Chapter 4

Integrated Sensors:
Linear and Digital Devices

While it is certainly possible to build one's own Hall-effect sensors using transducer elements and discrete signal-processing components, using techniques such as those described in Chapter 3, it is usually unnecessary to do so for most applications. Because Hall-effect sensors are widely used, a number of semiconductor companies include a variety of integrated Hall-effect sensors among their standard product offerings. These devices contain a silicon Hall-effect transducer as well as the bias, amplification, and signal-processing circuitry needed to obtain an easy-to-use output signal. These circuits come in integrated circuit packages that can be soldered into printed circuit boards, or to which discrete wires can be attached. Some examples of the packages in which Hall-effect ICs are manufactured are shown in Figure 4-1.

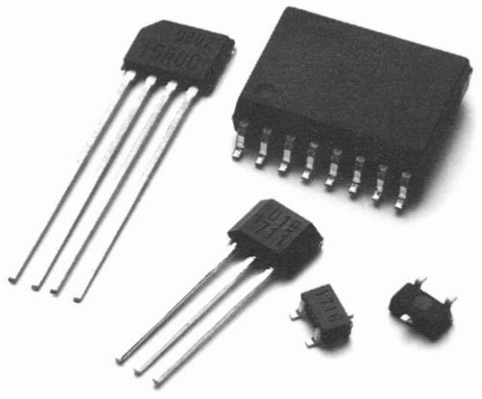

Figure 4-1: Hall-effect ICs in various packages. *(Courtesy of Melexis USA, Inc.)*

Adding electronics to the transducer allows integrated Hall-effect ICs to provide several types of functions for the user, in addition to merely providing a linear output signal. These integrated sensors can be roughly divided into four categories:

- Linear output devices
- Digital-output threshold-triggered devices (switches and latches)
- Speed sensors
- Application-specific devices ("none-of-the-above")

Linear output sensors provide a continuous output that is proportional to magnetic field strength.

Switches and latches provide a digital output that actuates and resets when an applied magnetic field exceeds and drops below preset threshold levels. These types of integrated Hall-effect sensors are by far the most widely used.

Speed sensors (also called *geartooth sensors*) consist of one or more Hall-effect transducers combined with application-specific circuitry designed to detect the passage of moving ferrous targets such as gear teeth.

Application-specific devices are arbitrarily defined by the author as those that do not fall into one of the above three categories. These devices are developed to meet the needs of a specific application, typically those of a specific customer. These devices tend to enter a manufacturer's "standard" product line when exclusivity agreements with the original customer expire.

Of all the integrated Hall-effect sensors manufactured today, the most commonly applied devices in terms of unit volume are switches, latches, and linear-output devices. These simple devices are the fundamental building blocks implementing Hall-effect based applications. This chapter will describe the characteristics of these particular integrated sensors.

4.1 Linear Sensors

From a user-level standpoint, a linear Hall-effect sensor provides an output voltage proportional to applied magnetic field. Integrated linear Hall-effect sensors employ many of the techniques described in Chapter 3, suitably adapted for use on a monolithic IC. By integrating the support circuitry required to interface to a Hall transducer, significant advantages are obtained in terms of size, power consumption, and cost.

Linear Hall ICs are typically based on one of three overall architectures: linear, transducer switching, and digital.

Figure 4-2 shows the typical organization of a *linear architecture* linear Hall IC. The key components are a bias source, the Hall sensor, a differential amplifier, and a regulator circuit for consistently biasing the amplifier. The amplifier is often designed so that its gain and offset can be permanently adjusted at the time of manufacture, typically through the use of either fusible links or through "zener zapping." For good stability, this type of sensor is almost always made in a precision bipolar process, resulting in fairly large die sizes. The Allegro Microsystems A1301 is an example of this type of device.

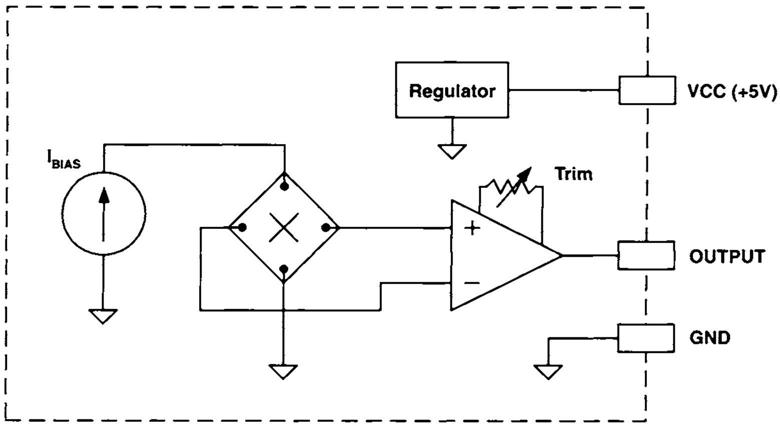

Figure 4-2: Linear Hall-effect IC.

Transducer switching architectures, often referred to as *chopper-stabilized*, *auto-zeroing*, or *auto-nulling*, utilize the dynamic offset compensation techniques described in Chapter 3. A typical auto-nulling Hall IC is shown in Figure 4-3.

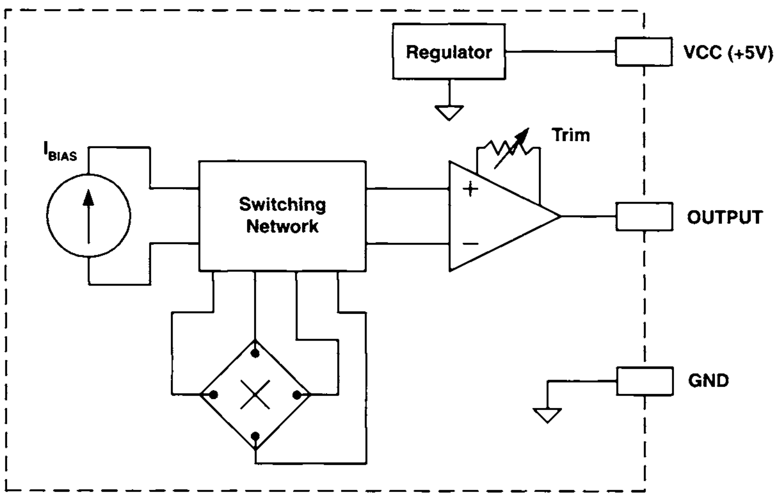

Figure 4-3: Auto-nulling linear Hall-effect IC.

