PRODUCT DESCRIPTION

Technical Paper
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THE STATE OF THE ART IN HALL EFFECT TECHNOLOGY AND ITS IMPLICATIONS FOR APPLIANCE DESIGN AND DEVELOPMENT

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ABSTRACT

Hall effect sensor technology has advanced significantly, offering high performance, accuracy, consistency, reliability, and new feature sets at reasonable costs. Now leading the way in high-volume automotive applications, which are cost-sensitive, quality and reliability conscious, and subjected to harsh environments, Hall effect devices have distinguished themselves, and have become the preferred technology for many critical safety and performance uses involving the sensing of: motion, position, speed, direction, proximity, and electrical current. The highly successful application of Hall effect sensors in the automotive sector in many cases is directly transferable to appliances.

Hall effect devices may not completely replace mechanical switches, but they do offer significant advantages for appliances. Their major advantage versus other switch technologies is contact-less, bounce-free switching. This virtually eliminates failures induced by physical “wear and tear,” and they are not affected by dirt, dust, or other environmental factors normally associated with “harsh” conditions, but which are important for appliances as well.

This paper briefly reviews the basic principles of Hall effect technology and its evolution to today’s state of the art. This includes a look at historic areas of concern for the technology, and how these have been addressed. It also provides a comparison with mechanical switch technology. Lastly, an overview of how Hall effect technology has, and can be, used in various appliance applications is presented.

THEORY OF OPERATION

The basic element in a Hall effect device is a small sheet of semiconductor material represented by figure 1. When a constant voltage source is applied to the element, as shown in figure 2, it forces a constant bias current to flow in the element. The output takes the form of a voltage, which can be measured across the width of the sheet.

On its own, this voltage has negligible strength, but if the biased Hall element is placed in a magnetic field that has flux lines at right angles to the Hall current (figure 3), then the voltage output is amplified, becoming directly proportional to the strength of the magnetic field. This is the Hall Effect, discovered by E. F. Hall in 1879.

This phenomenon is the basis of all Hall effect devices today. Using modern semiconductor manufacturing techniques and circuits, the basic Hall element can be augmented by: a) adding a voltage regulator to provide a stable power source over a wide range of input volt-ages, and b) adding an amplifier to increase the usable signal.

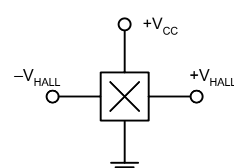

Fig. 1. Basic Hall element

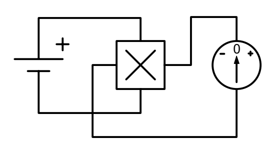

Fig. 2. Basic Hall device circuit

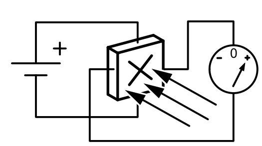

Fig. 3. Magnetic flux applied

These enhancements are shown in figure 4. The combination of these elements is the basic building block in most practical HEDs (Hall effect devices). It comprises the typical structure of linear HEDs, which provide an output voltage that is proportional to the strength of the magnetic field. For example, the block in figure 4 can be combined with a Schmitt trigger threshold detector with built-in hysteresis (a device which turns on and off depending on a predefined level of voltage or magnetic field strength), and either an open-collector NPN or an open-drain MOSFET output transistor, to create a Hall effect (digital) switch (figure 5).

Implementing a Hall effect element in this way creates a circuit with digital output capabilities. When the applied magnetic flux density exceeds a certain limit, referred to as the Operate point (B_{op}), the trigger provides a clean transition from off to on without contact bounce or "chatter." The transistor shown in figure 5 is usually a saturated switch, which shorts the output terminal to ground whenever the applied flux density is higher than the B_{op} trip point. When the magnetic field falls below B_{op} by a certain limit, referred to as the Release point (B_{rp}), the trigger provides a clean transition from on to off. A defined and built-in hysteresis (B_{hys}) eliminates oscillation (spurious switching of the output) by introducing a magnetic dead zone, in which switch action is disabled after the threshold value is passed.

This type of switch is typically compatible with all digital logic families, when used with a pull-up resistor. The output transistor can typically sink enough current to directly drive many loads, including: relays, triacs, SCRs, LEDs, and lamps. Such a circuit is usually limited to 24 V and 25 mA. For inductive loads, such as relays, an external flyback diode is usually required. Switching higher voltages or currents usually requires an additional relay, or a discrete power device such as: a bipolar or MOSFET transistor, an SCR, or a triac with biasing resistors.

