Application Note

Application of magnetic sensors in brushless motors

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Senis has produced a demonstrator IC to showcase the new patented magnetic angle sensor technology. The SENIS® Fast Magnetic Angle Sensor (FAMAS) SENA2Dx is an integrated high speed magnetic angle sensor. When coupled with a magnet, it serves as an effective encoder, offering precise motor control and feedback. With SPI controls, non-volatile memory and the ability to operate at speeds up to 200,000 RPM (with overclocking the maximum speed can be increased by 30%), it caters to diverse high-speed applications, whether mounted on-shaft with a bipolar magnet or off-shaft with multipole magnets. Pole pair selection for off-shaft magnets allows UVW outputs from the sensor to be directly used for commutation. Additionally, it features variable speed modes, with lower modes offering higher resolution. SENA2Dx supports UVW or ABZ output for commutational or positional sensing. Importantly, it maintains consistent performance across all speed modes without degradation. Furthermore, it provides absolute angle output via SPI parallel to digital UVW and ABZ signals, enabling comprehensive motor position tracking and control.

Currently undergoing redesign for further enhancement, a future version is set to deliver even greater performance and functionality.

When talking about brushless motors, you may encounter terminological confusion. Historically speaking, these are motors where commutation was done mechanically with brushes, and later, with the development of electronics, solid-state electronic commutation was designed. Now, when we talk about electronically commutated motors we mean Brushless DC motors (BLDC) and Permanent Magnet Synchronous Machine (PMSM).

Electronically commutated motor (ECM), is a synchronous motor using a direct current (DC) electric power supply. Commutation is the process of managing the current flow in the motor's coils, ensuring synchronized and efficient rotation. It uses an electronic controller to switch DC currents to the motor windings producing magnetic fields that effectively rotate in space and which the permanent magnet rotor follows. The controller adjusts the phase and amplitude of the DC current pulses to control the speed and torque of the motor. This control system is an alternative to the mechanical commutator (brushes) used in many conventional electric motors.

As the rotor nears coil W1, coil W2 is energized. As the rotor nears coil W2, coil W3 is energized. After that, coil W1 is energized.

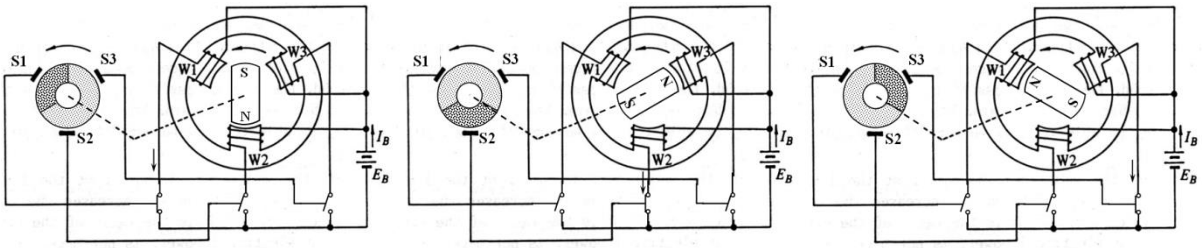


Figure 1. Three-phase unipolar-driven brushless dc motor working principle.

A humorous analogy help to remember it is to think of BLDC operation like the story of the donkey and the carrot, where the donkey tries hard to reach the carrot, but the carrot keeps moving out of reach (see Fig. 2).

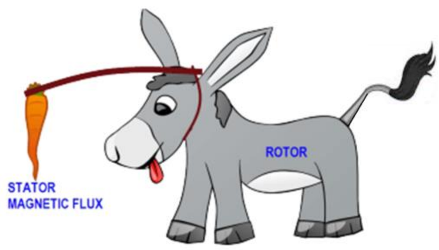


Figure 2. A humorous analogy.

Direct current is applied to the drive circuits of brushless motors, but an alternating current flows through the motor. For this reason, brushless motors are sometimes called AC synchronous motors.

Different types of Brushless DC motors exist. These are categorized according to the design, kind of component, power signal, and other factors. The various device types are employed in multiple applications because each offers a unique set of advantages. The design of the motor can determine the type of commutation as shown in Figure 3.

