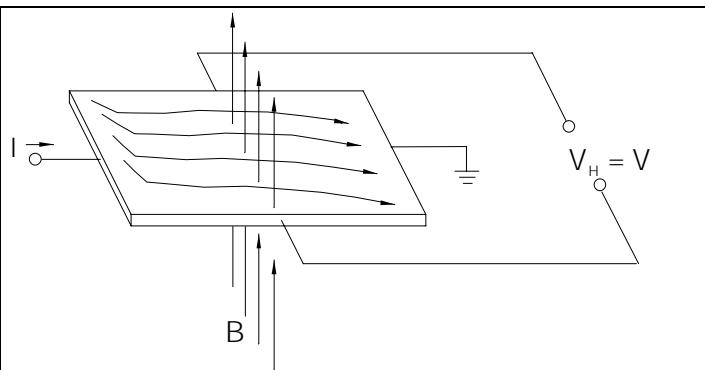

Figure 2-2 Hall effect principle, magnetic field present

Basic Hall effect sensors

The Hall element is the basic magnetic field sensor. It requires signal conditioning to make the output usable for most applications. The signal conditioning electronics needed are an amplifier stage and temperature compensation. Voltage regulation is needed when operating from an unregulated supply. Figure 2-4 illustrates a basic Hall effect sensor.

If the Hall voltage is measured when no magnetic field is present, the output is zero (see Figure 2-1). However, if voltage at each output terminal is measured with respect to ground, a non-zero voltage will appear. This is the common mode voltage (CMV), and is the same at each output terminal. It is the potential difference that is zero. The amplifier shown in Figure 2-4 must be a differential amplifier so as to amplify only the potential difference – the Hall voltage.

The Hall voltage is a low-level signal on the order of 30 microvolts in the presence of a one gauss magnetic field. This low-level output requires an amplifier with low noise, high input impedance and moderate gain.

Figure 2-3 Hall element orientation

Figure 2-4 Basic Hall effect sensor

A differential amplifier with these characteristics can be readily integrated with the Hall element using standard bipolar transistor technology. Temperature compensation is also easily integrated.

As was shown by equation 2-1, the Hall voltage is a function of the input current. The purpose of the regulator in Figure 2-4 is to hold this current constant so that the output of the sensor only reflects the intensity of the magnetic field. As many systems have a regulated supply available, some Hall effect sensors may not include an internal regulator.
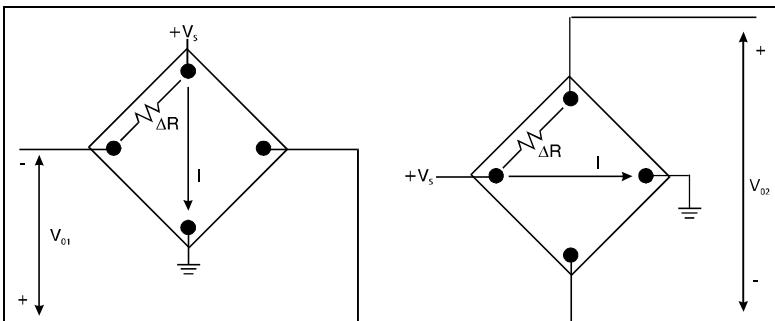
Analog output sensors

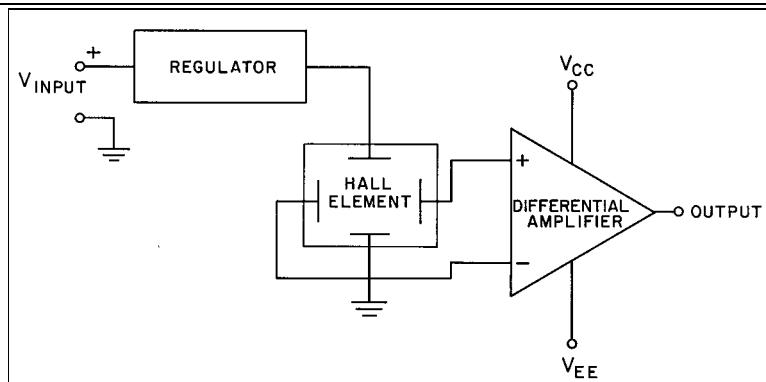The sensor described in Figure 2-4 is a basic ana-log output device. Analog sensors provide an output voltage that is proportional to the magnetic field to which it is exposed. Although this is a complete device, additional circuit functions were added to simplify the application.