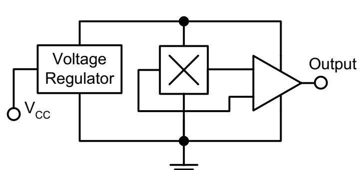

Fig. 4. Circuit building block with signal augmentation circuitry

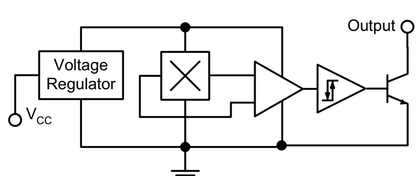

Fig. 5. Practical Hall effect switch circuit

MAGNETIC OPERATION CHARACTERISTICS

HED switches are classified based on mode of operation in various magnetic fields. These classifications, or product families, are distinguished based on magnetic operate (B_{op}) and release (B_{rp}) characteristics as follows:

- Unipolar switches – Operate and release with respect to the south pole (figure 6)
- Omnipolar switches – Operate and release with respect to the south pole or operate and release with respect to the north pole (figure 7)

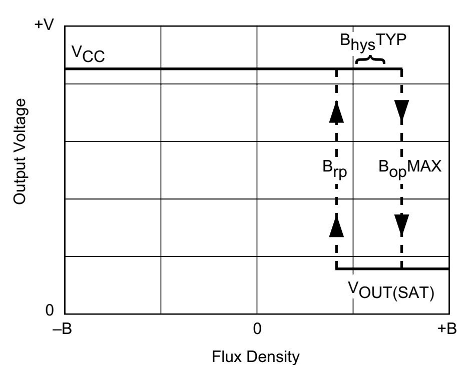

Fig. 6. Unipolar switch or bipolar switch in unipolar mode

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- Bipolar latches – Operate with respect to the south pole and release with respect to the north pole (figure 8)
- Bipolar switches – Three alternative modes, all typically attempting to switch as close to 0 gauss as possible:
  – Unipolar mode. Operate and release with respect to the south pole (figure 6).
  – Latch mode. Operate with respect to the south pole, and release with respect to the north pole (figure 8).
  – Negative unipolar mode. Operate and release with respect to the north pole (figure 9).

Each of these magnetic switching characteristics is important, depending on the application requirements. For appliance applications, the unipolar or omnipolar modes of operation should meet the vast majority of user needs.

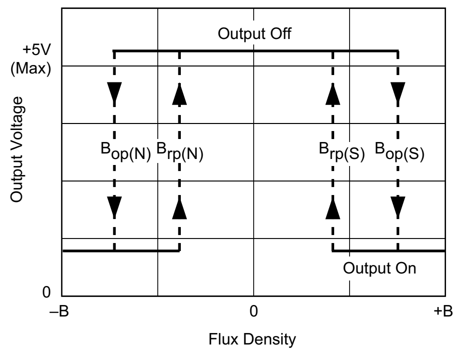

Fig. 7. Omnipolar switch. N, relative to north pole; S, relative to south pole.

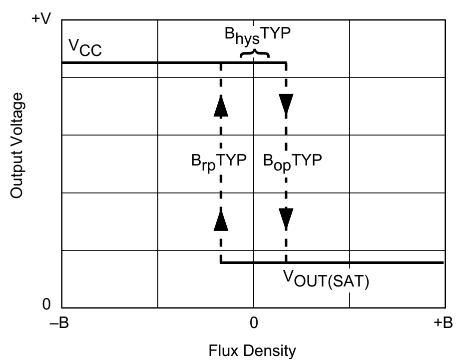

Fig. 8. Bipolar latch or bipolar switch in latch mode

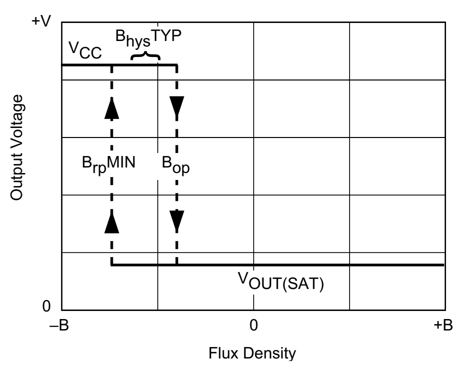

Fig. 9. Bipolar latch, negative unipolar mode

THREE-WIRE VERSUS TWO-WIRE OPERATION

HEDs can be configured to operate with either three or two control wires. In three-wire operation, you need to provide connections for supply voltage, ground, and output (figure 10a). Two-wire operation, however, only requires connections for supply voltage and ground (figure 10b).

