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Research Article

Ultra-sensitive CMOS digital Hall effect sensor for low magnetism effect applications

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Abstract

Integrated CMOS Hall sensors have been widely used to measure magnetic fields. However, they are difficult to work with in a low magnetic field environment due to their low sensitivity and large offset. This project describes a highly sensitive digital Hall sensor fabricated in 0.18 μm high voltage CMOS technology for low field applications.

The sensor consists of a switched cross-shaped Hall plate and a novel signal conditioner. It effectively eliminates offset and low frequency 1/f noise by applying a dynamic quadrature offset cancellation technique. The measured results show the optimal Hall plate achieves a high current related sensitivity of about 310 V/AT. The whole sensor has a remarkable ability to measure a minimum ±2 mT magnetic field and output a digital Hall signal in a wide temperature range from −40 °C to 120 °C.

Keywords: *Hall sensor, CMOS technology, Dynamic offset cancellation, Chopped technique.*

1. Introduction

The Hall effect is named after the American physicist Dr. Edwin Hall, who discovered it in 1879 while he was investigating the magnetic behavior of a bismuth sample. An electric current was passed through the sample transversal to a weak magnetic field. Hall's goal was to check Kelvin's 30-year-old theory of electron flow. He found that if a magnet was placed perpendicular to one edge of a gold bar carrying current, an electromotive force (EMF) appeared at the transverse side. He did so by discovering the voltage generated from the conductor was dependent on both the current and magnetism (or, magnetic induction) of the wire. Though Hall got what he was after, and by the standards of his day his experiment worked (in fact a bit too well), the Hall effect found little practical use outside of theoretical physics for the next 70 years. The first introduced the Hall effect to semiconductor research in the 1950s. But it was too expensive to be used. It started in 1965 when Everett Vorthmann and Joe Maupin, Sr. development engineers at MICRO SWITCH Sensing and Control came up with an affordable and useful semiconductor sensor. They considered many ideas and eventually settled on the Hall effect for one very simple reason: It can be made entirely in a single chip of silicon. One of the earliest commercial uses was in semiconductor keyboards for radios where very high reliability was required. MICRO SWITCH Sensing & Control has manufactured almost one billion Hall sensors for keyboards and sensor products. The Hall effect has been a known phenomenon for over 100 years and its application is only past the 30-year mark! It's sensor device used in this way even before 1950s practial limitations, (not just in laboratory experiments) for many decade microwave power detectors why HALL SENSOR has been available. The mass production of the semiconductors made it possible to carry out the Hall effect with low-cost. General Information In 1968 a Hall Effect semiconductor keyboard revolutionized the keyboard industry by MICRO SWITCH Sensing & Control. For the first time hall sensor elements and their electronics were implemented in a common circuit. Hall effect sensors are now commonly used in a wide range of applications, from home computers and sewing machines to electronic projects and cars and airplanes to medical equipment.

1.1 Hall Effect sensors

The Hall Effect is an ideal sensing technology. The Hall element is constructed from a thin sheet of conductive material with output connections perpendicular to the direction of current flow. When subjected to a magnetic field, it responds with an output voltage proportional to the magnetic field strength. The voltage output is very small (μV) and requires additional electronics to achieve useful voltage levels. When the Hall element is combined with the associated electronics, it forms a Hall effect sensor. The heart of every MICRO SWITCH Hall effect device is the integrated circuit chip that contains the Hall element and the signal conditioning electronics. Although the Hall effect sensor is a magnetic field sensor, it can be used as the principal component in many other types of sensing devices (current, temperature, pressure, position, etc.). 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. Figure (1.1) shows a block diagram of a sensing device that uses the Hall effect. In this generalized sensing device, the Hall sensor senses the field produced by the magnetic system. The magnetic system responds to the physical quantity to be sensed (temperature, pressure, position, etc.) through the input interface. The output interface converts the electrical signal from the Hall sensor to a signal that meets the requirements of the application [1].

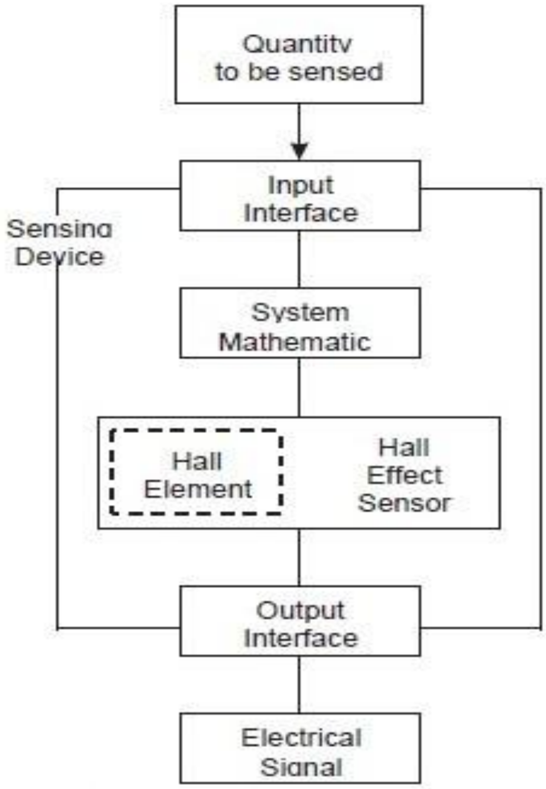

Figure (1.1): General sensor based on the Hall effect

1.2 Why use the Hall Effect?

The reasons for using a particular technology or sensor vary according to the application. Cost, performance and availability are always considerations. The features and benefits of a given technology are factors that should be weighed along with the specific requirements of the application in making this decision.

General features of Hall Effect based sensing devices are:
- True solid state.
- Long life (30 billion operations in a continuing keyboard module test program).
- High speed operation - over 100 kHz possible.
- Operates with stationary input (zero speed).
- No moving parts.
- Logic compatible input and output.
- Broad temperature range (-40 to +150°C).
- Highly repeatable operation.

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 (1.2) 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 (1.2), current distribution is uniform and no potential difference is seen across the output. When a perpendicular magnetic field is present, as shown in Figure (1.3), 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 (VH). The interaction of the magnetic field and the current is shown in equation form as equation (1.1). 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.

$$V_H \propto I \times B \qquad (1.1)$$

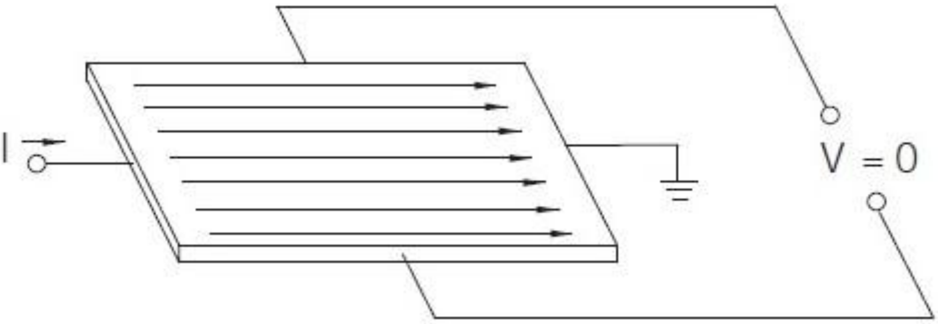

Figure (1.2): Hall effect principle, no magnetic field

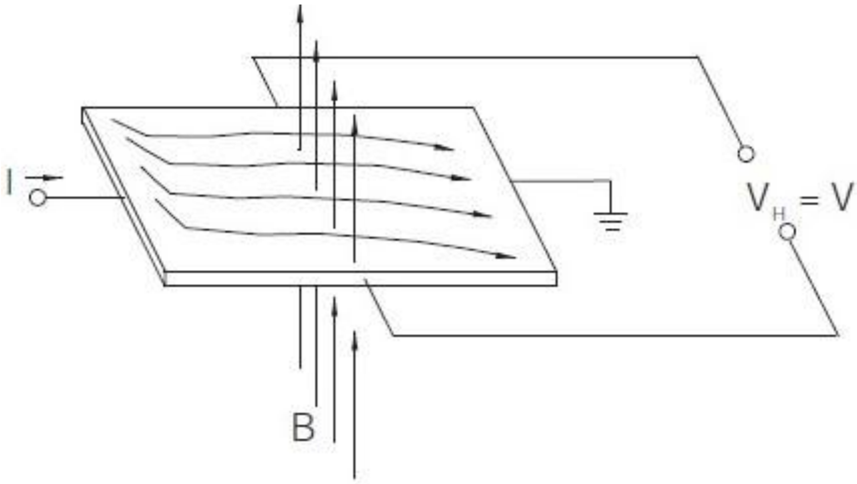

Figure (1.3): Hall effect principle, magnetic field present

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 µv/Vs/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 (1.4) 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.

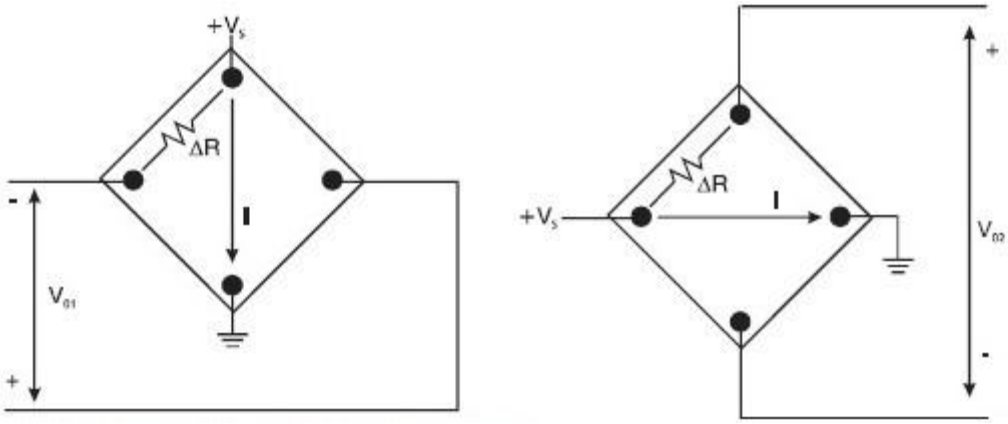

Figure (1.4): Hall elements direction

1.3 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 (1.5) illustrates a basic Hall effect sensor. If the Hall voltage is measured when no magnetic field is present, the output is zero (see Figure 1.2). 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 (1.5) 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. 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 (1.2), the Hall voltage is a function of the input current. The purpose of the regulator in Figure (1.5) 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.