The sensed magnetic field can be either positive or negative. As a result, the output of the amplifier will be driven either positive or negative, thus re-quiring both plus and minus power supplies. To avoid the requirement for two power supplies, a fixed offset or bias is introduced into the differen-tial amplifier. The bias value appears on the output when no magnetic field is present and is referred to as a null voltage. When a positive magnetic field is sensed, the output increases above the null volt-age. Conversely, when a negative magnetic field is sensed, the output decreases below the null voltage, but remains positive. This concept is il-lustrated in Figure 2-5.

The output of the amplifier cannot exceed the limits imposed by the power supply. In fact, the amplifier will begin to saturate before the limits of the power supply are reached. This saturation is illustrated in Figure 2-5. It is important to note that this saturation takes place in the amplifier and not in the Hall element. Thus, large magnetic fields will not damage the Hall effect sensors, but rather drive them into saturation.

Figure 2-5 Null voltage concept

Figure 2-6 Simple analog output sensor (SS49/SS19 types)

To further increase the interface flexibility of the device, an open emitter, open collector, or push-pull transistor is added to the output of the differential amplifier. Figure 2-6 shows a complete analog output Hall effect sensor incorporating all of the previously discussed circuit functions.

The basic concepts pertaining to analog output sensors have been established. Both the manner in which these devices are specified and the implication of the specifications follow.

Output vs. power supply characteristics

Analog output sensors are available in voltage ranges of 4.5 to 10.5, 4.5 to 12, or 6.6 to 12.6 VDC. They typically require a regulated supply voltage to operate accurately. Their output is usually of the push-pull type and is ratiometric to the supply voltage with respect to offset and gain.
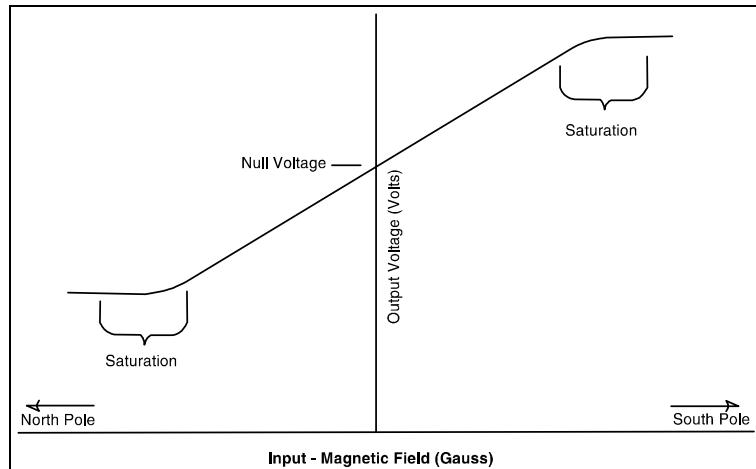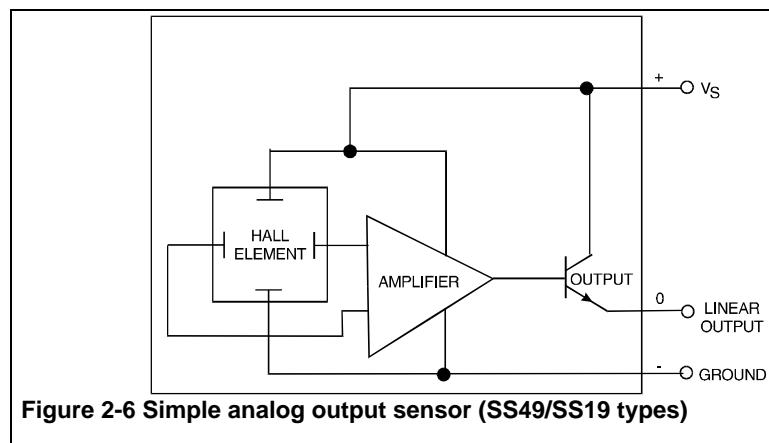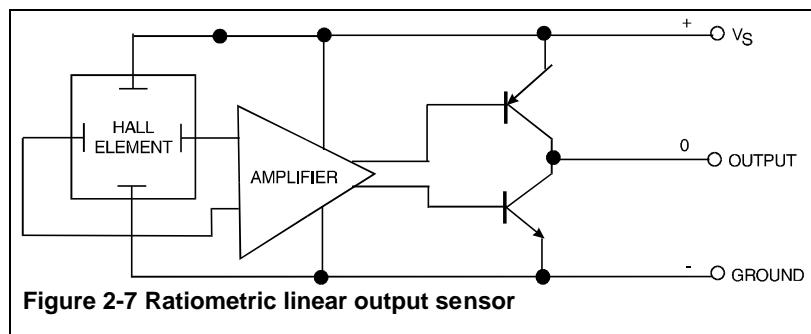