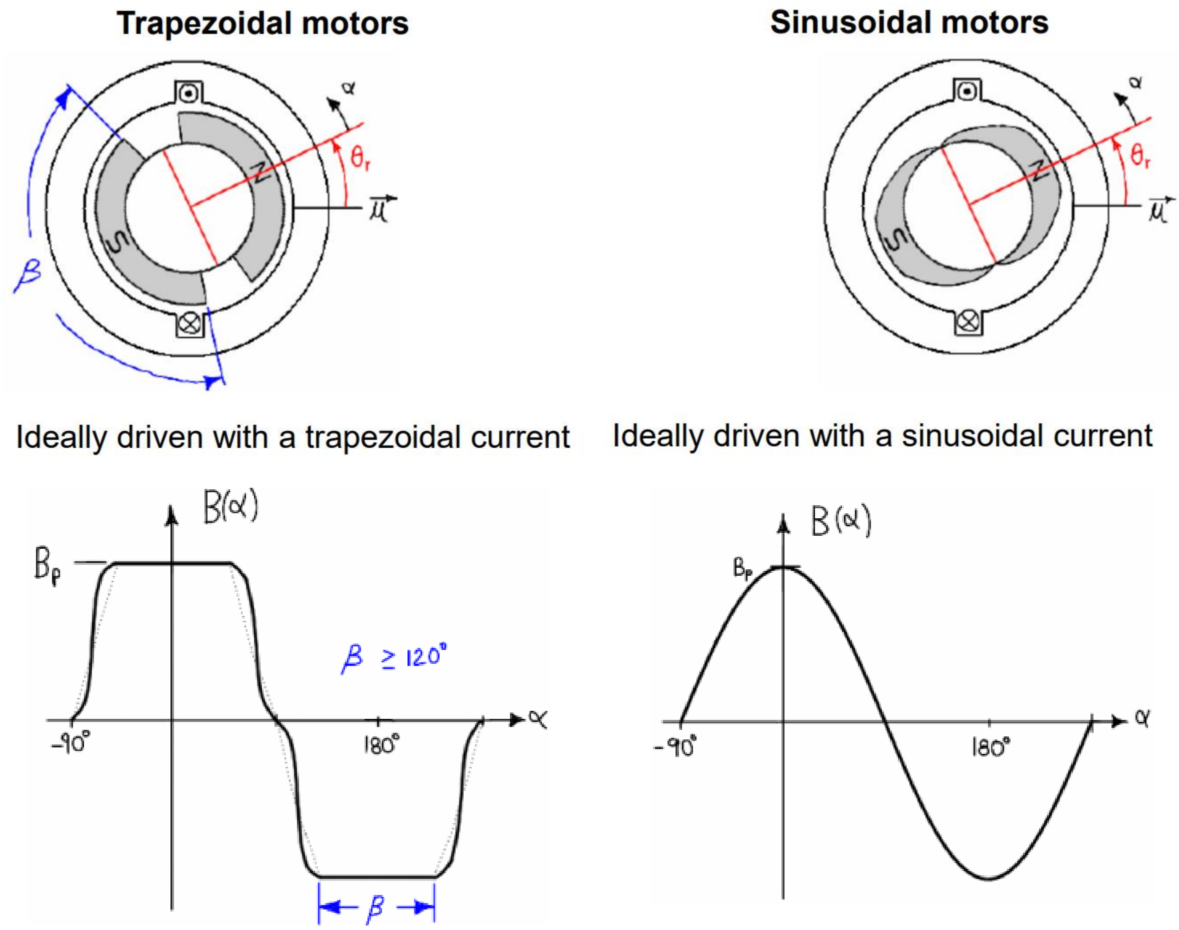


Figure 3. Motor design and air-gap flux density profiles for BLDC (Trapezoidal) and PMSM (Sinusoidal) motors.

Motor startup and driving methods can be broadly divided into two types (Fig. 4):

- Position sensored driving (A motor driving method requiring a sensor that detects the motor rotation speed and rotation position);
- Position sensorless driving (A motor driving method not requiring such a sensor).