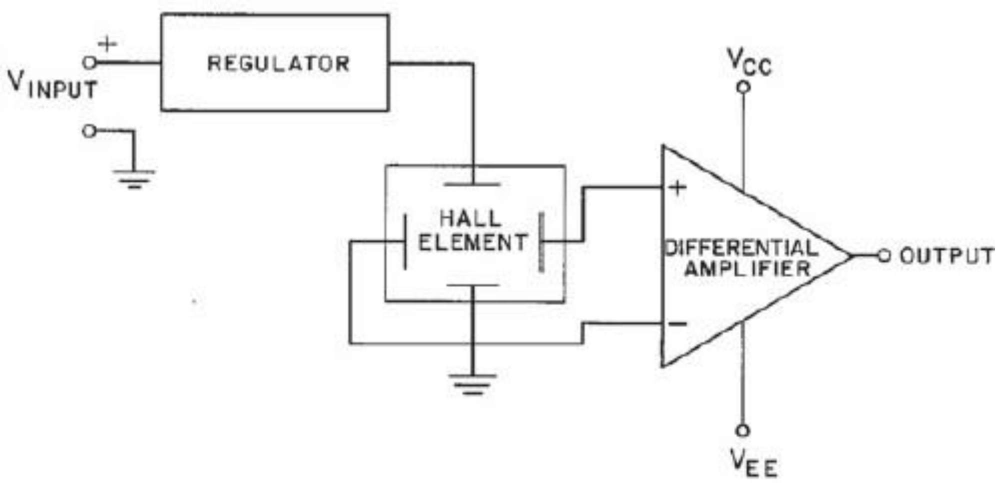

Figure (1.5): Basic block diagram of Hall effect sensor

1.3.1 Analog output sensors:

The sensor described in Figure (1-4) is a basic analog 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 requiring both plus and minus power supplies. To avoid the requirement for two power supplies, a fixed offset or bias is introduced into the differential 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 voltage. Conversely, when a negative magnetic field is sensed, the output decreases below the null voltage, but remains positive. This concept is illustrated in Figure (1-5). 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 (1-5-1). 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. 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 (1-6) 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.

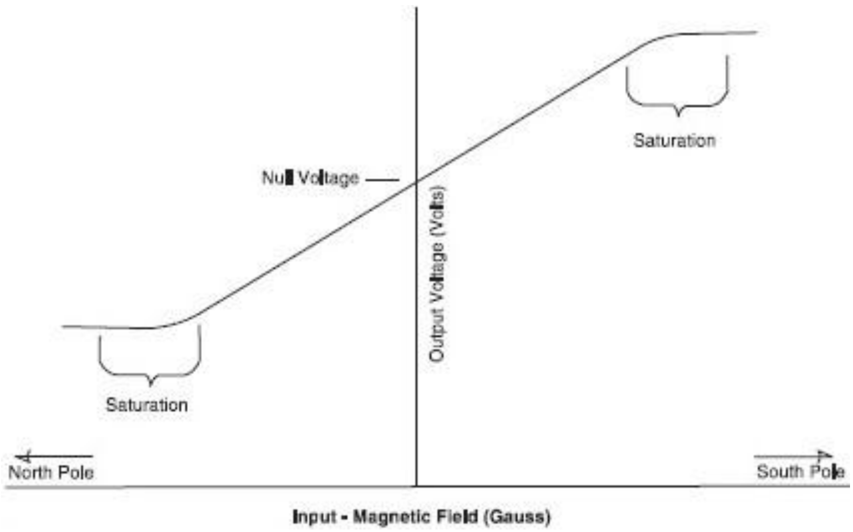

Figure (1.5.1): Null voltage concept.

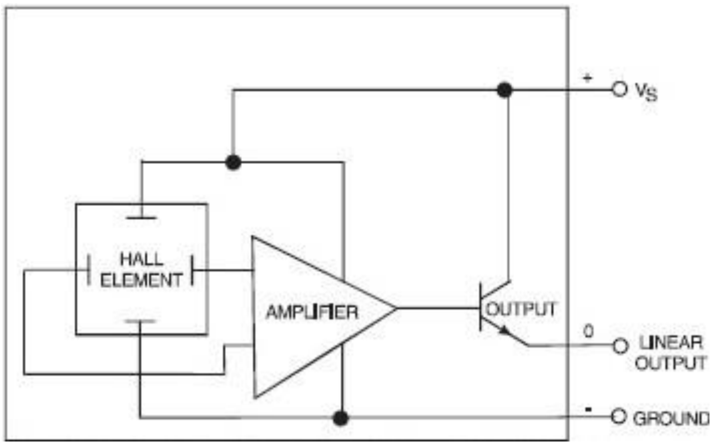

Figure (1.6): Simple analog output sensor (SS49/SS19 types).

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 ratio metric to the supply voltage with respect to offset and gain. Figure (1-7) illustrates a ratio metric analog sensor that accepts a 4.5 to 10.5 V supply. This sensor has a sensitivity (mV/Gauss) and offset (V) proportional (ratio metric) 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).

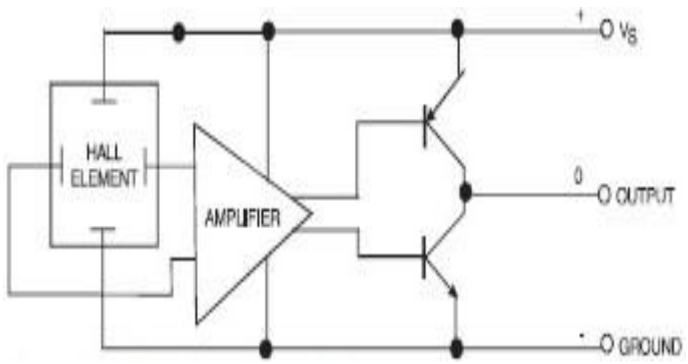

Figure (1.7): Ratiometric linear output sensor.

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 (1-8).

Equation (1-2) is an analog approximation of the transfer function for the sensor.

$$V_{out}(Volts) = (6.25 \times 10^{-4} \times V_s)B + (0.5 \times V_s) \quad (1.2)$$
$$-640 < B\,(Gauss) < 640$$

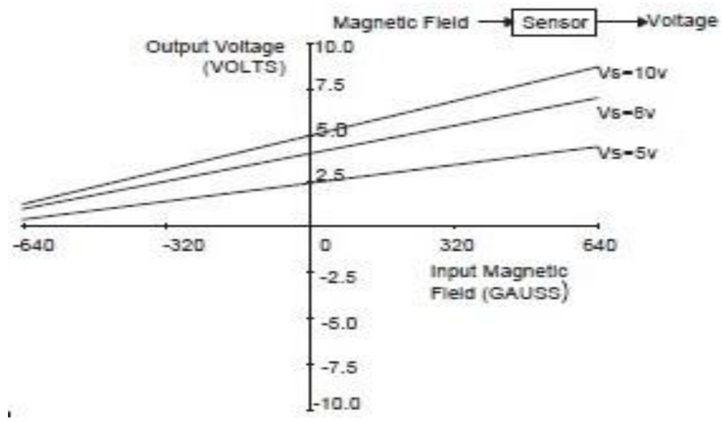

Figure (1.8): Transfer function (Analog output sensor).

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 $\{(6.25 \times 10^{-4} \times V_s)B\ \}$ in equation (1-2) 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 (8), null offset is the output voltage at 0 gauss and a given supply voltage. The second term in Equation (1-2), $(0.5 \times V_s)$, 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:

$$\text{Span} = V_{out}\ @\ (+)\ \text{gauss} - V_{out}@\ (-)\ \text{gauss} \quad (1.3)$$

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. 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 (1-9) illustrates the sensitivity shift over temperature for the miniature ratio metric linear Hall effect sensor.

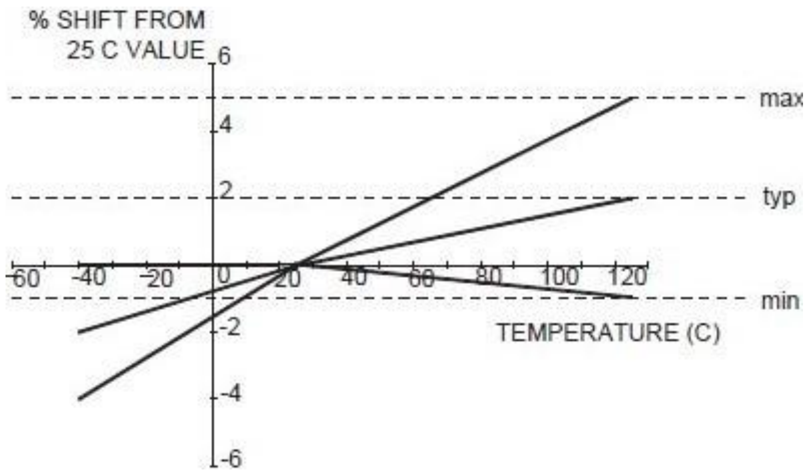

Figure (1.9): Sensitivity shift vs temperature.