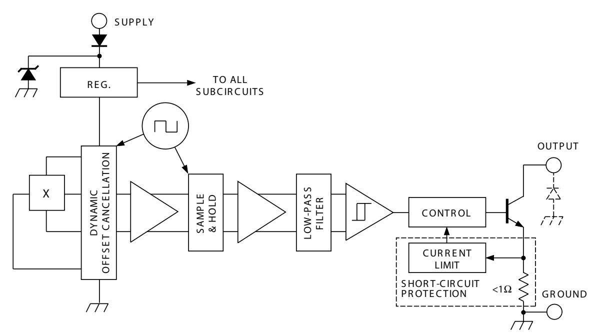

Fig. 10a. Three-wire configuration

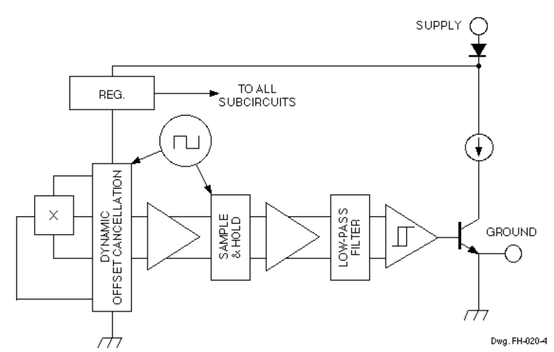

Fig. 10b. Two-wire configuration

In the three-wire configuration, the output turns on or off, thereby completing the circuit, given the proper presence of the required magnetic field. Usually, there is a external voltage supply resistor (often referred to as a “pull-up” resistor) that limits the current that goes through the output switch. If you look at the output voltage, assuming 12 V is applied, you get the output switching from 12 V to just above ground (less the voltage drop of the output switch or the saturation voltage, typically 0.2 V to 0.4 V). This is shown in figure 11a.

The two-wire configuration operates by changing the amount of current that is allowed to flow through the output, regardless of what voltage is applied. The typical output current goes high/on (14 mA) or low/off (6 mA) given the presence of the appropriate required magnetic field. As a result, the two-wire mode cannot be used to drive a load, and operation is limited to providing a control signal. This is shown in figure 11b.

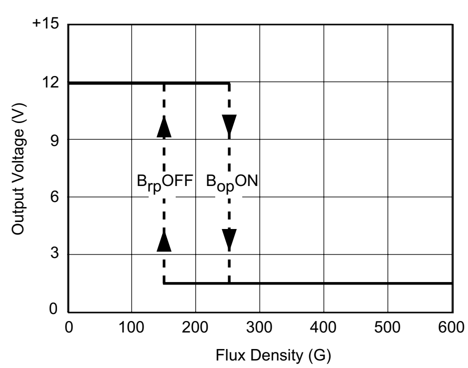

Fig. 11a. Voltage mode (three-wire)

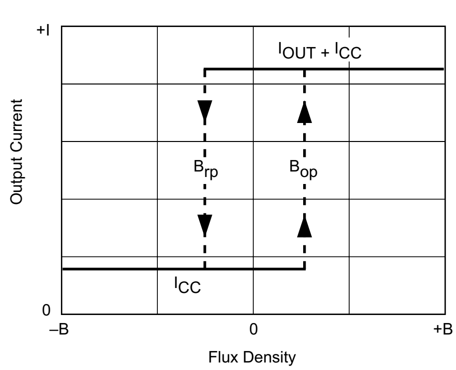

Fig. 11b. Current mode (two-wire)

Compared to three-wire mode, two-wire mode reduces the quantity of connectors, the wiring count, and associated manufacturing cost, while providing a functional operation diagnostic capability. Although two-wire mode adds to the interface circuit complexity and those associated costs, the increasing use of microprocessors and microcontrollers is reducing the interface cost and complexity factor.

An inherent advantage of the current-based two-wire mode is that it allows the detection of fault conditions. If the sensor, wiring, or wiring harness is subjected to a short circuit, then current will be higher than the maximum limit. If the sensor, wiring, or wiring harness is subjected to an open circuit, then current will be zero or below the minimum limit. Any current level between the predefined output on and output off states indicates a fault condition. Figure 12 illustrates this point.