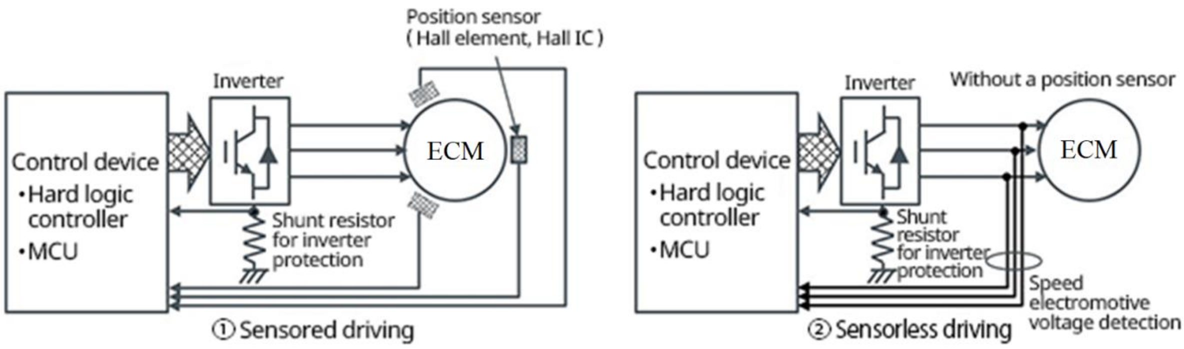


Figure 4. Basic configurations of motor driving system.

Different types of brushless DC motors have different advantages when used in specific applications. Understanding the structure, advantages and disadvantages of the types can be helpful in deciding on the best high efficiency brushless motors for project planning.

Sensored Electronically Commutated Motors

A sensored BLDC motor uses sensors to provide information about the rotor's position. The sensors deliver precise information at lower RPMs, enabling a smooth rotation. The advantages of sensored driving are that it ensures position and rotation detection during motor startup and driving, and smooth motor driving and rotation control are possible from lower to higher speeds using a motor driver that incorporates a hard logic controller. These BL motor varieties offer dependable performance at slower speeds.

At at very high speeds, as the sensor feedback degrades, the major flaw of sensored motors becomes apparent. Harsh conditions like dusty or hot settings also impact the sensors and, thus, the operation of the motor. Disadvantages include the need to consider the precision of the sensor mounting position due to the need to mount a sensor such as Hall element/Hall IC in the motor, and the need for wiring to connect the sensor to the motor controller. These motors work best in situations with low rpm.

Sensorless Electronically Commutated Motors

Sensors are not used in this sort of motor. Instead, the controller uses the counter electromotive force produced in the stator coils to determine the rotor position. These brushless DC motors provide the best high-speed performance. The advantages of sensorless driving are the ability to drive motors in which it is not physically possible to install a sensor, and the ability to drive motors subjected to harsh environments such as high temperatures and the presence of water, oil, and the like. These motor types suit challenging environments, low-cost applications, and fast speeds. Also, these types of motors suit low-cost applications and high speeds.

Their flaw is most noticeable at low speeds when the counter EMF is too small for the controller to detect or when starting from a stationary position. Moreover, in place of a position and rotation detection sensor, the motor current, voltage, and motor parameters (R and L of the motor windings) are used in the computational estimation, so that the result is affected by differences between individual motors. In sensorless driving, there are also methods in which a hard logic dedicated controller other than an MCU causes startup by an external forced commutation signal, and thereafter the speed electromotive voltage is used as a position signal.

Sensorless controllers mainly use three basic principles of work:

- EMF method with zero crossing,
- Observer-based EMF method,
- Magnetic anisotropy methods.

Sensorless brushless DC motors are so called because they do not have a sensor that measures the position of the rotor, but they have electronic circuits or sensors that convert voltage or current into a control signal.

Types of Position Sensors for Electronically Commutated Motors

The position sensor plays a role in determining the position of the rotor pole in the BLDC motor, and provides correct phase change information for the logic switch circuit. It converts the position signal of the rotor magnetic steel pole into an electrical signal, and then controls the stator winding phase change. There are many kinds of position sensors and each has its own characteristics. There are few kinds of position sensors commonly used in brushless dc motor, namely electromagnetic position sensor, magnetic sensitive position proximity sensor, photoelectric position sensor and capacitive commutation encoders.