Because auto-nulling techniques can greatly reduce the effects of amplifier input offset in addition to the offsets resulting from the Hall-effect transducer, CMOS amplifier circuits, with their notoriously poor performance, can be effectively used for signal processing. One advantage of implementing this type of sensor in CMOS is that the switching network is straightforward to implement with CMOS transistors. Although it is possible to use bipolar devices to perform the necessary switching functions, such circuits can be complex and difficult to implement. Additionally, since circuitry can be built more densely in CMOS processes than in precision bipolar processes, a CMOS Hall-effect sensor can incorporate more features than a bipolar one of comparable cost. For this reason, auto-nulled linear Hall-effect sensors such as the Melexis MLX90215 can incorporate user-programmable gain, offset, and temperature compensation, all for a modest additional cost over that of nonadjustable bipolar linear devices.

The use of CMOS technology can be taken to even more of an extreme in the case of a linear Hall-effect sensor that uses digital signal processing techniques. In this device, the signal from the Hall transducer is amplified and fed into an analog–to-digital converter (ADC). Gain and offset correction are then performed digitally, through binary multiplication and addition (Figure 4-4). The result is then converted back into an analog signal with a digital-to-analog converter (DAC).

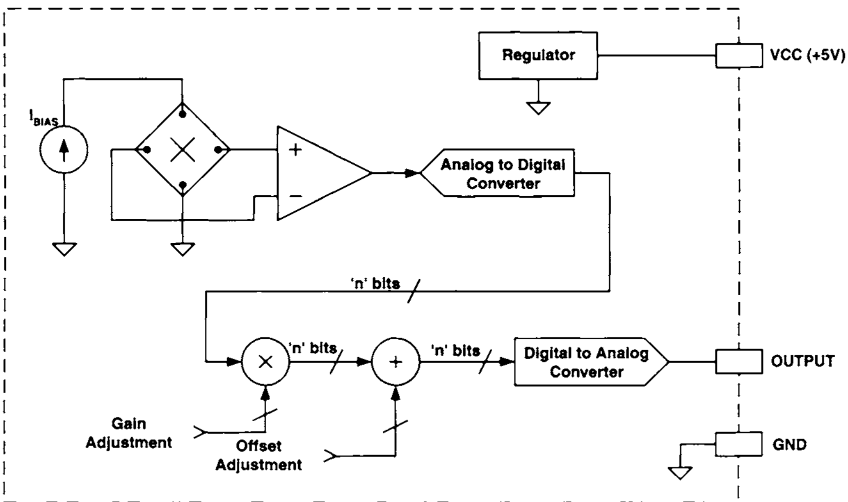

Figure 4-4: Digital linear Hall sensor

This digital signal processing (DSP) architecture offers many implementation advantages. Because the sensor's signal processing chain now consists almost entirely of digital logic, it can be fabricated with very high-density processes, reducing manufacturing cost. Another benefit of this approach is that gain and offset can now be stored in tables that are accessed as a function of temperature, allowing for very precise calibration of the device. One example of this type of device is the Micronas HAL805.

While there are quite a few ways in which to implement a linear Hall sensor, a device's performance can be usefully described by a few common characteristics. Some of the more important of these characteristics are described in the following sections.

4.2 Linear Transfer Curve

The most basic characterization of a linear transducer is its transfer curve. This function defines the relationship between the magnetic field sensed by the device and its corresponding electrical output. An example of a transfer curve from a "typical" Hall sensor IC is shown in Figure 4-5. Some of the defining features of this curve are:

1) ***Zero-flux Intercept.*** This defines output voltage under conditions of zero magnetic field. This point is variously referred to as *quiescent voltage out* (Q_{VO}), and *zero-field* offset.

2) ***Slope*** dV/dB. This feature defines the sensor's gain, or sensitivity. Because the slope is not constant over the transfer curve and is difficult to directly measure at a given point, manufacturers typically pick two points (B_1, B_2) within the device's "linear" range, often symmetric about zero flux, and calculate average sensitivity over this range as $S = (V_2 - V_1)/(B_2 - B_1)$.

3) ***Output Saturation Voltages.*** Unless unusual design measures are taken, the signal output range of a device operating from a single 5V power supply will be limited between 0V and 5V. The minimum and maximum limits between which the output signal can vary are known as the saturation points. Since most linear sensors are designed to operate from a single 5V supply, negative saturation (V_{SAT-}) is usually specified with respect to ground, while positive saturation (V_{SAT+}) is specified as how close the output can swing to the positive supply rail. Because many popular analog-to-digital converters have input ranges of 0–5 volts, most manufacturers offer "rail-to-rail" outputs on many of their newer linear Hall-effect sensors, for ease of interface. While the output voltages on these devices can't really swing all the way to the supply rails, they can often come within a few tens of millivolts if they are not required to drive an excessive load.

4) ***Useful linear range.*** Even though a device's output can have a wide range of operation before it saturates, the linearity may significantly degrade long before saturation is reached. The useful linear range is both a function of the device and the nonlinearity error a given application can tolerate. For most modern Hall sensor ICs, the linearity error is well below 1% over the majority of their specified sensing range. The limits of the effective linear range are denoted as B_{SAT+} and B_{SAT-} on the transfer curve. Note that, in the example shown, the output voltage continues to increase and decrease past these limits, but becomes significantly more nonlinear. In addition to being a function of a given sensor's design, the useful linear output range can also be a function of the electrical load the sensor must drive.

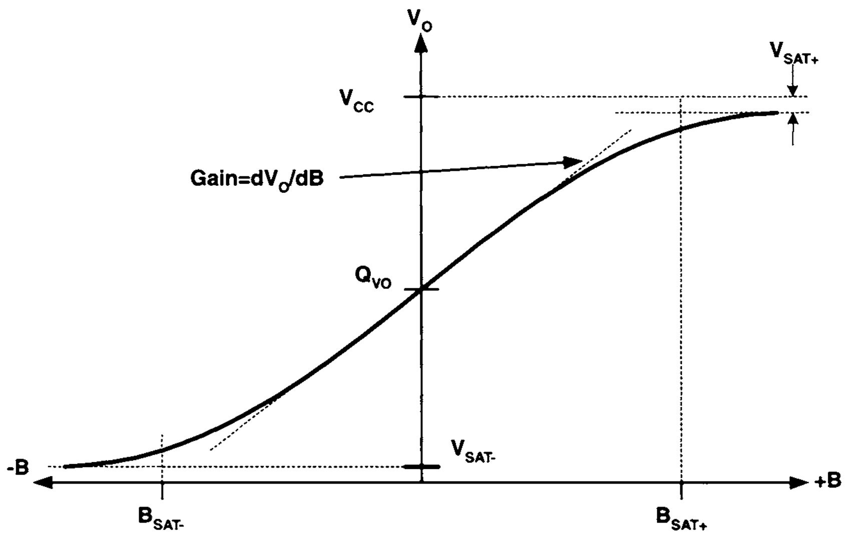

Figure 4-5: Linear Hall-effect sensor transfer curve.