This feature can be used to develop diagnostic capabilities for better determining where a problem exists. It can thus help to reduce warranty and repair costs. It also helps in facilitating remote diagnosis of problems. A three-wire HED or a mechanical switch does not provide this kind of capability without additional components and complexity.

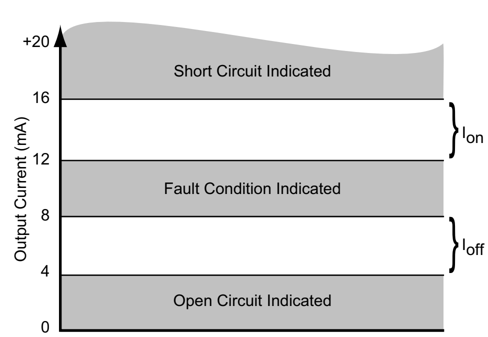

Fig. 12. Inherent fault detection (two-wire)

MAGNETIC FIELD PRESENTATION MODES

After you have selected the device type and the wire configuration needed, the method of actuating the device needs to be determined. Even with a simple bar or rod magnet, there are several possible paths for the magnet to take relative to the sensor, for sensing either motion or position. The first possibility is that the magnet could move along a path that is perpendicular to the plane of the active face of the Hall device (figure 13). This is called the "head-on" mode of operation. In practical terms, the magnet is moving straight toward or away from the Hall sensor. The resulting flux density at the sensor is a function of TEAG (Total Effective Air Gap). TEAG is the sum of the depth of the active area plus the distance between the package surface and the magnet surface. The typical TEAG for a cylindrical magnet is shown in figure 13.

The second possibility is to move the magnet in a path parallel to the active face of the Hall device. This is known as the "slide-by" mode of operation A head-on orientation is illustrated in figure 14. In practical terms, the magnet is moving across the Hall sensor. This method typically results in better sensing precision, with smaller magnet travel, than the head-on mode, but requires the use of strong magnets or magnets with ferrous flux concentrators.

Further precision can be obtained by using a lateral orientation, so both poles are part of the magnetic circuit, as illustrated in figure 15. Due to the large magnetic slope between both poles, you can use the effect to obtain very precise switch point locations.

A third possibility is referred to as vane interrupter switching. In this configuration, the activating magnet and the Hall device are mounted on a single rigid assembly with a small air gap between them. The Hall device is held in the on state by the activating magnet. If a ferromagnetic plate, or vane, is placed between the magnet and the Hall device, as shown in figure 16, the vane forms a magnetic shunt that distorts the flux field away from the Hall device. Use of a movable vane is

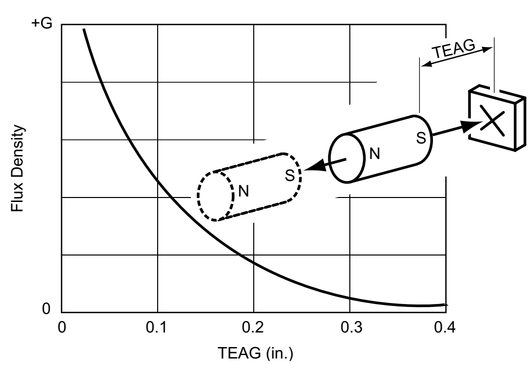

Fig. 13. Head-on motion and orientation

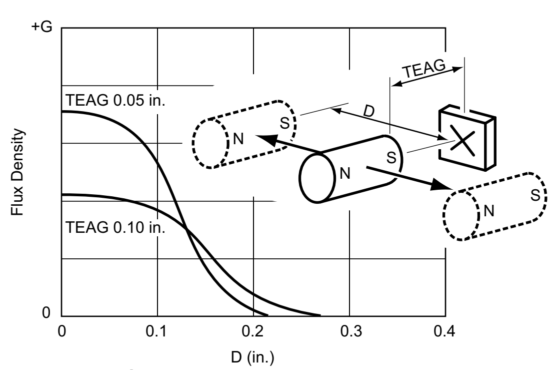

Fig. 14. Slide-by, head-on orientation

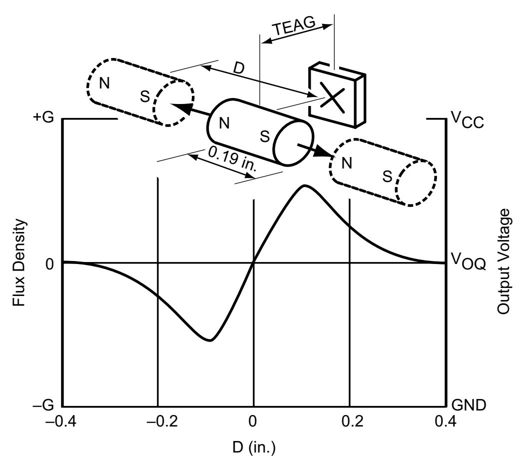

Fig. 15. Slide-by, lateral orientation

a practical way to switch a Hall device. The Hall device and magnet can be molded together as a single unit, thereby eliminating alignment problems and producing an extremely rugged switching assembly. The ferrous vane or vanes that interrupt the flux can have linear motion or rotational motion. The ferrous vane can be made in many configurations, as shown in figure 17.