Electromagnetic position sensor

Brushless dc motor with electromagnetic position sensor is equipped with electromagnetic sensor components on stator assembly. When the rotor position of permanent magnet changes, electromagnetic effect will cause the electromagnetic sensor to produce high-frequency modulation signal (its amplitude varies with the rotor position). Common electromagnetic sensors are rotational variable differential transformers (RVDT), resolvers, induktosyn, inductive proximity switches, and so on.

Magnetic sensitive position sensor

A magnetically sensitive position sensor is a semiconductor sensor whose electrical parameters vary with the surrounding magnetic field according to certain laws. A BLDC motor with a magnet-sensitive position sensor is installed on the stator assembly to detect changes in the magnetic field created by the permanent magnets and rotors. The basic principles in use are the Hall effect and the magnetoresistance effect. Common components are Hall sensor or Hall device, magnetic resistor, magnetic diode, etc.

Photoelectric position sensor

Photoelectric position sensor is made of photoelectric effect. It consists of a light shield that rotates with the rotor of the motor, a fixed light source and a photocell. BLDC motor with photoelectric position sensor is equipped with photoelectric sensor parts in a certain position on stator assembly. The rotor is equipped with a light shield and the light source is led or small bulb. When the rotor rotates, due to the role of the shader, the photosensitive components on the stator will generate pulse signals intermittently at a certain frequency.

Capacitive commutation encoders

Optical encoders use very small LEDs to transmit light through a disk with notches at specific intervals to generate output patterns. The capacitive commutation encoders encoders can be described in a similar manner, but instead of transmitting light via LEDs, an electrical field is transmitted. In the place of an optical disk is a PCB rotor containing a sinusoidal-patterned metal trace that modulates the electrical field. The receiving end of the modulated signal is then passed back to the transmitter where it is compared against the original via a proprietary ASIC.

BLDC Motor Control with Hall Sensors

The sensors can be placed directly inside the motor, at the end of a motor's shaft, or around a ring magnet attached to the rotor shaft, as illustrated in Figure 5.

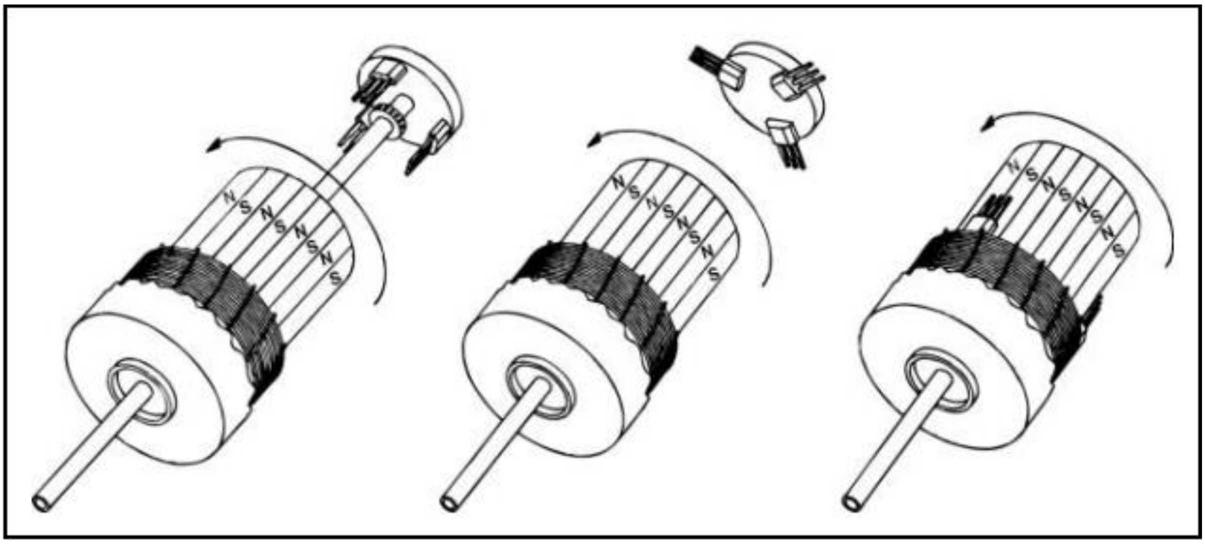


Figure 5. Typical sensor locations.