Figure 2-7 Ratiometric linear output sensor

Figure 2-7 illustrates a ratiometric analog sensor that accepts a 4.5 to 10.5 V supply. This sensor has a sensitivity (mV/Gauss) and offset (V) proportional (ratiometric) to the supply voltage. This device has "rail-to-rail" operation. That is, its output varies from almost zero (0.2 V typical) to almost the supply voltage (Vs - 0.2 V typical).

Transfer Function

The transfer function of a device describes its output in terms of its input. The transfer function can be expressed in terms of either an equation or a graph. For analog output Hall effect sensors, the transfer function expresses the relationship between a magnetic field input (gauss) and a voltage output. The transfer function for a typical analog output sensor is illustrated in Figure 2-8.

Figure 2-8 Transfer function . . . Analog output sensor

Equation 2-2 is an analog approximation of the transfer function for the sensor.

$$V_{out} \text{ (Volts)} = (6.25 \times 10^{-4} \times Vs)B + (0.5 \times Vs) \quad \textbf{(2-2)}$$

$$-640 < B(\text{Gauss}) < +640$$

An analog output sensor's transfer function is characterized by sensitivity, null offset and span.

Sensitivity is defined as the change in output resulting from a given change in input. The slope of the transfer function illustrated in Figure 2-8 corresponds to the sensitivity of the sensor. The factor of $\{B (6.25 \times 10^4 \times V_S)\}$ in equation 2-2 expresses the sensitivity for this sensor.

Null offset is the output from a sensor with no magnetic field excitation. In the case of the transfer function in Figure 2-8, null offset is the output voltage at 0 gauss and a given supply voltage. The second term in Equation 2-2, $(0.5 \times V_S)$, expresses the null offset.

Span defines the output range of an analog output sensor. Span is the difference in output voltages when the input is varied from negative gauss (north) to positive gauss (south). In equation form:

$$\text{Span} = V_{OUT} @ (+) \text{ gauss} - V_{OUT} @ (-) \text{ gauss} \quad \textbf{(2-3)}$$

Although an analog output sensor is considered to be linear over its span, in practice, no sensor is perfectly linear. The specification linearity defines the maximum error that results from assuming the transfer function is a straight line. Honeywell's analog output Hall effect sensors are precision sensors typically exhibiting linearity specified as -0.5% to -1.5% (depending on the listing). For these devices, linearity is measured as the difference between actual output and the perfect straight line between end points. It is given as a percentage of the span.