4.3 Drift

Unfortunately, a transfer curve is only valid under a given set of environmental conditions. For many Hall-effect sensor applications, the most germane environmental influence is usually temperature. While it is certainly possible to characterize a device with a family of transfer curves, each corresponding to performance at a given temperature, the more typical approach is to provide characterization of only the sensitivity and zero-flux output voltage over temperature.

Simplifying the temperature characterization in this manner makes it easier to specify screening parameters for testing individual ICs. Devices can be readily screened against both absolute limits and drift limits for both zero-flux output voltage and sensitivity.

One important point to keep in mind is that low-temperature drift for either zero-flux offset or sensitivity (gain) does not necessarily imply low temperature drift for the other. This is particularly evident in the case of auto-nulled devices, which can exhibit offset drifts on the order of a few gauss over their rated temperature range. Some of these same devices can also exhibit sensitivity drifts on the order of ±5% over that same temperature range, a drift comparable to that of many older bipolar Hall-effect sensors. Conversely, an old-style bipolar Hall sensor can have excellent sensitivity stability, but poor offset drift characteristics. The moral of this story is that you need to determine which device characteristics are important for your application and then to make sure that the device selected provides adequate performance in those areas.

4.4 Ratiometry

One of the primary design objectives when developing a Hall-effect sensor is to develop a device that is minimally susceptible to environmental influences. There is, however, one environmental factor, other than magnetic field, to which many devices are deliberately made very sensitive. Many linear Hall-effect sensor ICs are designed so that their sensitivity and zero-flux offset are linear functions of the supply voltage. A device with this property is referred to as having a ratiometric output.

A ratiometric Hall sensor has a zero-flux output voltage set at some fraction (often ½) of the supply voltage, and a sensitivity that is proportional to the supply voltage. This means that if you vary the supply voltage by 10%, the zero-flux output will increase by 10%, and so will the sensitivity. While increasing the device's sensitivity to power supply variation may seem to be counterproductive, a ratiometric sensor can actually be very useful as a system component.

Consider the case in which the output of a Hall-effect sensor is fed into an analog-to-digital converter (ADC) shown in Figure 4-6. In this example, a voltage regulator provides both the power supply for the Hall-effect sensor (V_{CC}) and a reference voltage (V_{REF}) for the ADC.

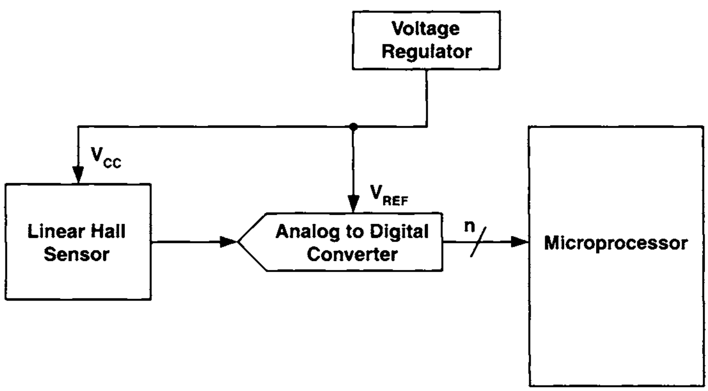

Figure 4-6: Example of system benefiting from a ratiometric Hall-effect sensor.

In this example, first let us consider the case of a nonratiometric sensor, in which the Hall-effect sensor provides a fixed sensitivity regardless of supply voltage. If the voltage regulator's output voltage were to rise, the Hall-effect sensor would still provide the same sensitivity as it would at a lower regulator voltage. Because the full-scale span of the ADC would increase with rising regulator voltage, the sensor's output would "fill" less of the ADC's range, resulting in smaller reported measurements by the ADC.

One solution might be to insist on using a highly stable voltage regulator to prevent this type of error from occurring. To implement a Hall-effect sensor with a sensitivity that is supply-voltage independent, however, requires that some kind of precision voltage or current reference be put inside the sensor IC. In this situation, there are now really two separate references that must be stable—one inside the sensor and one outside. It is always more difficult to maintain precision across two references than one.

Now let us consider the case in which the gain and offset of the Hall sensor is proportional or ratiometric to its power supply. If the voltage regulator's output should increase, the sensor's offset voltage and sensitivity will increase proportionately. The ADC's input span will also increase by the same amount. The sensor's output range will map to the ADC's input range in the same way regardless of small variations in regulator voltage. This means that, for a given magnetic field, the ADC will output the same binary code independent of the reference voltage.

Ratiometric output Hall sensors, however, are not without their drawbacks. To make absolute measurements, a stable voltage source is needed at some point, if only for initial calibration. Another problem is that of power supply noise rejection. For the case of a device exhibiting "ideal" ratiometric behavior, you would expect to see approximately half of the power supply noise to appear at the output. The power-supply noise susceptibility of actual devices will vary depending on the details of their implementation.

4.5 Output Characteristics

The output of a linear Hall-effect sensor can be usefully modeled by a voltage source (v_O) in series with a resistor (r_O), as shown in Figure 4-7.

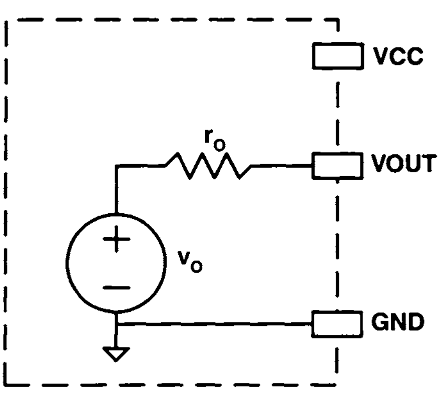

Figure 4-7: Equivalent model of linear Hall-effect sensor output.

Most contemporary devices employ negative feedback in their output amplifier stages, mainly because this improves output linearity. Negative feedback also provides an additional benefit of low dynamic output impedance, often a few ohms or less. The low output impedance of such devices simplifies the design of interface circuits. When these types of sensors are used to drive load impedances greater than a few thousand ohms, gain errors resulting from loading effects tend to be minimal.

A low output impedance, however, does not imply that a given sensor can sink or source a large amount of output current. Typical output currents tend to be limited to a few milliamps. If a load circuit sinks or sources more than the rated current from a device, it can seriously degrade the device's effective gain, zero-flux offset, and linearity. In some cases, excessive output current can also damage the device.