To simplify the process of mounting the Hall sensors onto the stator, some motors may have the Hall sensor magnets (commutation magnet) on the rotor, in addition to the main rotor magnets. These are a scaled down replica version of the rotor. Therefore, whenever the rotor rotates, the Hall sensor magnets give the same effect as the main magnets.

Typically, BLDC motors have more magnet poles and coils than displayed in the figures. The more coils and rotor magnetic poles that are used, the finer the control of the magnet. The magnets can be implemented as multiple bar magnets adjacent to each other, where adjacent magnets have opposite polarity from each other. Using more magnets increases the number of state transitions seen by the Hall sensor in a given time, thereby decreasing how much the rotor has to rotate for the Hall sensors to cycle through all their possible states.

The three Hall position sensors should be placed so that the angle differences between their respective outputs are 120 ° offset from each other. This angle is referred to as the electrical angle, which may differ from the actual angle at which the devices are mechanically placed from each other. From the center of the motor axis, the number of degrees to space each sensor (the mechanical angle) can be set to 2 / [number of poles] × 120° to create the necessary 120 electrical degrees.

In the four-pole example in Figure 6, the mechanical and electrical angles are equal, 120 degrees. However, in the four-pole example in Figure 7, the mechanical and electrical angles are not equal. In general, for systems having multiple magnetic poles, the electrical angle and the mechanical angle need not be equal due to the increased number of magnetic poles reducing the cycle time through different combinations of the Hall output state. This is exactly what is illustrated in Figures 6 and 7 where the electrical angle is the same but differs mechanically (the angle between the Hall sensors in Figure 3 is 120 degrees and in Figure 7 it is 60 degrees).

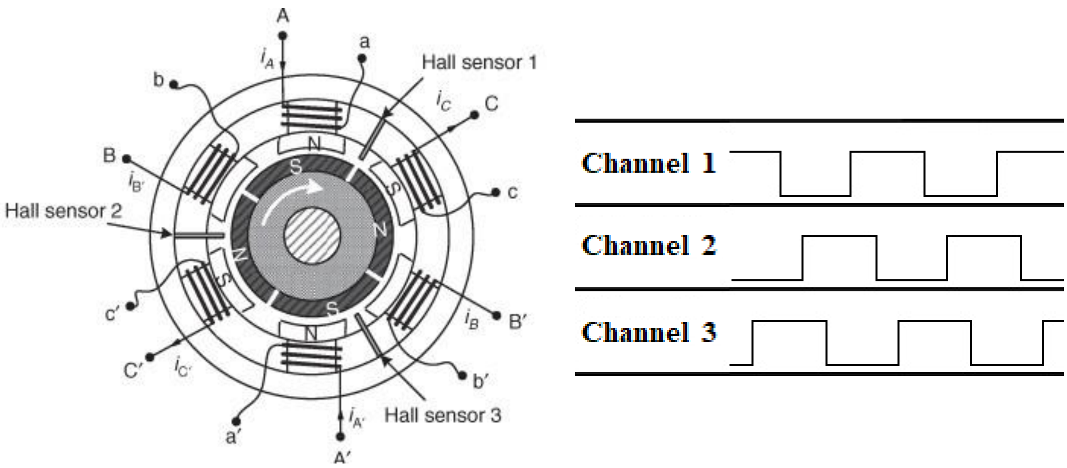


Figure 6. BLDC Motor Model, and commutation steps for example of three Hall effect ICs placed at locations offset by 120° degrees on a 4-pole rotor and its index detection.