The basic Hall device is sensitive to variations in temperature. Signal conditioning electronics may be incorporated into Hall effect sensors to compensate for these effects. Figure 2-9 illustrates the sensitivity shift over temperature for the miniature ratiometric linear Hall effect sensor.
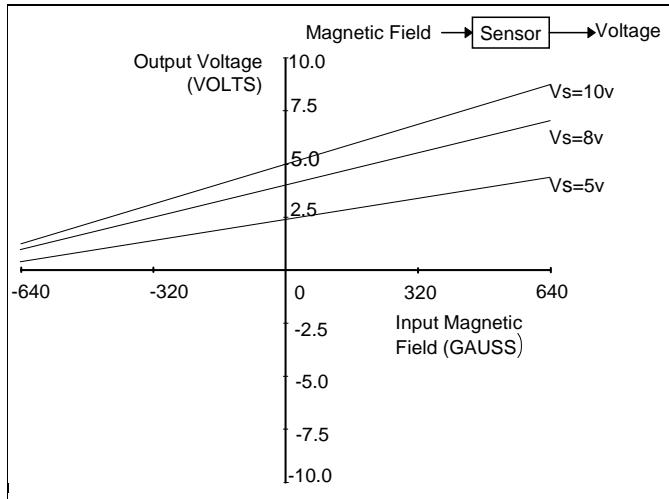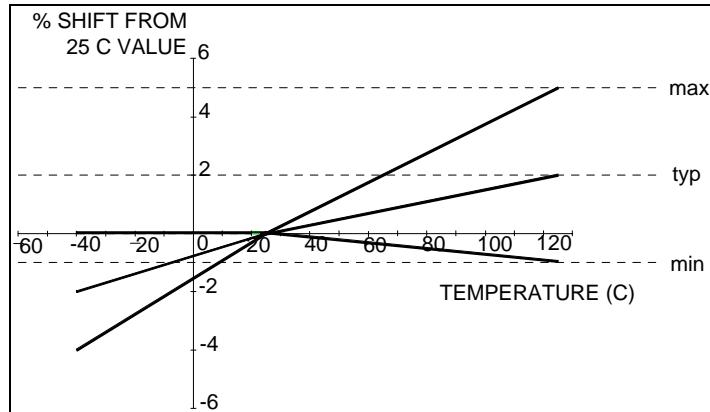

Figure 2-9 Sensitivity shift versus temperature

Digital output sensors

The preceding discussion described an analog output sensor as a device having an analog output proportional to its input. In this section, the digital Hall effect sensor will be examined. This sensor has an output that is just one of two states: ON or OFF. The basic analog output device illustrated in Figure 2-4 can be converted into a digital output sensor with the addition of a Schmitt trigger circuit. Figure 2-10 illustrates a typical internally regulated digital output Hall effect sensor.

The Schmitt trigger compares the output of the differential amplifier (Figure 2-10) with a preset reference. When the amplifier output exceeds the reference, the Schmitt trigger turns on. Conversely, when the output of the amplifier falls below the reference point, the output of the Schmitt trigger turns off.

Hysteresis is included in the Schmitt trigger circuit for jitter-free switching. Hysteresis results from two distinct reference values which depend on whether the sensor is being turned ON or OFF.

Transfer function

The transfer function for a digital output Hall effect sensor incorporating hysteresis is shown in Figure 2-11.

The principal input/output characteristics are the operate point, release point and the difference between the two or differential. As the magnetic field is increased, no change in the sensor output will occur until the operate point is reached. Once the operate point is reached, the sensor will change state. Further increases in magnetic input beyond the operate point will have no effect. If magnetic field is decreased to below the operate point, the output will remain the same until the release point is reached. At this point, the sensor's output will return to its original state (OFF). The purpose of the differential between the operate and release point (hysteresis) is to eliminate false triggering which can be caused by minor variations in input.