4.6 Bandwidth

The bandwidth, or frequency response, of a linear system can be described by a Bode plot, which is a graph of gain and phase lag vs. frequency. For both traditional and practical reasons, the frequency and gain axis are usually expressed in either logarithmic units (dB for gain) or on a log scale (for frequency). A Bode plot corresponding to what is called a "first-order, low-pass system" is shown in Figure 4-8.

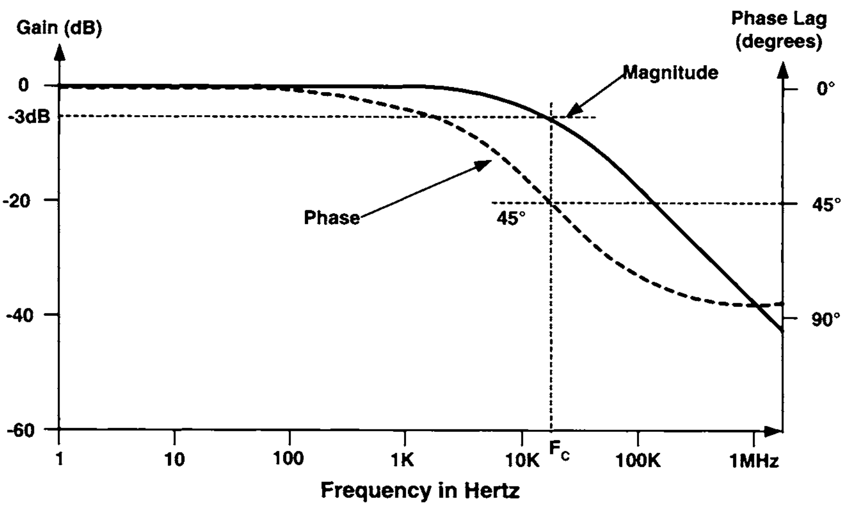

Figure 4-8: Bode plot of first-order linear system.

Some of the key features of the system described in the Bode plot are:

1) ***Corner frequency*** F_C, often called the –3 dB point. At this frequency the value of system gain or sensitivity is only $1/\sqrt{2}$ (0.707) of its value at DC (zero frequency).
2) ***Attenuation rate***. Beyond the corner frequency the sensitivity of a first-order system rolls off at the rate of –20 dB per decade of frequency. Another way to look at it is that the response drops a factor of 10 for every 10× increase in frequency.

3) ***Phase shift***. At the corner frequency, the system will delay a sinusoidal input signal by 45°. As one increases the signal frequency, this phase delay increases asymptotically to 90°.

While measurements such as the corner frequency describe a system's response to sinusoidal stimuli, they also provide some insight into how a device behaves in response to other stimuli. One common example is the system's response to an input in the form of an abrupt step, usually called the *step response*. The time that a first-order system needs to settle to within 37% of its final value (called the system *time constant*, represented by τ) is given by $1/(2\pi f_c)$. Figure 4-9 shows the step response of a first-order, low-pass system.

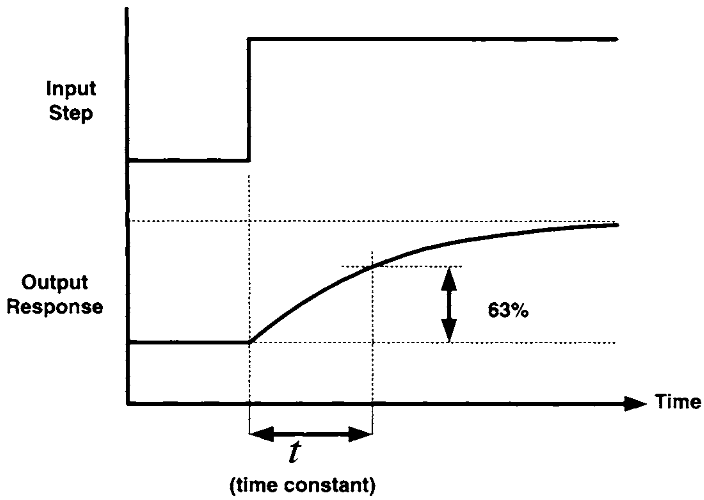

Figure 4-9: Step response of first-order, low-pass system.

The amount of time this system needs to settle to within a specified error bound can be expressed as a function of τ, as shown in Table 4-1.

Table 4-1: Error vs. settling time, ideal first-order system.

Settling time in τ units	% Error
1	36.8
2	13.5
3	5.0
4	1.8
5	0.6

A typical linear Hall-effect sensor has a corner frequency in the range of 10 kHz–25 kHz. This corresponds to a τ of about 6 to 16 microseconds.

Although a linear Hall-effect sensor is much more complex than a first-order system, especially if it employs auto-nulling techniques, using a first-order model is a useful approximation for many applications. Manufacturers of linear Hall-effect devices will usually publish "typical" corner frequency values in the data sheets for their devices.

4.7 Noise

Noise can be loosely defined as any signal you are not interested in seeing. All linear electronic systems generate some amount of internal noise, which they add to their output signal. This is also true for linear Hall-effect sensors. Manufacturers typically specify the internal noise of their linear Hall-effect sensors in one of two ways. The first is to express it as a peak-to-peak measurement, when looked at over a specified frequency range. The other method is to express the noise as an RMS (root-mean-square) equivalent noise voltage, also over a specified frequency range. Comparing peak-to-peak noise measurements to RMS noise measurements is difficult, especially if they are specified over different frequency ranges. Fortunately, detailed noise measurements for a given device can be readily performed with common electronics lab equipment such as a spectrum analyzer or an RMS voltmeter. A spectrum analyzer is an especially useful tool because it tells you how much noise appears at any given frequency. Knowing the frequency distribution of the noise often allows it to be at least partially filtered out.

4.8 Power Supply Requirements for Linear Sensors

Modern linear Hall-effect sensors have modest power supply requirements. In contrast to many analog circuits, linear Hall-effect sensors almost always operate from a single positive power supply (often +5V or +12V) for operation. Current consumption through the power supply lead is often less than 10 mA. A power supply decoupling capacitor, with a value typically ranging between 0.001 μF and 0.1 μF is often connected across the sensor's power supply terminals to reduce noise and guard against spurious operation. Power supply decoupling is especially important for ratiometric sensors, as power supply noise can readily couple through to the output.

While many integrated Hall sensors (switches, latches, speed sensors) have significant protections against conditions of supply voltage overload and reversal (reverse battery protection), many linear devices, especially those providing rail-to-rail output drive capabilities, don't. Linear devices tend to be much more susceptible to electrical damage through the power supply terminals than their digital counterparts. Special care should be taken to ensure that devices are not exposed to power supply conditions that exceed their absolute maximum ratings.