Ferrous vane assemblies are often used where precision switching is required. This is due to the steep flux density/distance curves that can be achieved.

Proximity switching and gear tooth sensing (either for speed or position) can be achieved by back-biased specialized HEDs which sense changes in the magnetic field caused by the varying presence of ferrous material. The ferrous material shunts, or attracts, the magnetic field of the back-biasing magnet to the Hall device. Figure 18 illustrates this application with a notched wheel and a toothed gear. However, targets can be other ferrous objects of various shapes and sizes, such as notches in plates, moving arms, and so forth.

Back-biased sensors can have a single sensing element or dual elements. In either case, this type of sensor is generally more expensive than a simple Hall switch and a discrete magnet, due to the additional circuitry and calibration required to accommodate the large back-biasing fields. However, these sensor types do eliminate the need to worry about magnet placement and selection, once target size, shape, material, and air gap have been optimized.

Because Hall effect technology relies on magnetic fields for switching, protective materials can be used between the magnet and the HED that do not interfere with these magnetic fields. These materials include: plastic, epoxies, aluminum, phenolic resin, cardboard, paper, and others. Only

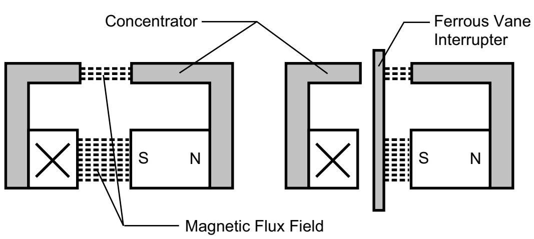

Fig. 16. The right panel shows the vane shunting the magnetic field

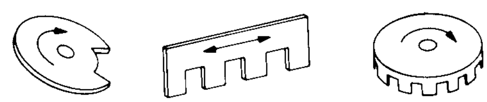

Fig. 17b. Alternative vane designs

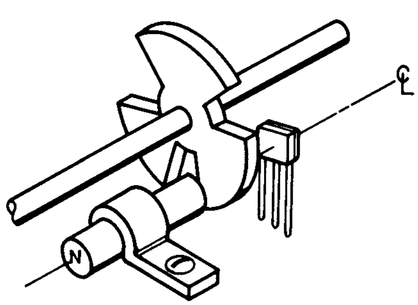

Fig. 17a. Axle-mount vane interrupter

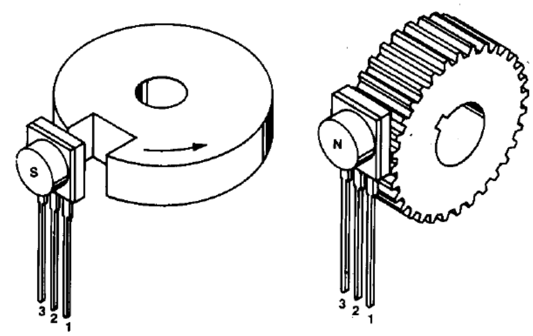

Fig. 18. Promimity and gear tooth sensing

ferrous materials, like sheet steel and iron, would prevent proper sensing of the magnetic fields.

CURRENT SENSING

HEDs also can be used to sense current, by making an electromagnet of the current running through a wire or conductor. Through the use of toroids and other structures acting as flux concentrators, the typical current sensor converts current to a magnetic field, which in turn can be sensed by a linear HED or a Hall switch for limit switching. Figure 19a shows an integrated current sensor. Figure 19b and figure 19c show examples of Hall devices in current sensors.