1.3.2 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 (1.4) can be converted into a digital output sensor with the addition of a Schmitt trigger circuit. Figure (1.10) illustrates a typical internally regulated digital output Hall effect sensor. The Schmitt trigger compares the output of the differential amplifier Figure (1.10) 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.

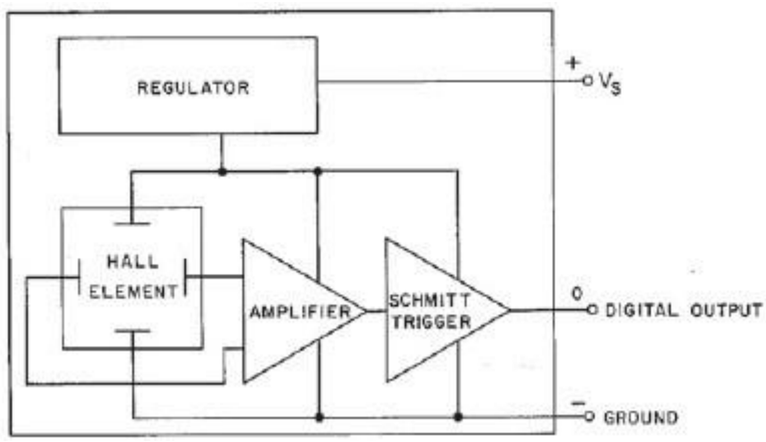

Figure (1.10): Digital output Hall effect sensor.

Transfer function:

The transfer function for a digital output Hall effect sensor incorporating hysteresis is shown in Figure (1.11). 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 (1.12).

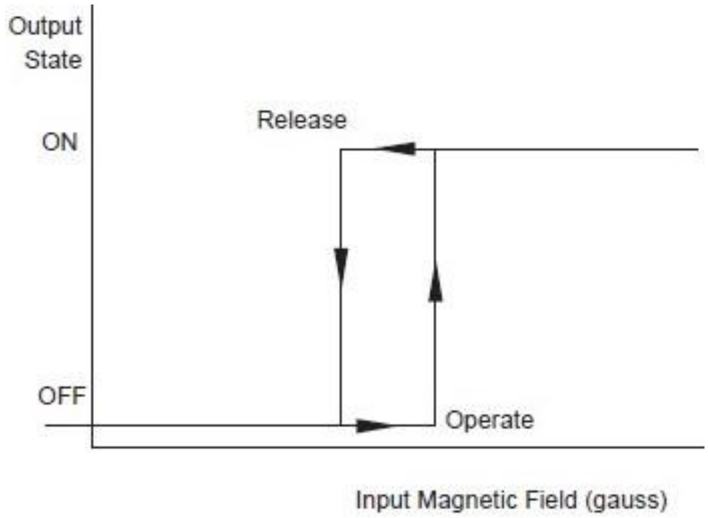

Figure (1.11): Transfer function hysteresis (Digital output sensor).

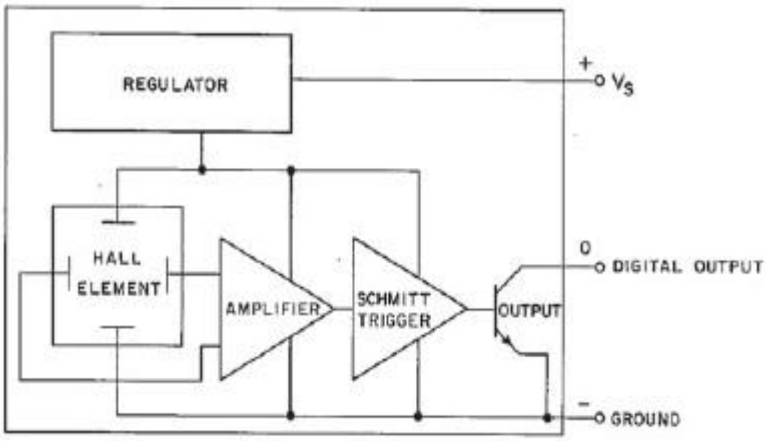

Figure (1.12): NPN (Current sinking) Digital output sensor.

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 $\pm$ 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 (1-13) 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 (1-14). 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.

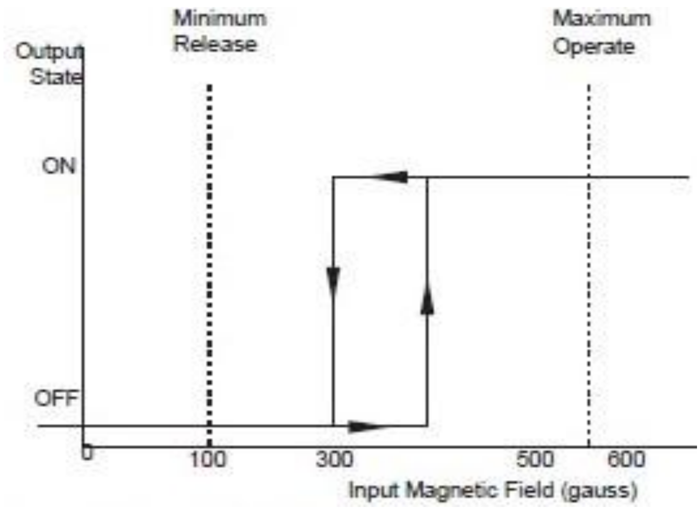

Figure (1.13): Unipolar input characteristics (Digital output sensor).

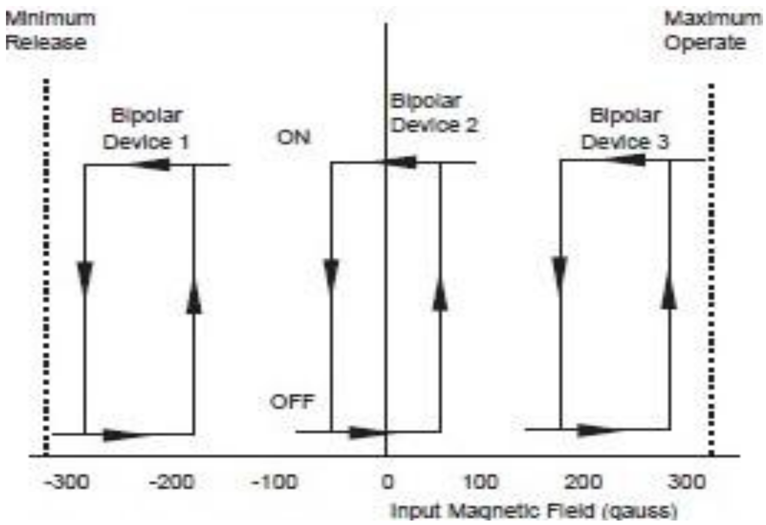

Figure (1.14): Bipolar input characteristics (Digital output sensor).

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.

2.1 Five Key Applications of Hall Effect Sensors:

Hall effect sensors find use in a broad range of applications across five major industries, which are [12]:

Automotive and Automotive Safety:

The automotive and automotive safety industries use both digital and analog Hall effect sensors in a variety of applications.

Examples of digital Hall effect sensor applications in the automotive industry include:

- Sensing seat and safety belt position for air-bag control.
- Sensing the angular position of the crankshaft to adjust the firing angle for spark plugs.

Some examples of the use of analog type sensors include:

- Monitoring and controlling wheel speeds in anti-lock braking systems (ABS).
- Regulating voltage in electrical systems [12].

Appliances and Consumer Goods:
The appliance and consumer goods industries integrate various types of Hall effect sensors in numerous product designs. For example:
- Digital unipolar sensors help washing machines maintain their balance during wash cycles.
- Analog sensors serve as availability sensors for power supplies, motor control indicators and shut-offs on power tools, and paper feed sensors in copier machines [12].

Fluid Monitoring:
Digital Hall effects sensors are commonly used for monitoring flow rate and valve position for manufacturing, water supply and treatment, and oil and gas process operations. In fluid monitoring applications, analog Hall effect sensors are also used to detect diaphragm pressure levels in diaphragm pressure gauges [12].

Building Automation:
In building automation operations, contractors and subcontractors integrate both digital and analog Hall effect sensors.

Digital, proximity-sensing devices are often used in the design of:
- Automatic toilet flushing mechanism.
- Automatic sinks.
- Automatic hand dryers.
- Building and door security systems.
- Elevators.

Analog sensors are used for:
- Motion sensing lighting.
- Motion sensing cameras [12].

Personal Electronics:
This is another area where both analog and digital Hall effect sensors continue to grow in popularity.

Applications for digital sensors include:
- Motor control devices.
- Timing mechanisms in photography equipment.

Applications for analog sensors include:
- Disk drives.
- Power supply protectors [12].

2.2 Problems with traditional Hall effect current sensing method:
In the power cable, if an AC flow, then the magnetic field is generated outside the insulator. This magnetic field changes with the waveform of the current due to Ampere's circuital law. Hall sensors have been researched with respect to their ability to sense the variations in a magnetic field and to decrease the overall size of traditional CTs. Based on the principle of the Lorentz force, Hall sensors operate in a quick response time and can measure a wide range of magnetic fields. To exhibit steady performances and high sensitivity related compensation circuits can be integrated into Hall sensors to form Hall ICs to enable these sensors. Mainly, Hall Effect transducers are used in the following types such as open loop Hall Effect transducers and closed loop Hall Effect transducers. Both these transducers contain cores and are mainly used to measure small currents with large bandwidths. Because of these attributes, the problem of core saturation still exists, and the size of the transducers is almost the same as that of traditional CTs. Moreover, even if some specific Hall-effect transducers can be used for performing large cur-rent measurements without core saturation, they still cannot be used extensively as of now because of the high price of their special core materials. So, the pro-posed model method is to measure the current with coreless method by the introduction of magnetic shielding [10].