4.9 Temperature Range

Linear Hall-effect sensors are available over a number of operating temperature ranges. The most common are:

Commercial:	0° to 70°C
Industrial:	–40° to 85°C
Automotive:	–40° to 125°C

Devices are also sometimes available over other ranges. Those intended for under-the-hood (engine compartment) automotive applications are often rated to operate at temperatures up to 150°C.

4.10 Field-Programmable Linear Sensors

Sensor-based products are often required to meet some kind of parametric performance requirements. For example, in the case of a position sensor, the device may be required to provide a predictable change in voltage output corresponding to a specified change in positional input. The individual components of a Hall-effect-based sensing system all have some finite unit-to-unit variation associated with them. The magnetic components used in the assembly are also subject to variation in material properties and dimensions, resulting in unit-to-unit variation in magnetic output. The Hall-effect sensors will also show some unit-to-unit variation in their sensitivities and offsets. The "stack-up" of all these sources of variation can make it exceedingly difficult to implement a design that meets a tight set of performance objectives.

While it is often possible to perform a unit-by-unit adjustment of the magnetic and mechanical portions of a sensor to meet a performance target, these kinds of operations may be difficult to realize in a cost-effective manner in a production environment. Another option is to add external circuitry to the sensor to allow for gain and offset adjustment. Again, however, this can add considerable cost to a product.

One recently available solution that has emerged to address this problem is the field-programmable linear Hall-effect sensor. Many types of Hall sensor ICs are adjusted electronically on a one-time basis at the time of manufacture. The idea of the field-programmable linear Hall-effect sensor, however, is to allow the end-user to perform this adjustment, after the device has been assembled into the final product. A block diagram of a typical field-programmable linear sensor is shown in Figure 4-10.

A typical field-programmable sensor provides several adjustable features:

Coarse and Fine Gain – A coarse gain setting is often provided to select a general range of sensitivity (mV/gauss) for the sensor, while the fine range setting is used for trimming the sensitivity to exactly what the user wants. For example, one may select a coarse range of 1–2.5 mV/gauss, and then use the fine range to adjust the gain to 1.50 mV/gauss. A combination of coarse and fine gain settings is typically provided because

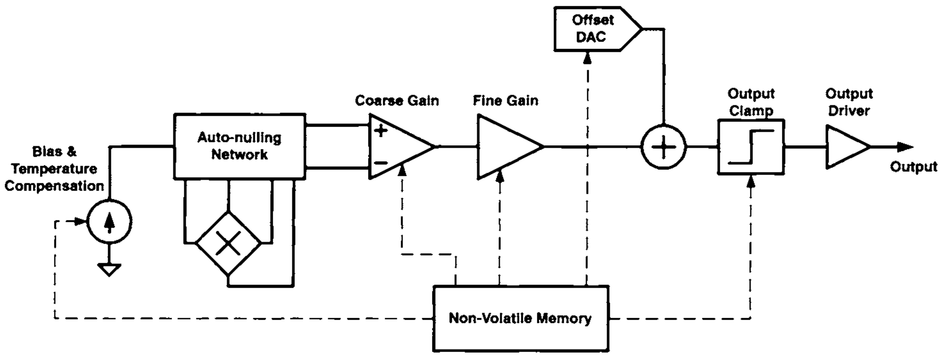

Figure 4-10: Field-programmable linear hall sensor.

it is usually simpler and less costly to implement two separate gain stages, one with wide dynamic range and the other with high resolution, than it is to implement a single stage with comparable dynamic range and resolution.

Output Offset Voltage – A DAC is often provided to adjust the output offset voltage. While offset voltages in modern auto-nulled linear Hall sensors are typically fairly low to begin with, this feature is often more useful to deliberately bias the output. For example, if the device will only be sensing fields of one polarity, a negative offset can be set so the device will output zero volts for zero field. Any applied field would then drive the output up towards the positive supply rail (e.g., +5V). For a typical nonprogrammable device, in comparison, the output for zero flux is usually a voltage halfway between ground and the positive supply rail (e.g., ~2.5V). In this application, the ability to offset the output effectively increases the device's output signal swing. Another application for adjusting the output voltage offset is to offset the effects of any baseline applied field. As an example, consider a position sensor assembly where the magnetic field varies from 100 gauss to 200 gauss from the beginning to the end of its travel range. By offsetting the Hall-effect sensor's output voltage to compensate for the 100-gauss starting point, the sensor's output voltage could be 0 volts at the beginning point of travel. By appropriately adjusting the gain, one could also make the sensor report 5V at the endpoint of travel.

Output Clamp – For some applications it is desirable to limit the sensor's output voltage swing to a narrow range. This is common when designing sensors into systems that must be able to identify failures and attempt to "fail safe." As an example, consider a sensor operating from a +5V supply and providing a valid output ranging from 0V to 5V. In the event the sensor became disconnected from a system relying on its output, that system would read zero volts, and have no way of detecting the fault. Similarly, if the sensor output line was to be shorted to the +5V sensor supply line, the monitoring system would see +5V and also have no way of determining that there was a fault condition. A clamping function can be used to limit the sensor's output voltage excursion to a known voltage range, such as 1V to 3V. Figure 4-11 shows the effects of a clamping function on the sensor's output voltage.

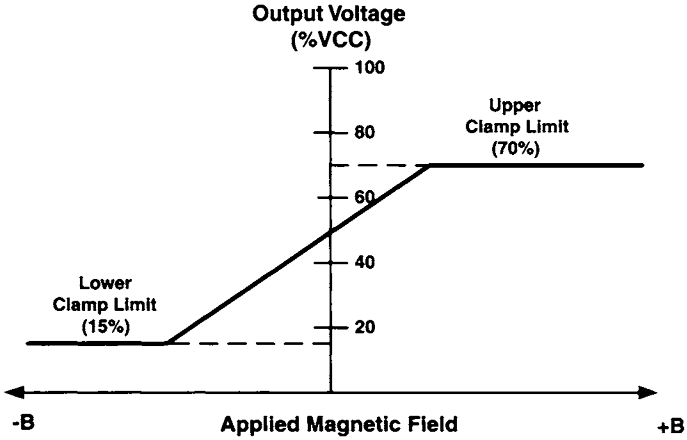

Figure 4-11: Effect of clamping function.

Because the sensor limits its valid output signals to levels located between the clamp limits, any signal falling outside these limits can then be interpreted as a fault condition by downstream electronics, and handled appropriately. Field-programmable sensors often provide the user with the ability to either select from several predetermined clamping limits, or provide the ability to set the clamp limits at arbitrarily selected voltage levels.