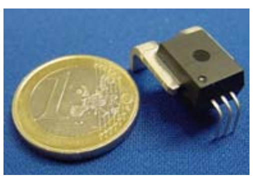

Fig. 19a. Hall current sensor IC

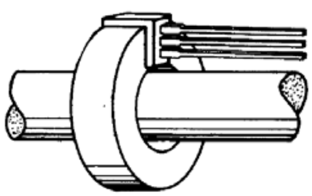

Fig. 19b. Use of split gap toroid for sensing higher current levels

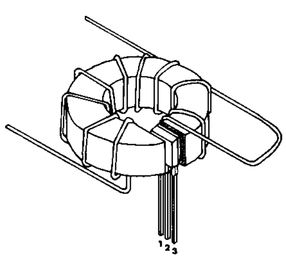

Fig. 19c. Use of multiple windings to increase flux density for low current sensing

STRESS RELATED EFFECTS ON OPERATION VERSUS DEVICE CONFIGURATION

Early Hall-effect sensor designs utilized a single Hall element, or plate, illustrated in Figure 20a. This single-plate approach is susceptible to both thermal and mechanical stresses, which cause the output voltage to be inconsistent, changing with temperature, pressure, and mechanical stress, with results as shown in figure 20b. To address this dependence, many designs have been originated recently that utilize a four-plate Hall-element array, shown in Figure 21a. This can be considered a resistor array similar to a Wheatstone bridge. The quadratic array places four Hall plates in parallel, providing a "mechanically averaged" Hall voltage. Offset errors and mechanical stresses tend

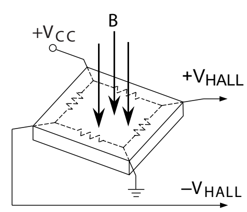

Fig. 20a. Early single-element Hall device

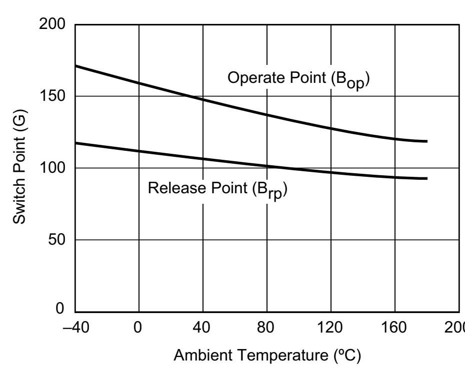

Fig. 20b. Early single-element results

towards canceling out, although not entirely, as indicated in figure 21b. A performance improvement in the order of 10 times is realized in both stability and stress immunity by using this quadratic element scheme.

Most Hall effect sensors are now designed using a "chopped" Hall plate illustrated in figure 22a. Terms such as "chopper stabilized" or "dynamic offset cancellation" also are used to describe this function. This newest technique again utilizes a single Hall plate. A four-terminal element is chopped (electrically rotated) at a high frequency (typically 100 kHz to 500 kHz), depending upon the sensor function and the manufacturer. This has resulted in a superior and stable device, minimizing the effects of thermal and mechanical stress, and effectively eliminating offset and mechanical stress error. Figure 22b demonstrates the superior performance of the modern day chopper-stabilized Hall element.

REDUCING SUPPLY CURRENT REQUIREMENTS

A typical Hall effect switch requires from 3 mA to 8 mA of supply current to operate properly. For some applications, this current draw is too high. To address this, a low average power scheme has been employed. Internal timing circuitry activates the sensor for a very short time (60 µs) and deactivates it for the remainder of the period (240 µs or 60 ms, depending on the device). This is shown in figure 23. The result, at 3.0 V to 5.5 V, is a typical average current draw in the range from 5 µA to 11 µA, when a 60 ms period is employed, and from 295 µA to 460 µA when a 240 µs period is

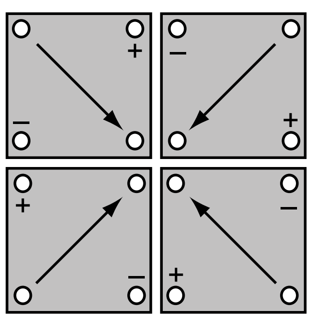

Fig. 21a. Four-element Hall device (arrows indicate current)