2.2.1 Hall effect based current measurements:
In this proposed model Linear ratio metric Hall sensor IC A1301 is used which is shown in the Figure (1-15). It is a continuous-time, radiometric, linear Hall-effect sensor IC. This Hall Effect Integrated Circuit included in each device includes a Hall circuit, a linear amplifier, and a CMOS Class A output structure [10].

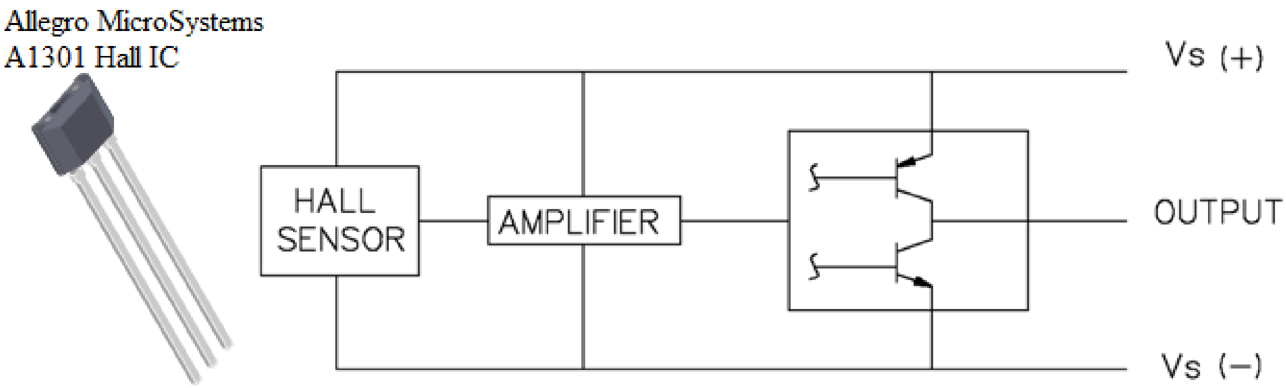

Figure (1.15): Ratio metric linear Hall-effect sensor IC

Integrating the Hall circuit and the amplifier on a single chip minimizes many of the problems normally associated with low voltage level analog signals. It is optimized to accurately provide a voltage out-put that is proportional to an applied magnetic field. These devices have a quiescent output voltage that is 50% of the supply voltage. The Figure (1-16) shows the functional block diagram of Hall IC A1301.

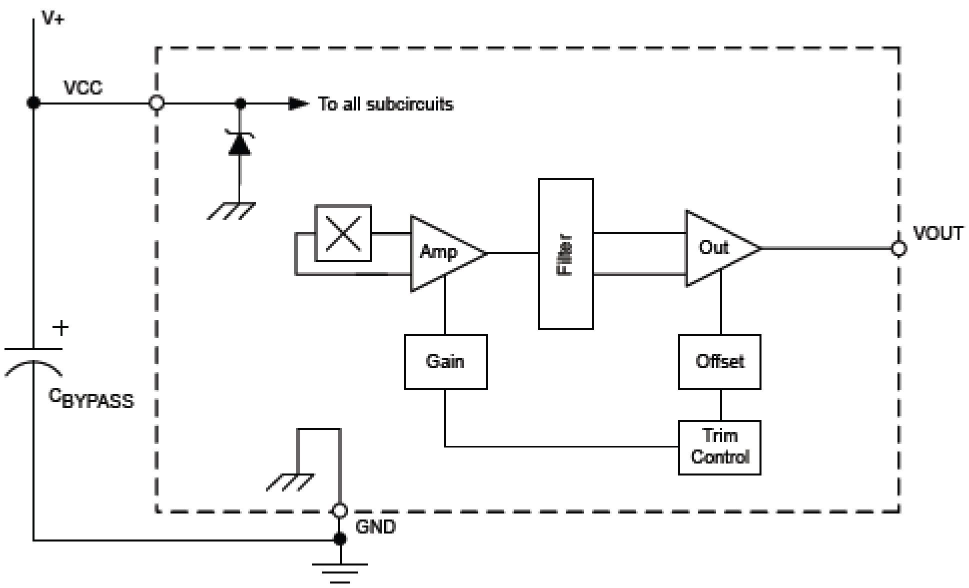

Figure (1.16): Functional Block Diagram of A1301

The Salient Features of this Hall Effect sensor are Low noise output, Fast power-on time, Ratio metric rail-to-rail output is 4.5 to 6.0V operation, Factory programmed at end-of-line for optimum performance, Robust ESD performance and Solid-state reliability.

2.2.2 Instrumentation Circuits:

The Summing Amplifier is used as weighted adder for averaging circuit. It averages the output Hall voltages for four hall sensors. The inverting adder con-figuration is used. The input resistance is four times the feedback resistance. As a result added voltage is divided by four and averaging operations of four Hall voltages is achieved. Here the operation is compared among the four, two hall sensors and also one hall sensor with magnetic shielding. The same circuit is used for two hall sensors to increase the input resistance as two times the feedback resistance with the help of jumper in the circuit. The summing amplifier circuit is shown in Figure (1-17).

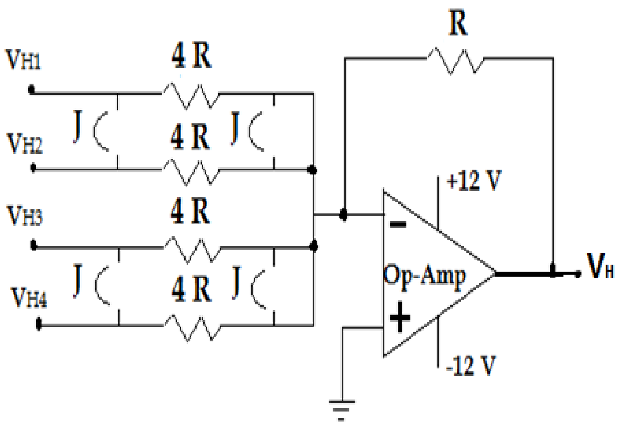

Figure (1.17): Summing Amplifier circuit

This Hall Effect device has a quiescent output volt-age that is 50% of the supply voltage. In the quiescent state (no significant magnetic field: B = 0), the output, V_{OUTQ}, equals one half of the supply voltage, V_{CC}, throughout the entire operating ranges of V_{CC} and ambient temperature, T_A. Due to internal component tolerances and thermal considerations, there is a tolerance on the quiescent output voltage, ΔV_{OUTQ}, which is a function of both ΔV_{CC} and ΔT_A. The Figure (1-18) shows the plot of quiescent voltage versus supply voltage.

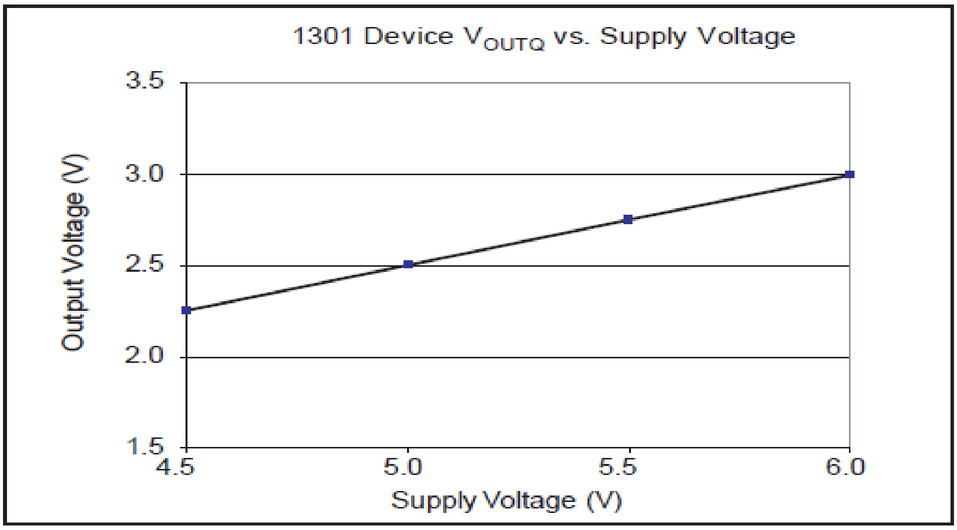

Figure (1.18): Quiescent voltage Vs supply voltage

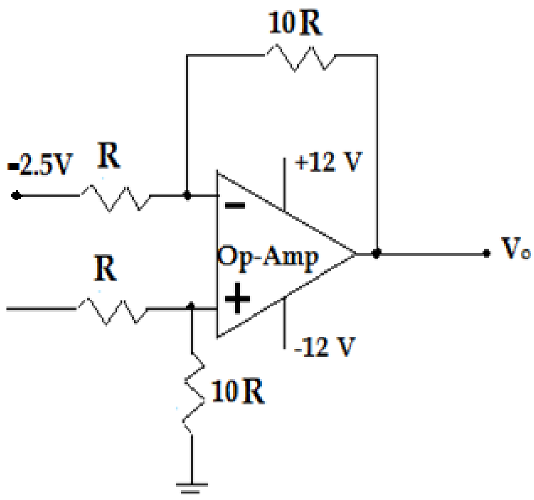

Figure (1.19): Quiescent Voltage Nullification Circuit

The Figure (1-19) shows the circuit diagram of the nullification circuit of quiescent voltage.