Adjustable Temperature Compensation – By making the transducer bias current a function of temperature, it is possible to make the sensor's overall gain also vary with temperature. While temperature coefficients are usually things to be minimized in the case of traditional nonprogrammable linear sensors, adjustable temperature coefficients can be a valuable feature in a user-programmable device. The primary application for setting the sensor's temperature coefficient for gain is in matching its response so as to compensate for the temperature coefficients of magnetic materials it may be used to sense. For example, NdFeB magnets typically have a negative temperature coefficient on the order of –0.1%/°C, meaning that their magnetic field output goes down as temperature goes up. By setting the sensor's temperature coefficient to offset that of the magnet (e.g., +0.1%/°C) it is possible to reduce the system's overall temperature coefficients to very low levels.

4.11 Typical Linear Devices

Table 4-2 lists a few typical linear Hall-effect linear ICs from various manufacturers, as well as their nominal room-temperature gains.

Table 4-2: Selected linear hall ICs.

Device	Manufacturer	Nominal Gain (mV/G)	Comments
A1301	Allegro	2.5	Continuous time, Not auto-nulling
A1373	Allegro	Note 1	Auto-nulling
MLX90251	Melexis	Note 1	Auto-nulling
HAL805	Micronas	Note 1	DSP

Note 1: Parameter is user-programmable.

4.12 Switches and Latches

Many magnetic sensing applications merely require knowing if a magnetic field exceeds a given threshold; a detailed measurement of the field is unnecessary. Because Hall-effect sensors are frequently used in this type of application, manufacturers have found it worthwhile to incorporate threshold-sensing electronics into their integrated sensors. The resulting sensor ICs provide a digital On/Off output. A block diagram of a "digital" or threshold-sensitive Hall-effect sensor is shown in Figure 4-12.

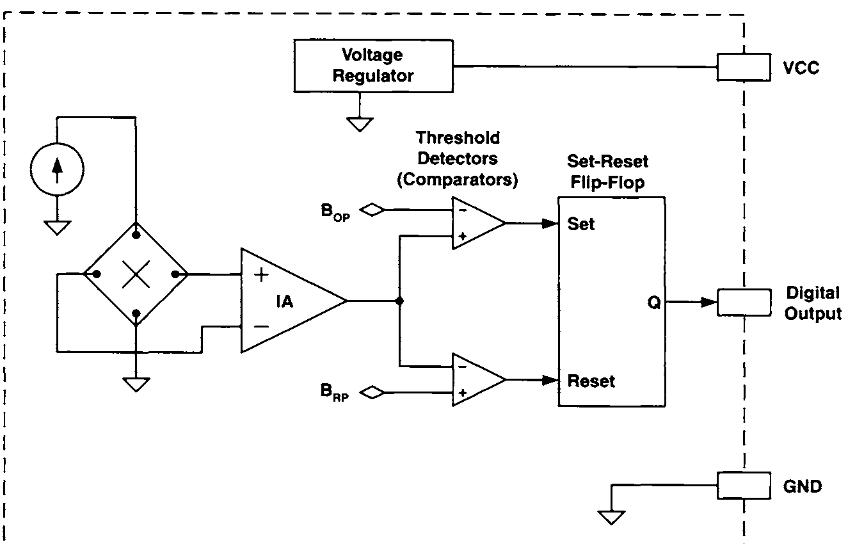

Figure 4-12: Functional block diagram of threshold-sensitive Hall IC.

A digital Hall-effect sensor essentially takes a linear device (regulator, bias circuit, Hall transducer, and amplifier) and adds a threshold detector and a digital output driver.

As in the case of linear devices, auto-nulling circuitry is often employed to improve stability. When the value of the sensed magnetic field exceeds an arbitrary turn-on threshold (often referred to as B_{OP}, for B, Operate Point), the upper comparator activates the SET input on the flip-flop, forcing it into the ON state. The flip-flop subsequently drives the output ON. When the value of the magnetic field drops below an arbitrary turn-off threshold (often referred to as B_{RP}, for B, Release Point) the lower comparator activates the RESET input of the flip-flop, forcing it into the OFF state. The output is then driven into the OFF state. When the value of the magnetic field is between the two limits, the flip-flop maintains the state to which it was last set or reset. This effect is called hysteresis, and prevents the output of the device from oscillating between the ON and OFF states when the magnetic field is near a threshold. The amount of hysteresis (B_H) for a given device is determined by $|B_{OP} - B_{RP}|$. Figure 4-13 shows two ways of viewing the behavior of a digital-output Hall sensor. If one ramps the magnetic field (B) up and down again as a function of time (Figure 4-13a), the device turns on when the field exceeds B_{OP}, and the device turns off when the field is reduced below B_{RP}. Digital Hall-effect devices are characterized by ramping a known magnetic field up and down and noting the flux densities (B) at which the device turns on and turns off.

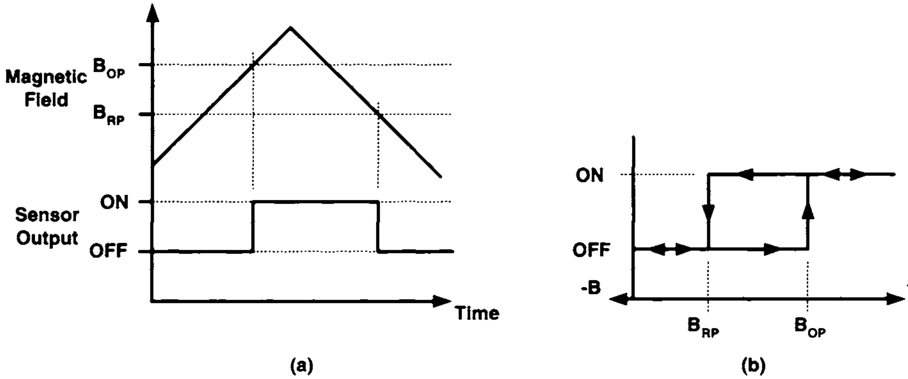

Figure 4-13: Digital sensor reaction to ramped field (a), and transfer function (b).

Another way to visualize the device's behavior is to plot the transfer curve of output vs. magnetic field, as is shown in Figure 4-13b. Because the transfer function varies depending on the direction in which one sweeps the magnetic field, one ends up with two overlapping curves, with the width of the "eye" between the up and down curves indicating the amount of hysteresis.

One important point to remember is that the digital sensors described in this section react to magnetic field as an algebraic quantity. This means that a "positive" field is always interpreted as greater than a "negative" field. While there are devices that respond to the absolute value of the applied field, they constitute a minority of available devices and will be discussed in a later section. For various historical reasons, most contemporary digital Hall-effect sensors are designed so that a South magnetic pole presented to their front surface is interpreted as a positive field, while a North magnetic pole similarly presented is interpreted as a negative field.