As with analog output Hall effect sensors, an output transistor is added to increase application flexibility. This output transistor is typically NPN (current sinking). See Figure 2-12. The features and benefits are examined in detail in Chapter 4.

The fundamental characteristics relating to digital output sensors have been presented. The specifications and the effect these specifications have on product selection follows.
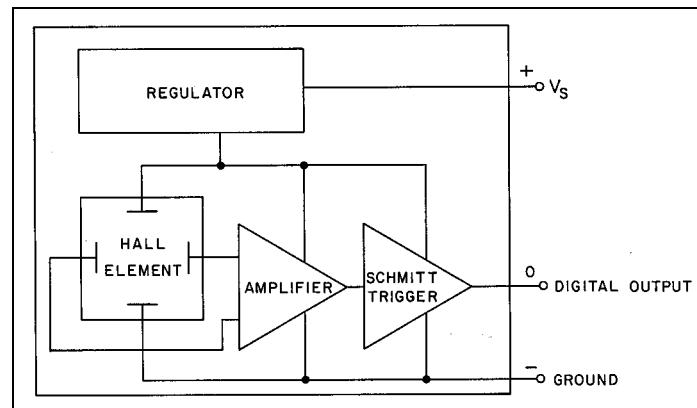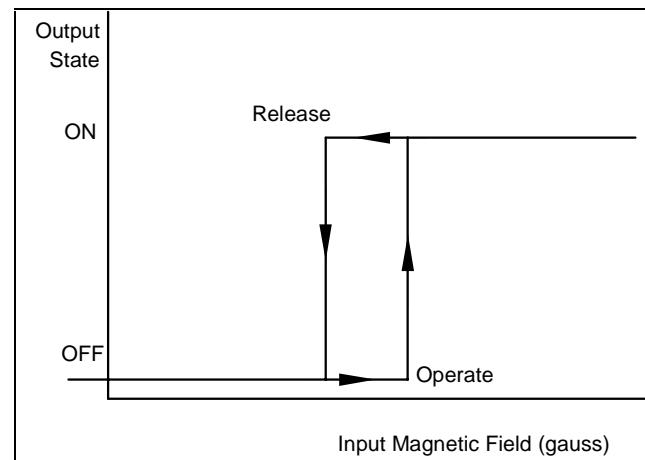

Figure 2-10 Digital output Hall effect sensor

**Figure 2-11 Transfer function hysteresis . . .
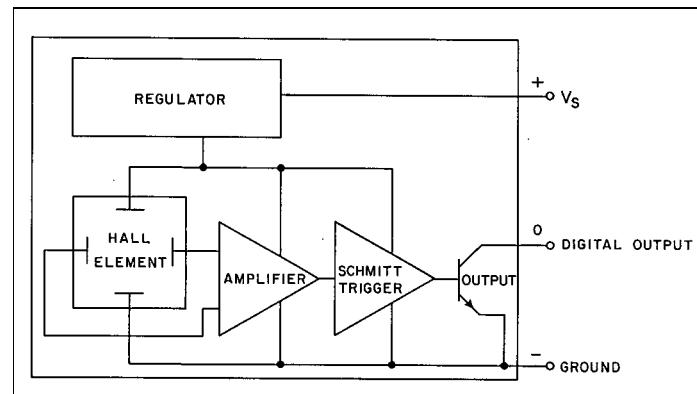Digital output sensor**

Figure 2-12 NPN (Current sinking) . . . Digital output sensor

Power supply characteristics

Digital output sensors are available in two different power supply configurations - regulated and unregulated. Most digital Hall effect sensors are regulated and can be used with power supplies in the range of 3.8 to 24 VDC. Unregulated sensors are used in special applications. They require a regulated DC supply of 4.5 to 5.5 volts (5 ± 0.5 v). Sensors that incorporate internal regulators are intended for general purpose applications. Unregulated sensors should be used in conjunction with logic circuits where a regulated 5 volt power supply is available.