2.3 Simulation:

NI Multisim (formerly MultiSIM) is an electronic schematic capture and simulation program which is part of a suite of circuit design programs, along with NI Ultiboard. Multisim is one of the few circuit de-sign programs to employ the original Berkeley SPICE based software simulation. To check whether the designed summing amplifier and quiescent voltage nullification circuit are given the accurate and desired result.

The Figure (1.20) shows the SPICE simulation schematics of summing amplifier circuit and quiescent voltage nullification circuit and Figure (1.21) shows the output of the simulation of weighted adder and differential amplifier.

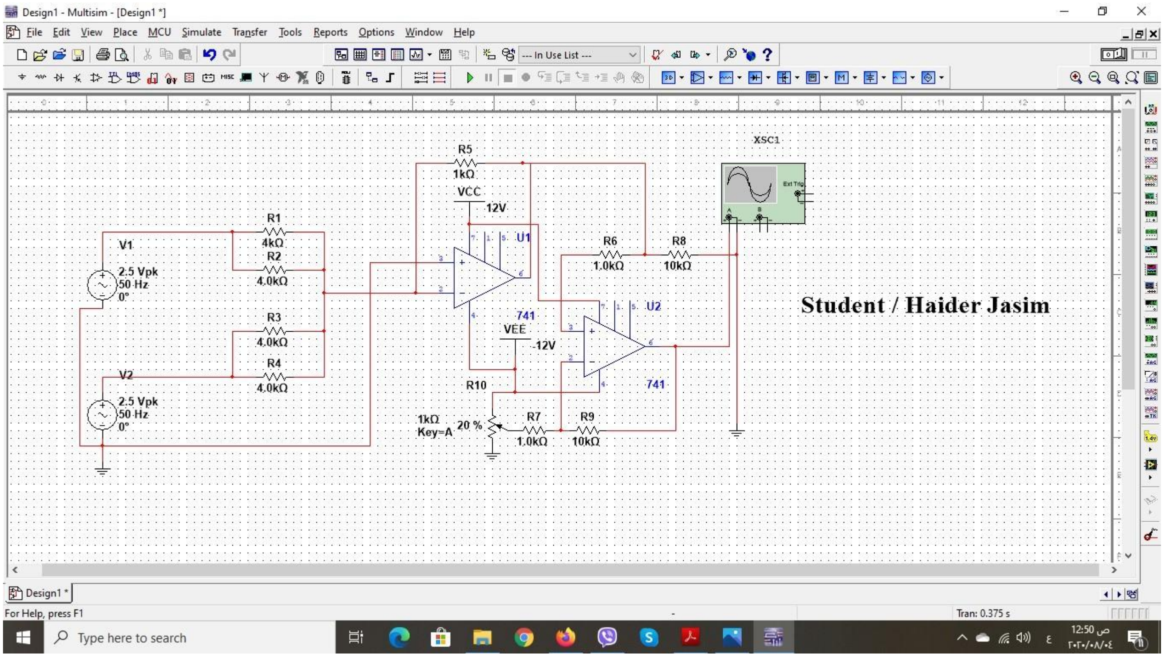

Figure (1.20): Schematic diagram – MultiSIM

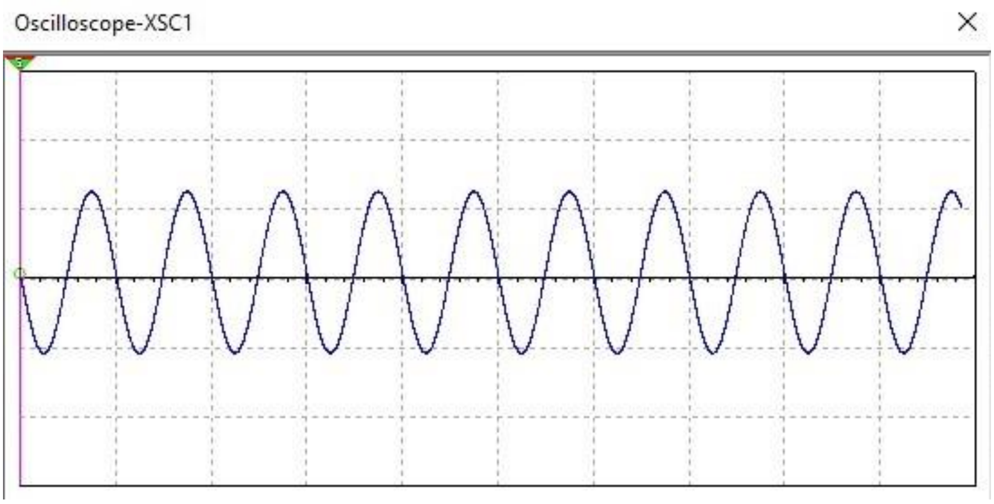

Figure (1.21): Simulated output of summing amplifier circuit and quiescent voltage nullification circuit

2.4 Magnetic Sensors Characteristics:

In all applications of Hall magnetic sensors, such as positioning, current sensing, medical and proximity switching, the most important characteristics are magnetic sensitivity, offset-equivalent magnetic field, 1= f noise-equivalent magnetic field, signal-to-noise ratio (SNR) and linearity. For an AC magnetic signal above the 1= f noise region, the signal-to-noise ratios of equivalent Hall plates in the voltage-mode and current-mode Hall sensor are similar. For a DC and low frequency magnetic field, a voltage-mode Hall sensor in which the current spinning technique is applied, is capable of reducing the offset and 1= f noise. For the first time an equivalent technique applicable in the current mode Hall sensor will be thoroughly explained in chapter 3 [11].

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., we will talk about how to design the Cross-Shaped Hall Plate and use the CMOS digital sensor in applications that operate within a low magnetic field.

3.1 Cross-Shaped Hall Plate:

The cross-shaped Hall plate as a horizontal Hall device has been broadly used due to its relatively high sensitivity and low offset. The structure of the CMOS cross-shaped Hall plate is schematically shown in Figure (2-1). It is fabricated in an N-well diffusion area which is built in a P-type substrate, with four N+ doped terminals [5-6]. The 90° rotation symmetrical structure makes it well suitable for spinning current use where the biasing and sensing terminals are periodically permutated. In order to reduce the 1/f noise and carrier surface losses, a shallow P+ top layer often covers the surface of the N-well. The P+ top layer and P-type substrate are usually connected to ground. When a voltage *V* or current *I* bias is supplied via one pair of terminals and a perpendicular magnetic field *BZ* is applied to the device surface, the Hall voltage *VH* appears on the other pair of terminals due to the Hall effect. Considering the geometry of a real Hall plate, *VH* can be expressed with the current related sensitivity *SI* [6]:

$$V_H = S_I I B_z \qquad (2.1)$$

With $S_I = G\mu_H R_{square} = \frac{G.r_H}{q n_{NW} t_{NW}}$. S_I is determined by the geometrical correction factor G, the Hall mobility μ_H or the Hall factor r_H, the doping concentration n_{NW} of the N-well, and the effective depth of the N-well t_{NW}.

Equation (2.1) can be rewritten with the voltage related sensitivity *SV*:

$$V_H = S_V V B_z \qquad (2.2)$$

With $S_V = \frac{S_I}{R_{square} N_{square}} = \frac{G}{2\frac{L}{W}+\frac{2}{3}}\mu_H$, L and W are the finger length and finger width of the cross-shaped Hall plate, respectively.

For a cross-shaped Hall plate, the geometrical correction factor can be calculated by [6]:

$$G = 1 - 5.0267 \frac{\theta_H}{tan(\theta_H)} e^{\frac{\pi}{2}\frac{W+L}{W}} \qquad (2.3)$$

Where θ_n is the Hall angle, equal to $\tan^{-1}(\mu_H B)$.

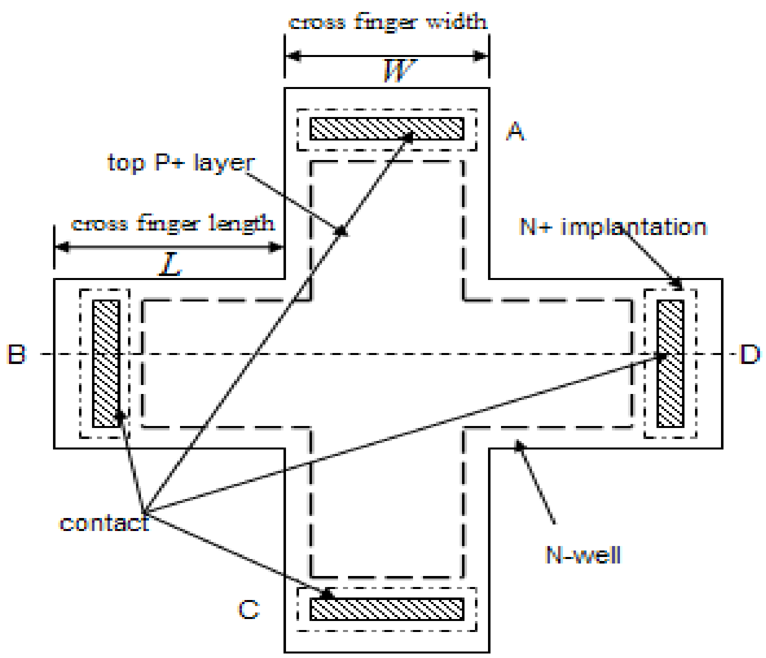

Figure (2.1): Traditional top section of cross-shape Hall plate.

Equation (2.1) means that *SI* is inversely proportional to the carrier concentration of the N-well. Therefore, a Hall device fabricated by a standard CMOS process has a low sensitivity due to high N-well doping concentration. In order to improve the current related sensitivity, we select a HV CMOS process to fabricate the Hall plate as it can provide an obviously lower N-well doping level than the standard CMOS process, despite a relatively deep N-well depth. On the other hand, the geometrical correction factor should also be enhanced, which is determined by the ratio of finger length *L* to finger width *W* in terms of Equation (2.3). In order to improve the voltage related sensitivity without reducing the current related sensitivity too much, an optimal cross geometry ($W/L = 2$) has been reasonably selected in the layout design.