4.13 Definition of Switch vs. Latch

The points at which B_{OP} and B_{RP} are set have a profound effect on how the sensor behaves in responses to magnetic stimuli. Assuming that $B_{OP} > B_{RP}$, the three cases are:

1) $B_{OP} > 0, B_{RP} > 0$
2) $B_{OP} > 0, B_{RP} < 0$
3) $B_{OP} < 0, B_{RP} < 0$

In case #1, where both B_{OP} and B_{RP} are positive, the device remains normally off when no magnetic field is applied, turning on only when a sufficiently strong, positive field is sensed. When the field is removed the device returns to the OFF state. This device is called a Hall-effect switch.

In case #2, where B_{OP} is positive and B_{RP} is negative, the device can be turned on by a sufficiently strong positive magnetic field, but only can be turned off with a sufficiently strong negative field. When the magnetic field is removed, the device remains in whatever state it presently is in. Because of this memory, or latching effect, this device is called a Hall-effect latch. Case #3 follows on the next page.

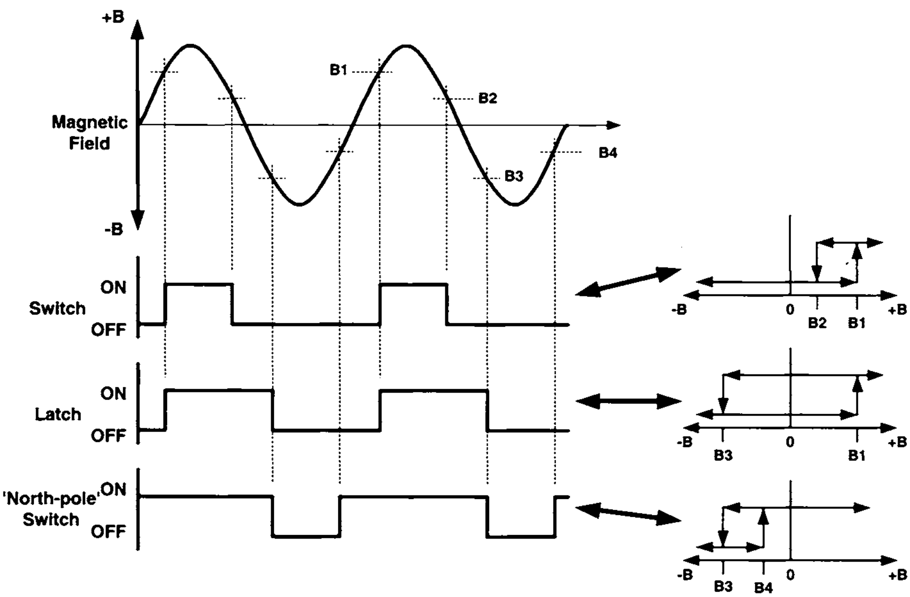

Figure 4-14: Behavior of switch (a), latch (b), north-pole switch (c).

Finally, in case #3, where both B_{OP} and B_{RP} are negative, the device remains normally on in the absence of applied field, and can only be turned off by a sufficiently strong negative field. Devices that exhibit this behavior are commonly referred to as North-pole switches, at least in the case when positive magnetic field is defined as South pole.

Figure 4-14 illustrates the behavioral differences among the three cases described previously. Now that we have described how digital Hall-effect sensors behave, and the concepts of operate and release points (B_{OP}, B_{RP}), and hysteresis (B_H), we will describe some of the other characteristics used to specify the devices.

4.14 Switchpoint Stability

The parameters B_{OP}, B_{RP}, and B_H all will drift over variations in ambient temperature and power supply voltage. For modern Hall-effect sensors, switchpoint (B_{OP}, B_{RP}) variation as a function of power supply voltage is usually minimal. Temperature-induced variations in the switchpoints is more of a concern in most applications. Hall-effect IC manufacturers will usually list limits within which these parameters must remain under a given range of conditions on their device data sheets.

Less commonly will a manufacturer place limits on the drift of these parameters. This is mainly because to do so requires the ability to track individual devices through multiple temperature tests, and use the characterization data from each of these tests to perform a final sorting operation. This type of testing, where one tracks unit-identity of individual devices through multiple tests, is much more expensive to perform than a more traditional test sequence, in which one rejects out-of-spec parts after each individual test operation.

Because the qualitative behavior of a digital part depends on the relationship of B_{OP} and B_{RP}, close attention must be paid to their performance over temperature. To have a latch turn into a switch at a temperature extreme, or vice-versa, can have catastrophic consequences on the system in which the sensors are employed.

4.15 Bipolar Switches

A bipolar switch, is not, as one might first believe from the name, a device that turns ON in response to either pole of a magnet. A bipolar switch is a Hall-effect IC for which the ranges of both the B_{OP} and B_{RP} specifications include zero. This means that, while the device is guaranteed to turn ON when the sensed field exceeds a specified positive threshold and is guaranteed to turn off when the sensed field drops below a specified negative threshold, it may or may not latch when the field is removed. It could be functionally either a latch, or a switch, or even a north-pole switch, the exact function varying on a unit-to-unit basis, even for devices of the same type, and manufactured together in the same lot. Because bipolar switches can exhibit qualitatively different behavior on a unit-to-unit basis, one should carefully review designs in which they are used to ensure that the possible operating-mode variation will not cause spurious operation or malfunctions in the system in which they are incorporated.

4.16 Power Supply Requirements for Digital Sensors

Digital devices tend to be more forgiving of power supply variation than their linear counterparts. Contemporary devices operate over wide supply ranges, with 4 to 24 volts not uncommon. Devices that were designed for automotive applications can often survive significant electrical overvoltage conditions, both negative and positive, on the power supply lead. Devices with a reverse-battery protection feature are designed to withstand continuous and significant (typically exceeding −12V) negative voltages on the power supply lead. While relatively common for digital Hall-effect devices, features such as reverse-battery protection are almost unheard of for most other ICs; applying negative supply voltage to most logic or analog ICs will usually destroy them in short order. Devices designed for automotive applications may also incorporate features to protect them from the short, high-energy transients that commonly occur in vehicle electrical systems.

Most digital Hall sensors draw a relatively small amount of supply current (usually <10 mA) in normal operation. Because the supply current can vary a few milliamperes depending on the output state, particularly in bipolar devices, placing a small bypass capacitor (0.01 – 0.1 μF) across the device's power supply terminals is highly recommended. Because of the on-off nature of the device's behavior, excessive noise on the power supply line can manifest itself as an unstable output state, with output oscillations occurring at times when the device is transitioning between the on and off states, as shown in Figure 4-15a. Connecting a capacitor between the device's output line and ground is NOT the way to fix this problem. While you may be able to damp output oscillations with a sufficiently large capacitor on the output, this tactic is only a superficial fix and does not address the root problem. In some cases a capacitor on the output may actually damage the device due to large current spikes flowing into the output when the device discharges the capacitor. The most effective way to reduce supply-noise oscillations is to appropriately filter and bypass the power supply lines. The simplest method of supply bypassing is to put a capacitor between the sensor's positive power terminal (VCC) and ground, as shown in Figure 4-15b.