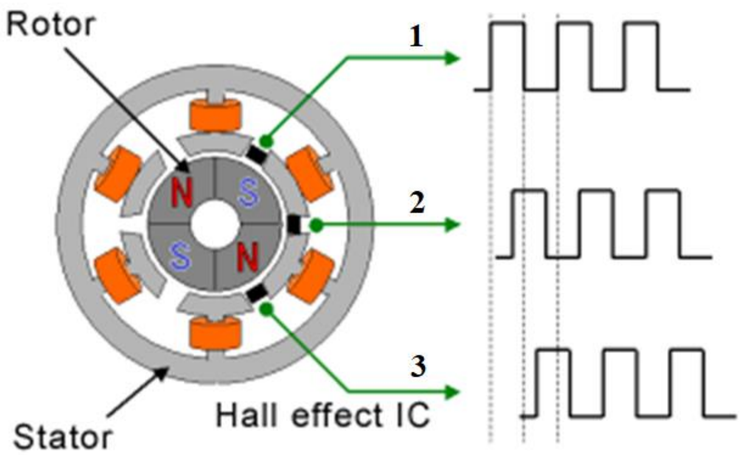


Figure 7. A typical example of three Hall effect ICs placed at locations offset by 60° on a 4-pole rotor and its index detection.

There are different types of PCBs with assembled Hall sensors on the market (Figure 8).

Figure 8. Different Hall sensor circuit boards.

A typical structure of Hall sensors used in these applications is shown in Figure 9.

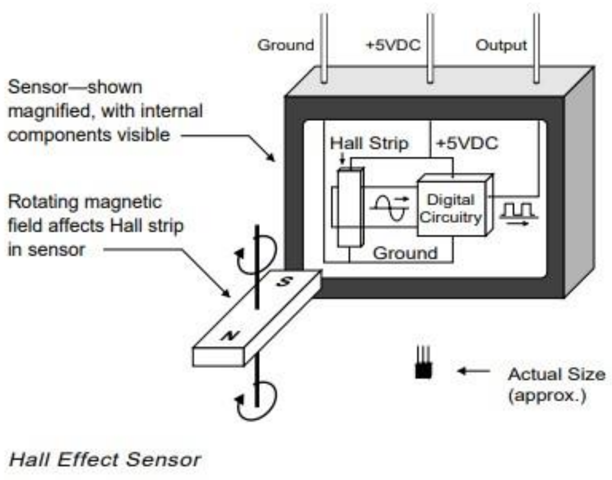


Figure 9. A magnified view of the Hall effect sensor.

Hall Effect Switch Classification

Magnetic Latch & Switch ICs rely on the principles of the Hall-effect to convert the information of a magnet into a digital signal (1 or 0). The output is therefore either On or Off, depending on the applied magnetic field. Through the position of a magnet, Latch & Switch ICs can thus determine the physical position of an object.

- Switch principle:

The output changes on a defined threshold (see Fig. 10).

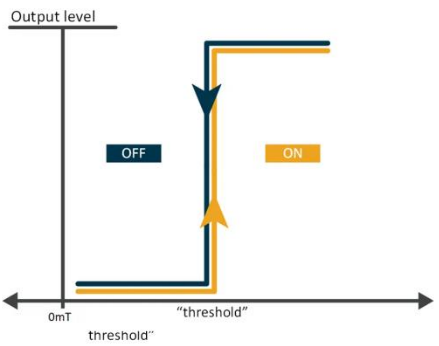


Figure 10. Switch principle.

- Latch principle:

It is a switch which depends on two opposite thresholds (see Fig. 11). The output first changes on one defined threshold (e.g. North pole value) and then changes on its opposite threshold (e.g. South pole value). In between these two thresholds the output is locked (it remains unchanged).

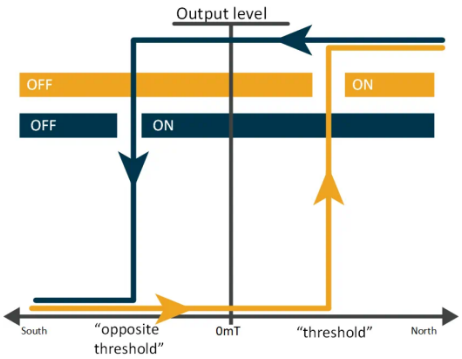


Figure 11. Latch principle.

Latch & Switch ICs can be divided into three main categories. For all three, the key parameters are the two switching thresholds: BOP, the magnetic operating point, and BRP, the magnetic release point.