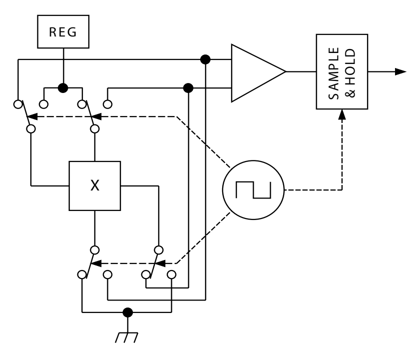

Fig. 22a. Chopper-stabilized Hall circuit

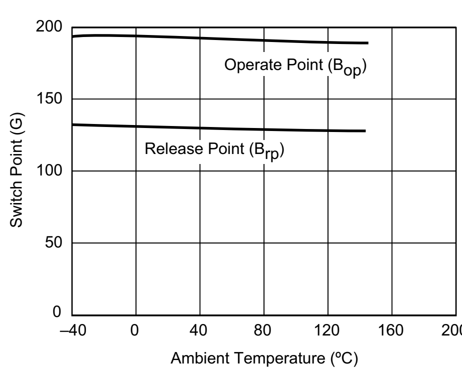

Fig. 21b. Four-element configuration results

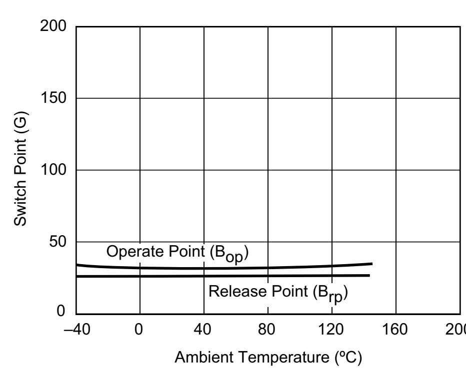

Fig. 22b. Chopper-stabilized results

employed. The short 60 µs "awake" time allows for stabilization prior to sensor sampling and data latching, which occurs on the falling edge of the timing pulse. During the "sleep" time, the output is latched in the last sampled state, and the device supply current is not affected by the output state.

MAGNET ORIENTATION ADDRESSED

The ability to operate on a north pole or a south pole (omnipolar) is advantageous in several applications and allows the user to avoid problems with orientation of the magnet. This is accomplished by using dual comparators after the amplifier, but before the Schmitt trigger, as illustrated in Figure 24.

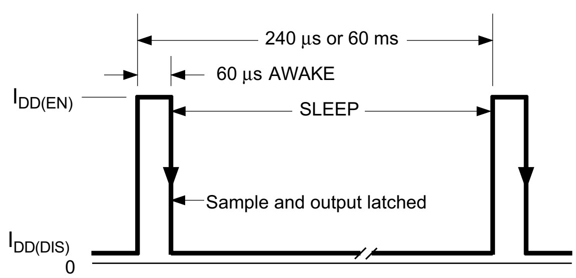

Fig. 23. Sleep mode to reduce current required

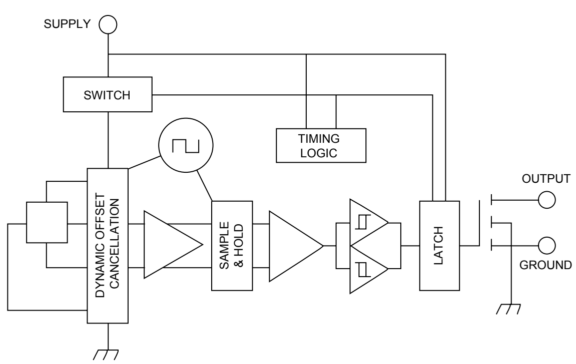

Fig. 24. Chopper-stabilized Hall circuit

SHORT CIRCUIT PROTECTION

Various HEDs now come with short-circuit protection, to prevent overcurrent conditions from damaging the device and its outputs (dashed box in figure 10a). The device monitors the current at the output, and protects the device by turning off, or folding back, the voltage that is allowed to the load. To do so, the device utilizes thermal protection features to turn the device off and on to limit current, until the resulting junction temperature returns to a safe operating level. Short-circuit protection features provide a greater robustness in comparison with earlier products, while improving reliability. This is accomplished at little to no additional cost.

REVERSE VOLTAGE

Reverse voltage, or biasing of a semiconductor, can cause failures and catastrophic damage. New generations of devices now include an internal diode to block voltage from being applied in the wrong direction. Like the short-circuit protection mention before, the reverse voltage protection feature also provides a greater robustness in comparison with earlier products, while improving reliability, at little to no additional cost.

PROGRAMMABILITY

In many applications, it may be advantageous to be able to trim critical parameters on the HED, either to improve the accuracy or the performance of the system. Historically, accurate switch points, quiescent voltages, sensitivity, and other parameter improvements have been achieved by a combination of extreme attention to detail regarding tolerances, as well as exacting specification of the mechanical aspect of the system, the magnet structures, and the HEDs employed. This contrib-

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uted to increased system and development cost, and greater complexity.