It is well known that CMOS Hall devices seriously suffer from a large offset. One of the main origins of offset comes from the mask-misalignment, which can be minimized by designing a Hall device with an appropriate and symmetric layout. In fact, the masks defining the terminals and N-well implant active layer of the Hall plate could be shifted or rotated relative to each other during photolithography. Any misalignment between terminals mask and the N-well mask will result in an offset, even in the absence of magnetic field. However, the smaller terminals designed within the N-well could lead to a larger masks misalignment. In the layout design, an optimized cross-shaped Hall plate structure is developed. Compared to the conventional Hall plate, the length of terminals reaches a maximum allowable value in the N-well for a given technology. Thus, the effect of the masks misalignment on the offset can be greatly reduced.

3.2 Front-End Signal Conditioning:

The block diagram of the new chopper stabilized instrumental chain is illustrated in Figure (2.2). At first, applying the spinning current technique, the output and supply terminals of Hall plate are periodically interchanged so that the useful Hall signals are separated from the offset and 1/f noise through input chopping modulation. Then, the modulated signals are amplified by a differential instrumentation amplifier. After this amplification, two high-pass filters remove the unwanted offset and 1/f noise. Finally, the output signal passing through the filters is demodulated and the digital Hall signal is generated by a switched hysteresis comparator.

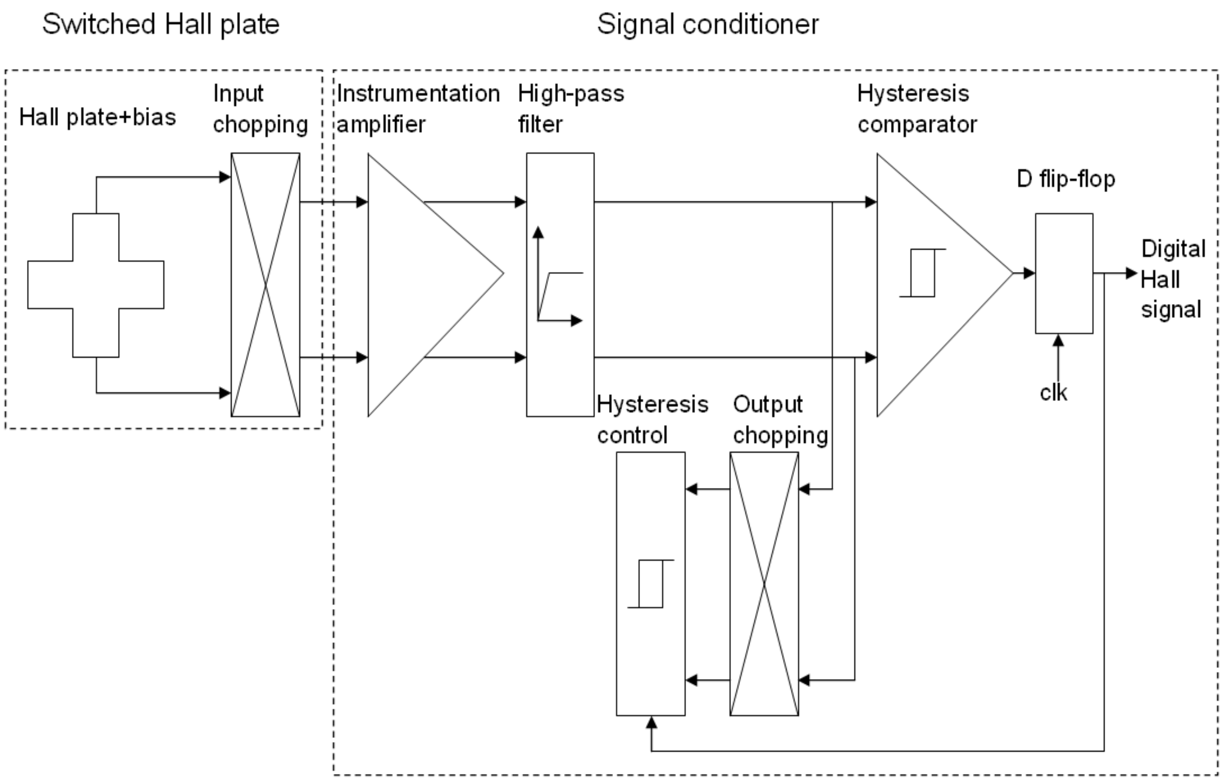

Figure (2.2): Shows the new chopper stabilized instrumental chain.

Figure (2.3) shows the switched Hall plate in Figure (2.2). Since the 90° rotation symmetrical Hall plate can be considered as a distributed resistive Wheatstone bridge from a dc point of view, the dynamic offset cancellation can be achieved by the spinning current method [2.3]. By periodical supply and output terminals permutation, the quadrature states are generated. One pair of complementary clocks of 100 kHz produce 0° and 90° states respectively. When CLK is high level, M2, M3, M5, and M8 turn on. The terminal a and terminal c of the Hall plate are connected to power and ground. Then current flows from terminal a to terminal c, and Hall signal appears between terminal b and terminal d. When NCLK is high level, M1, M4, M6 and M7 turn on, so there is a current flowing from terminal b to terminal d.

Accordingly, a Hall signal is present between terminal c and terminal a. Thus, if the change of the magnetic field is much slower than the clock frequency, the differential output Hall voltage VH periodically changes its polarities with the same magnitude in the course of current spinning. On the contrary, the differential output offset voltage VOP always keeps the same magnitude and a constant polarity, as the same imbalance occurs in adjacent branches of the equivalent Wheatstone bridge network. It is important to note that the offset VOA of the instrumentation amplifier becomes indistinguishable from VOP. Consequently, a demodulation should be performed to extract the Hall signal and eliminate the Hall offset and the instrumentation amplifier's offset simultaneously by the following signal conditioner at no extra cost.

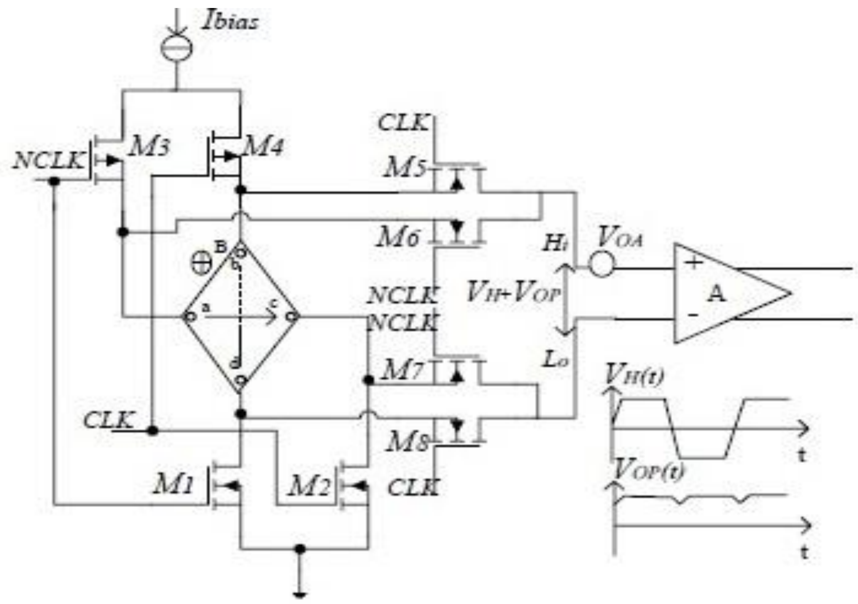

Figure (2.3.1): Switched Hall plate.

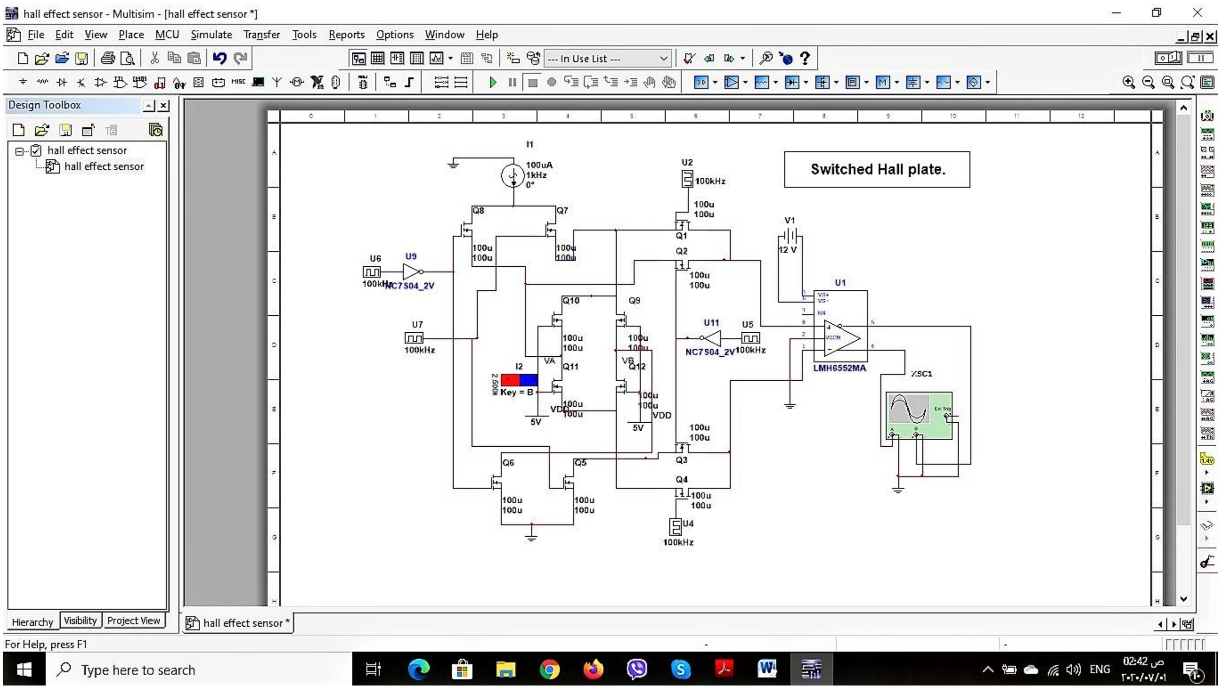

Figure (2.3.2): practically in NI Multisim.