Input characteristics

The input characteristics of a digital output sensor are defined in terms of an operate point, release point, and differential. Since these characteristics change over temperature and from sensor to sensor, they are specified in terms of maximum and minimum values.

Maximum Operate Point refers to the level of magnetic field that will insure the digital output sensor turns ON under any rated condition. Minimum Release Point refers to the level of magnetic field that insures the sensor is turned OFF.

Figure 2-13 shows the input characteristics for a typical unipolar digital output sensor. The sensor shown is referred to as unipolar since both the maximum operate and minimum release points are positive (i.e. south pole of magnetic field).

A bipolar sensor has a positive maximum operate point (south pole) and a negative minimum release point (north pole). The transfer functions are illustrated in Figure 2-14. Note that there are three combinations of actual operate and release points possible with a bipolar sensor. A true latching device, represented as bipolar device 2, will always have a positive operate point and a negative release point.
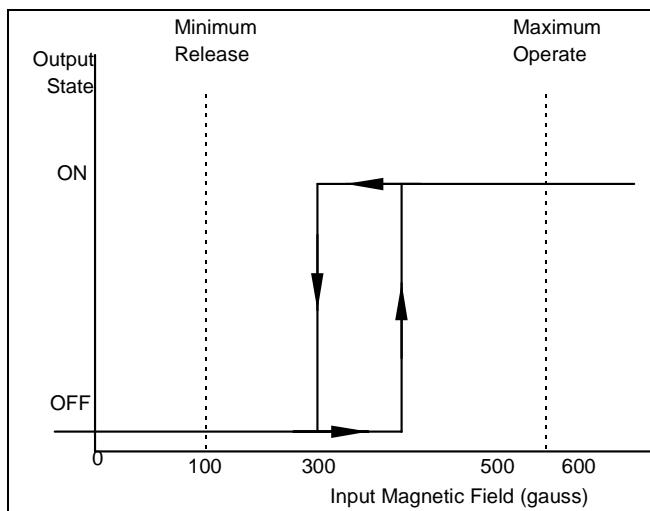
**Figure 2-13 Unipolar input characteristics . . .
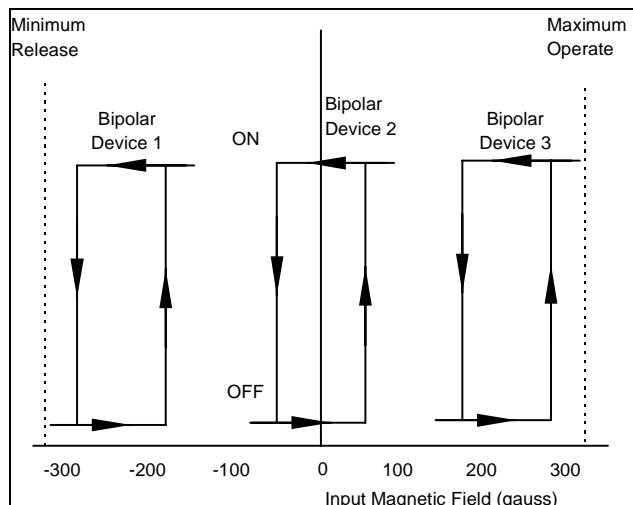Digital output sensor**

**Figure 2-14 Bipolar input characteristics . . .
Digital output sensor**

Output characteristics

The output characteristics of a digital output sensor are defined as the electrical characteristics of the output transistor. These include type (i.e. NPN), maximum current, breakdown voltage, and switching time. The implication of this and other parameters will be examined in depth in Chapter 4.

Summary

In this chapter, basic concepts pertaining to Hall effect sensors were presented. Both the theory of the Hall effect and the operation and specifications of analog and digital output sensors were examined. In the next chapter, the principles of magnetism will be presented. This information will form the foundation necessary to design magnetic systems that actuate Hall effect sensors.