This has been addressed through the offering of programmable HEDS. These can have critical parameters set by programming within the HED. Programmability allows for more relaxed mechanical, magnetic, and HED device parameters, which can then be optimized for the system and application during final assembly.

The programmable device usually is more expensive than a non-programmable device. However, given that semiconductor technology keeps coming down in price, while increasing circuit complexity, this difference is becoming less of a concern. Still, the price variance for a programmable versus a non-programmable device remains significant, and thus the need is predicated on the complexity of each application, on a case-by-case basis.

MECHANICAL SWITCH VERSUS HALL EFFECT SWITCH COMPARISON

Mechanical switches have mature, established technologies, which have a proven history and are generally well understood within the appliance industry. Due to this maturity, mechanical switches have cost structures that are hard to beat. To speculate that HED technology will replace all mechanical switches in the future would be misleading, foolish, and just plain wrong. With that said, however, HEDs have and will continue to find homes in the appliance world.

Mechanical switches and HEDs have certain advantages and disadvantages, listed in table 1.

Table 2 lists applications that either are currently using Hall effect ICs in appliances, or are seriously evaluating their use.

Table 1. Comparison of Mechanical Switches and Hall Effect Devices

Mechanical Switches	
Advantages	**Disadvantages**
• Low cost • Proven and understood reliability • Can switch high voltages and currents • Established industry-wide form factors	• Wear-out failure mechanisms including electrical (arcing) and mechanical (wear and fatigue) • Arc-induced EMI source • Contact bounce/chatter • Greater space and weight requirements • Mechanical/physical actuation required • Contact "wetting" requirements in some environments • No inherent diagnostic capability
Hall Effect Devices	
Advantages	**Disadvantages**
• Effectively no "wear out" failure mechanisms • Proven and understood reliability • Inherent diagnostic capability (2-wire) • No contact bounce/chatter • Small space and weight requirements • Eliminate trip buttons that can be tampered with • Elimination of complex mechanical arms and connecting rods • Semiconductor technology which follows Moore's Law of lower prices over time • Wide temperature range of operation: –40ºC to +85ºC, or –40ºC to +150ºC operation (+170ºC junction temperatures) • Short-circuit protection option • Programmability	• Limited voltage and current switching • Limited industry experience • Requires knowledge of magnetics and magnets

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Table 2. Current Appliance Applications for Hall Effect Devices

Appliance	Application	Device Type
Washer	Lid/door open/closed	Switch
	Motor current	Linear or integrated current sensor
	Drum speed	Gear tooth, proximity, switch
	Out of balance	Linear or switch
	Water level	Switch
	Cycle control dial	Multiple linears and switches
	Flow meter	Latches or bipolar switches
Dryer	Lid/door open/closed	Switch
	Motor current	Linear or integrated current sensor
	Drum speed	Gear tooth, proximity, switch
	Cycle control dial	Multiple linears and switches
Oven	Door oven light	Switch
	Self-cleaning door lock/interlock	Switch
Refrigerator	Ice maker full	Latch or switch
	Door light	Switch
	Motor current	Linear or integrated current sensor
	Shelf position	Linear or switch
Dishwasher	Door open/closed	Switch
	Motor current	Linear or integrated current sensor
	Sprayer motion	Gear tooth, proximity, switch
	Water level	Switch
	Flow meter	Latches or bipolar switches
Vacuum Cleaner	Motor current	Linear or integrated current sensor
	VR motor commutation	Latch or bipolar switch
	On/off	Switch
	Speed control	Linear or switch
Vending Machine	Home position	Switch
	Pulse count/encoder	Latch or bipolar switch
	Selection switch	Switch
Garage Door Opener	End stop positions	Switch
	Pulse count/encoder	Latch or bipolar switch
	Motor current	Linear or integrated current sensor
Blender	Speed control	Linear or switch
Water Softener	Valve position	Latch or switch

REFERENCES

J. Gilbert, "Technical Advances in Hall-Effect Sensing." Allegro MicroSystems technical paper STP 00-1. http://www.allegromicro.com/techpub2/stp/stp00-1.pdf

J. Gilbert, "Understanding Bipolar Hall-Effect Sensors." Allegro MicroSystems application note AN27705. http://www.allegromicro.com/techpub2/an/an27705.pdf

"Hall Effect IC Application Guide." Allegro MicroSysems application note AN27701. http://www.allegromicro.com/techpub2/an/an27701.pdf

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