The traditional signal conditioners execute sample-and-hold (S/H) and adding functions to remove offset without using low-pass filters [2.4]. First, the two differential outputs of the instrumentation amplifier are sampled and hold by S/H circuits during 0° and 90° states respectively. Next, the outputs of S/H circuits input the summing OP-AMP. Finally, the offset can be cancelled out by the summing OP-AMP. However, this signal conditioner layout requires four completely differential S/H circuits and a summing OP-AMP, thus it requires too large a chip size to fabricate four S/H capacitances. Moreover, the circuit structure is much more complicated. Later, a simplified circuit configuration was proposed [7].

Here, a capacitance clocked by sampling clock is used to realize the adding function, taking place of a summing OP-AMP. Further, it only needs two S/H capacitances, and the total number of capacitances decreases from four to three. Nevertheless, this circuit requires four-phase different clocks, and the timing relationship in the circuit is much more complex.

In this work, we propose a signal conditioner based on a high-pass filtering demodulation configuration, as shown in Figure (2.4.1). Here, the switched Hall plate is represented by block SWP. EN is the enable signal and high level is effective. Compared to other similar signal conditioners [8-9], the proposed signal conditioner has a simpler structure. In addition to the instrumentation amplifier A, it only consists of two high-pass filters and a switched hysteresis comparator B. The circuit properly works as follows: during the 0° state, the differential input voltage of the instrumentation amplifier is:

$$V_i(0^{\circ}) = V_H + |V_{OP}(0^{\circ})| + |V_{OA}| \quad (2.4)$$

During the 90° state, the differential input voltage of the instrumentation amplifier changes to:

$$V_i(90^{\circ}) = -V_H + |V_{OP}(09^{\circ})| + |V_{OA}| \quad (2.5)$$

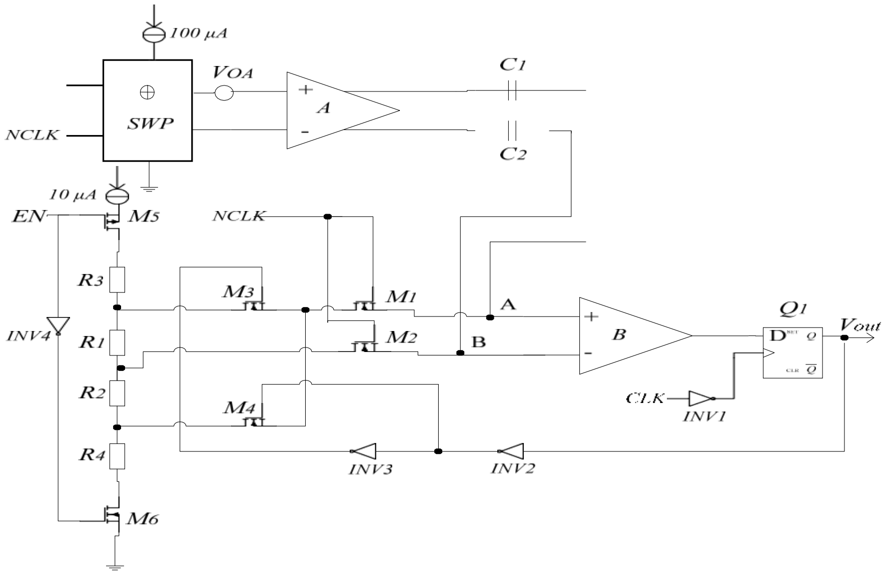

Figure (2.4.1): Signal conditioner of the digital Hall sensor.

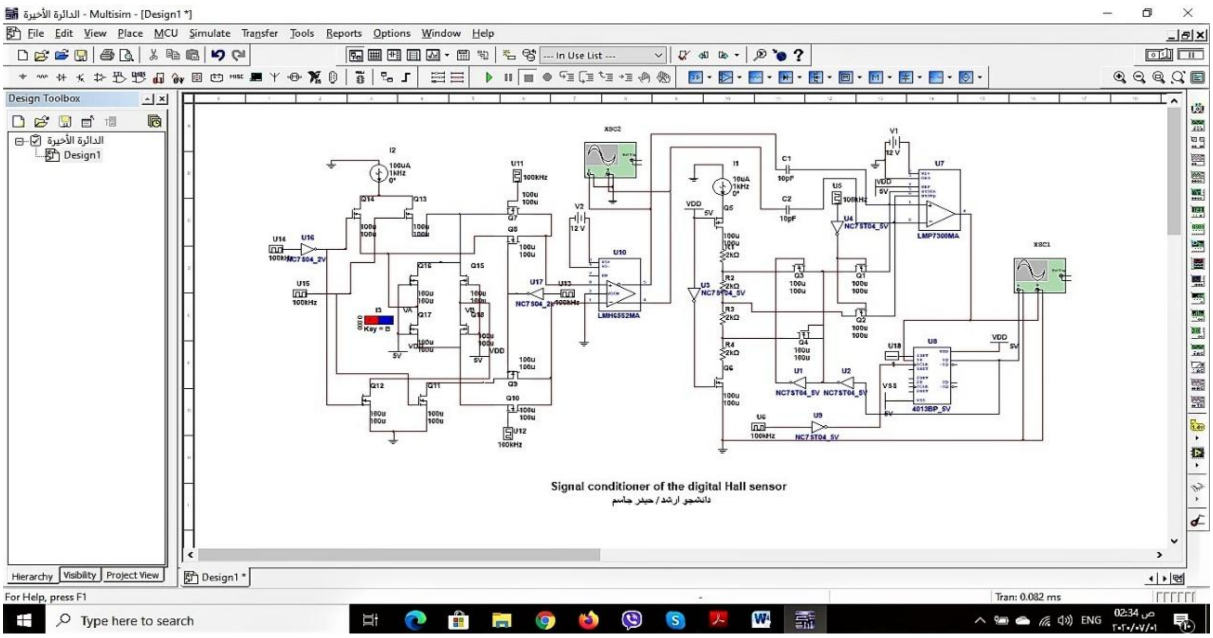

Figure (2.4.2): practically in NI Multisim.

After it is amplified by the instrumentation amplifier, the Hall signal can pass through the high-pass filters, but the offset and 1/f noise are blocked. It is important to notice that a simple passive first order high-pass filter is sufficient to perfectly cancel the offset and 1/f noise. The cut-off frequency of the high-pass filter has to be higher than the 1/f noise frequency, which is typically between 500 Hz and 1 kHz, so a first order high-pass filter with 2 kHz cut-off frequency can achieve this requirement. The cut-off frequency is determined by $1/C_1R_{AB}$ or $1/C_2R_{AB}$, where R_{AB} is the equivalent resistance between the points A and B. In order to obtain low 1/f noise performance, C_1 and C_2 are set to 10 pF. When NCLK is high level, switches M_1 and M_2 turn on, then, the differential input voltage of the comparator B is clamped to:

$$V_{AB} = V_{th} \quad (2.6)$$

Where V_{th} is a trigger threshold level and its polarity is controlled by the feedback Hall output signal. When the Hall output signal is high level, switch M3 turns on and V_{th} is equal to V_{R1} (the current of 10 µA flowing across resistor R_1). Otherwise, switch M4 turns on, then V_{th} becomes $-V_{R2}$ (the current of 10 µA flowing across resistor R_2). We selected R_1 = R_2 = R_3 = R_4 = 2 K to make V_{th} = ±20 mV. At the moment, the cut-off frequency of the high-pass filters is much higher than the chopping frequency of 100 KHz, hence both Hall signal and offset and 1/f noise are blocked. When NCLK is low level, switches M1 and M2 turn off. At this time, the cut-off frequency of the high-pass filters becomes less than 100 kHz but higher than 2 kHz. Thus, only the Hall signal can pass through the high-pass filters. Since the amount of electric charge on the capacitances C_1 and C_2 remains unchanged, the differential input voltage of the comparator B changes to:

$$V_{AB} = 2A_uV_H + V_{th} \quad (2.7)$$

Where, A_u is the voltage gain of the instrumentation amplifier A, and the residual offset voltage is neglected.

First assume that the initial state is $V_A > V_B$, so the output voltage of comparator B is a high level. At this time, V_{th} is equal to *VR1*. When $2A_uV_H$ reversely increases more than $|V_{R1}|$, the comparator B outputs a low level and V_{th} becomes $-V_{R2}$. Only when the value of $2A_uV_H$ forward increases more than $|V_{R2}|$, the output becomes a high level. In order to output a standard CMOS level, a D flip-flop (DFF) is used.

Therefore, the proposed signal conditioner not only effectively eliminates the offset and 1/f noise, but also realizes the hysteresis characteristics of a digital Hall sensor without a Schmitt trigger. Meanwhile, the whole signal conditioner only needs two capacitances, which further make the chip cost-effective.