In the case of latch-type sensors, good power-supply bypassing is absolutely critical for proper operation. Because a latch is expected to "remember" its present state in the absence of field, it is especially susceptible to having its state altered by spikes, noise, or "dropout" (brief voltage reductions) on the power supply line. One symptom of an improperly bypassed latch is to see its output occasionally return to a preferred state (ON or OFF) without any apparent magnetic stimulus to cause it to switch. In the author's experience, many types of latches seem to be more susceptible to being spuriously flipped by electrical noise on the power-supply lines when they are operated at supply voltages near their lower operating supply voltage limits.

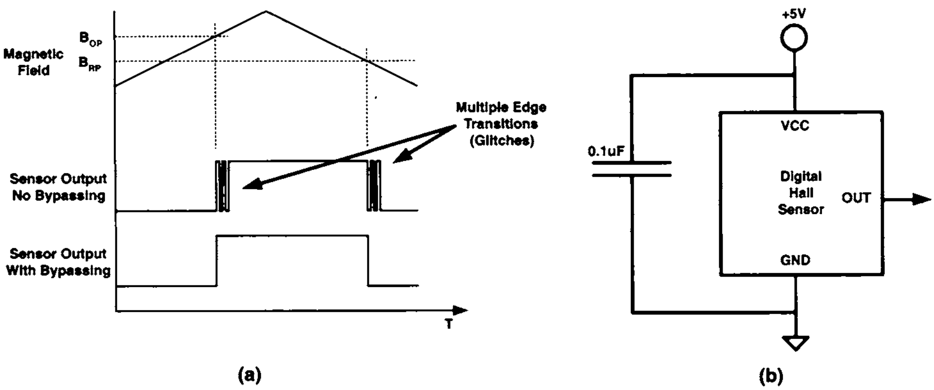

Figure 4-15: Effects of excessive supply-line noise on digital Hall-effect sensor output (a) and use of bypass capacitor (b).

4.17 Output Drivers

Overwhelmingly, the most common output driver found on digital Hall-effect sensors is the NPN open-collector output, shown in Figure 4-16a. When the device turns ON, it biases the output transistor, sinking current into the output. For devices fabricated with CMOS technologies, an N-channel MOSFET replaces the NPN bipolar transistor, and the output is referred to as *open-drain* (Figure 4-16b).

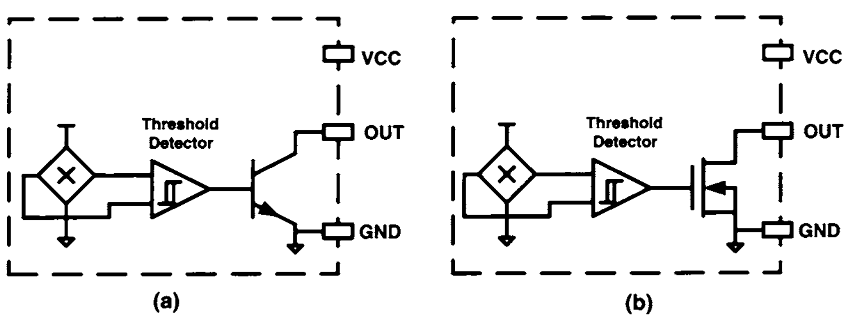

Figure 4-16: Open-collector (a) and open-drain (b) outputs.

Open-collector and open-drain outputs are popular because they are easy to interface to. The addition of a single pull-up resistor allows one to interface with both TTL and CMOS logic, as well as with most common microcontrollers. While a few devices incorporate the pull-up on-chip, most require it to be added externally. Forgetting to add the external pull-up resistor is the cause of a great many applications problems. This is probably the single most common problem encountered when first starting to use digital Hall-effect sensors. If a pull-up resistor is not added, you will not get a voltage-output signal out of the device. When viewed with a voltmeter or an oscilloscope, you will see either no signal out, or a small (<0.5V), highly corrupted signal. When operating with a properly sized pull-up resistor, the voltage output signal from an unloaded digital Hall-effect sensor will appear as a clean square wave with a low value near ground and a high value near the voltage to which the pull-up resistor is tied.

While an open-collector output behaves like a switch to ground, it is a solid-state device, and has a few characteristics that must be taken into account when designing interface circuits.

1) ***Maximum on-state sink current*** (I_{OMAX}). This is the maximum amount of current the output can sink in the on state without incurring damage.

2) ***Maximum off-state output voltage*** (V_{OMAX}). In the off state, this is the maximum voltage the output can tolerate without breaking down (turning into a short-circuit).

3) ***Output off-state leakage current*** (I_{OLK}). In the OFF state the output will sink a small amount of leakage current, typically on the order of nanoamperes or microamperes. This parameter defines the maximum amount of this leakage current under a given set of conditions.

4) ***Saturation voltage*** (V_{sat}). When the output is switched on, and is conducting a specified amount of current, the voltage at the output will not be quite zero. Saturation voltage defines the maximum value for the ON state output voltage for a given current.

5) ***Rise and Fall time*** (T_r, T_f). These parameters define how fast the output will transition between the ON and OFF states. These characteristics should NOT be confused with the amount of time the device needs to respond to a magnetic field. The response time of a digital device is a complex function of the packaging and circuit architecture used to implement the device. While rise and fall times are often measured in tens or hundred of nanoseconds, the actual response time is often measured in microseconds.

4.18 Typical Digital Devices

Table 4-3 lists a few devices representative of the vast (and I do mean vast!) assortment of digital Hall-effect ICs available today.

Table 4-3: Magnetic characteristics of various digital Hall-effect sensors.

Manufacturer	Device	Type[1]	"Typical" values[2] (gauss)		
			BOP	BRP	BH
Allegro Microsystems	A3121	Sw	350	245	105
	A3134	BSw	8.5	–19	27
	A3141	Sw	100	45	55
	A3240	Sw	35	25	10
	A3280	L	22	–23	45
Melexis	US3881	L	50	–50	90
	US5881	Sw	280	230	43
Micronas	HAL505	L	140	–140	280
	HAL506	Sw	72	50	27

Note 1: Sw=Switch, Bsw=Bipolar switch, L=Latch

Note 2: Typical values from manufacturer's data sheets for test conditions as specified by manufacturer.