3.3 Circuit simulation:

A SPICE simulation of the front-end chopper stabilized instrumental chain was performed with 100 kHz chopping clock frequency using a Cadence spectre simulator. The simulation model parameters of the devices were derived from the X-FAB 0.18 µm HV CMOS technology. The Hall plate is modeled by an equivalent simulation model written in Verilog-A language [13]. The Hall plate model produces a 1 kHz sinusoidal Hall output signal of 80 µV and a dc output offset of 2.5 mV when the input bias current is 100 µA and the perpendicular magnetic field is 2.5 mT. After the Hall plate output signals are modulated at 100 kHz by applying the spinning current technique, they are fed into the instrumentation amplifier for amplification. Figure (2-5) illustrates the transient voltage waveform between the differential inputs of the instrumentation amplifier. Unfortunately, some parasitic spikes are obviously observed during commutations. These spikes are generated by the various non-idealities of the switches, including charge injection, clock feed-through and parasitic capacitances of Hall plate and switches. Although a dummy switch can reduce the charge injection, it will increase the complexity of the spinning current circuit. Since the RC time of the spikes is dominated by the resistance of the Hall device and the parasitic capacitance the best method to suppress these spikes is the reduce the parasitic capacitance Therefore, we properly reduce the size of the switches without increasing the on-resistance too much and we employ a small Hall plate to reduce the parasitic capacitance in our design.

Figure (2-6) shows the transient simulation voltage waveform at the differential inputs of the comparator B. It is clearly observed that the high-frequency Hall signal is demodulated into the original low-frequency signal and the offset is effectively eliminated by the high-pass filters.

The digital Hall output signal waveform is shown in Figure (2.7). It can be seen that when the input Hall signal changes polarity, that is the magnetic field changes direction, the DFF output level changes synchronously. The simulation results also show that when the amplitude of the input Hall signal increases to 0.15 mV the signal conditioner can even cancel a maximum input Hall offset of 10 mV, which means that the signal conditioner can tolerate a large offset if the Hall signal becomes larger.

The simulated results indicate the improved signal conditioner has a remarkable ability to suppress the large offset and amplify the weak Hall signal.

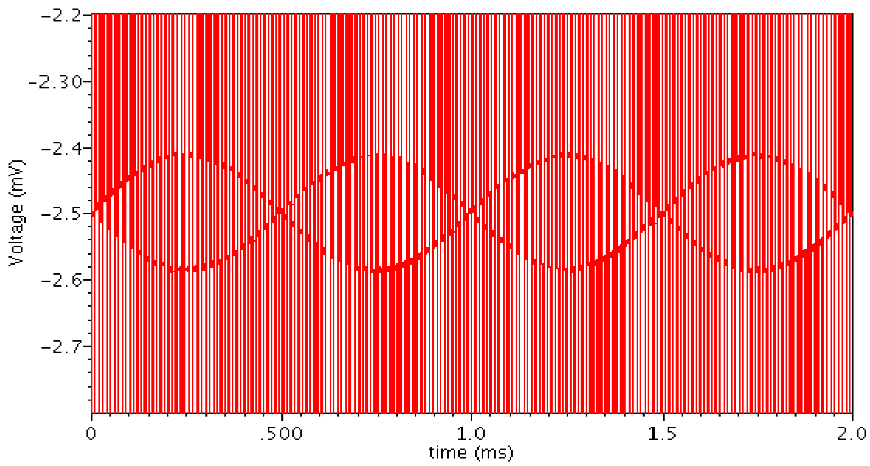

Figure (2.5): Simulated transient voltage waveform between the differential inputs of the instrumentation amplifier in NI Multisim.

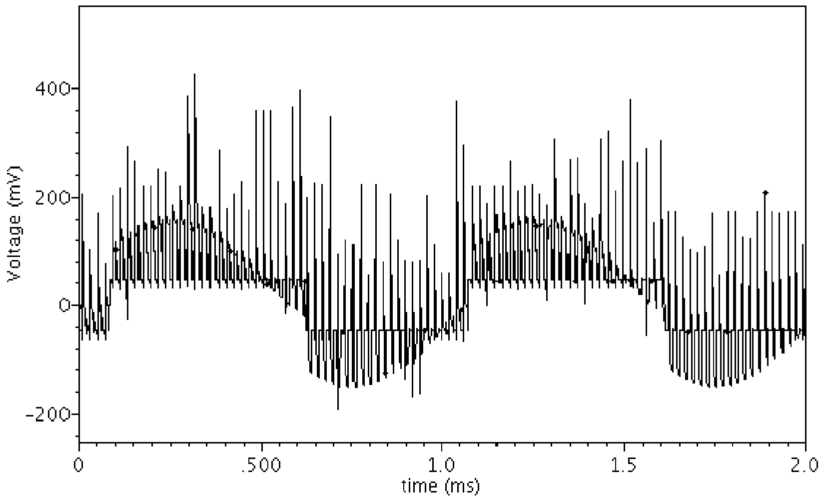

Figure (2.6): Simulated transient voltage waveform between the differential inputs of the comparator with NI Multisim simulation.

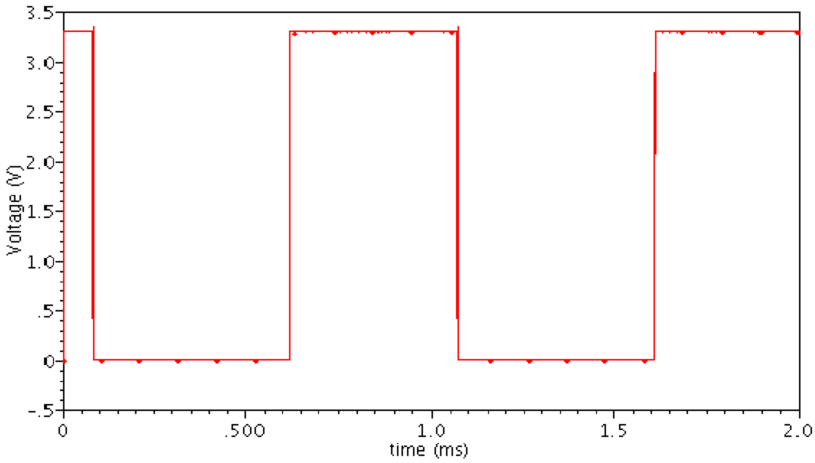

Figure (2-7): Simulated digital Hall output signal of the signal conditioner with NI Multisim simulation.

3.4 Conclusions:

A highly sensitive digital Hall magnetic sensor using the X-FAB 0.18 µm HV CMOS technology is introduced. The cross-shaped structure of Hall device is optimized to reduce Hall offset and improve sensitivity. In order to eliminate the relatively large offset, including Hall offset, amplifier's offset and 1/f noise, the dynamic offset cancellation technique through Hall current spinning is applied. A novel signal conditioner with a simple structure is proposed for saving chip area and improving the performance of the sensor. The recovery of digital Hall output and offset cancellation are achieved with only two high-pass filters and a switch-controlled comparator. The whole signal conditioner only requires a pair of complementary clocks. Additionally, it is convenient to change the hysteresis characteristics by adjusting resistances, without needing an actual Schmitt trigger. The experimental results show that the sensor has a remarkable ability to measure a minimum ±2 mT magnetic field and output a digital Hall signal over a wide temperature range from −40 °C to 120 °C. Therefore, this Hall sensor is well suited for low magnetic field applications, such as integrated brushless DC motor drivers which require small chip size and high sensitivity.

References:

1. Honeywell. (2020, March). *MICRO SWITCH Sensing and Control*.
2. Randjelovic, Z. B., Kayal, M., Popovic, R., & Blanchard, H. (2002). Highly sensitive Hall magnetic sensor microsystem in CMOS technology. *IEEE Journal of Solid-State Circuits, 37*(2), 151–158.
3. Blanchard, H., De, M. F., Hu, B. J., & Popovic, R. S. (2000). Highly sensitive Hall sensor in CMOS technology. *Sensors and Actuators A: Physical, 82*, 144–148.
4. Bilotti, A., & Monreal, G. (1999). Chopper-stabilized amplifiers with a track-and-hold signal demodulator. *IEEE Transactions on Circuits and Systems I: Fundamental Theory and Applications, 46*(4), 490–495.
5. Jovanovic, E., Pesic, T., & Pantic, D. (2004, May). 3D simulation of cross-shaped Hall sensor and its equivalent circuit model. In *Proceedings of the 24th International Conference on Microelectronics* (pp. 235–238).
6. Xu, Y., & Pan, H. B. (2011). An improved equivalent simulation model for CMOS integrated Hall plates. *Sensors, 11*(6), 6284–6296.
7. Hu, Y., & Yang, W. R. (2006, October). CMOS Hall sensor using dynamic quadrature offset cancellation. In *Proceedings of the 8th International Conference on Solid-State and Integrated Circuit Technology* (pp. 284–286).
8. Frick, V., Hebrard, L., Poure, P., & Braun, F. (2001, September). CMOS microsystem front-end for microTesla resolution magnetic field measurement. In *Proceedings of the 8th IEEE International Conference on Electronics, Circuits and Systems* (pp. 129–132).
9. Ouffoue, C., Frick, V., Kern, C., & Hébrard, L. (2009, June–July). New fully differential instrumental chain for Hall sensor signal conditioning integrated in standard 0.35 µm CMOS process. In *Joint IEEE North-East Workshop on Circuits and Systems and TAISA Conference* (pp. 1–4).
10. *International Journal of Advances in Computer and Electronics Engineering, 2*(1), 16–23. (2017, January).
11. Heidari, H. (2015). *Current-mode high sensitivity CMOS Hall magnetic sensors* (Doctoral dissertation). University of Pavia.
12. Vandyke, M. (2019, November 6). *Reliable magnetic switches.* Magnelink. Retrieved from https://magnelink.ink

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