1. The „Unipolar Hall effect switch" has a magnetic working threshold (Bop). If the Hall element is subjected to a magnetic flux density greater than the operating threshold, the output transistor will turn on; when the flux density falls below the operating threshold (Brp), the transistor turns off. The lag (Bhys) is the difference between the two thresholds (Bop-Brp). Even if there is external mechanical vibration and electrical noise, this built-in hysteresis page enables the net switch of output (see Fig. 12).

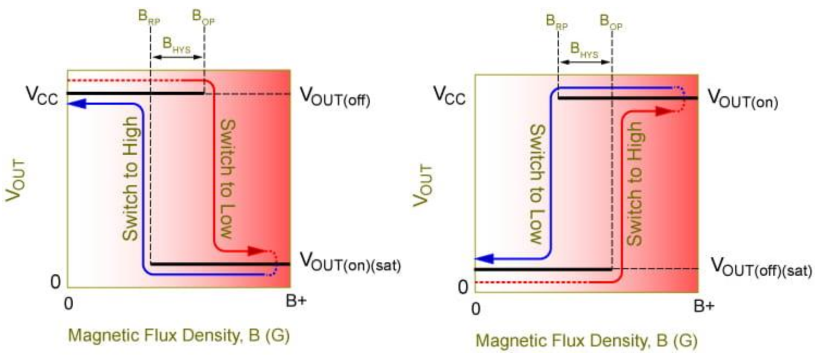


Figure 12. Unipolar switch output characteristics. The top panel displays switching to logic low in the presence of a strong south polarity field, and the bottom panel displays switching to logic high, also in a south polarity field.

2. The second category is a „Bipolar Hall effect Switch", also known as a Latch. A Latch is activated in one field spectrum and deactivated when the opposite field is applied. In this case, BOP defines when the output driver will be active (On), while BRP defines when the output driver will be inactive (Off). A Latch is normally used for brushless DC commutation for PLC motors or index counting for DC motors (see Fig. 13).

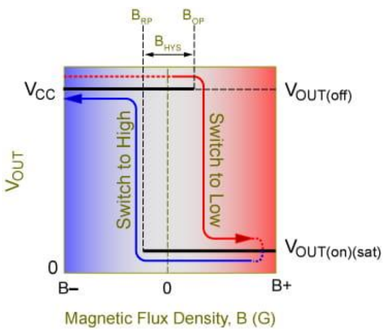


Figure 13. Latching switch output characteristics. The device output switches to logic low in the presence of a strong south polarity field, and switches to logic high in a strong north polarity field. In a weak field, the latch does not change output state.

3. The third category is an „Omnipolar Switch" which has the same capabilities as the Bipolar Switch but can attract both field spectrums at the same time. In other words they are active in both the North and South fields, and are used to detect a change in both spectrums (see Fig. 14).

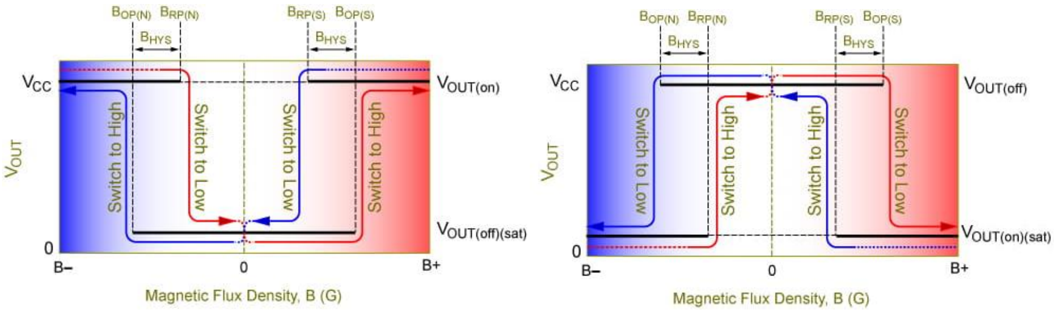


Figure 14. Omnipolar switch output characteristics. The top panel displays switching to logic high in the presence of a strong magnetic field, and the bottom panel displays switching to logic low, also in a strong magnetic field.

4. Zero crossing latch (ZCL) Hall effect technology realizes polarity changes detection and hold operation (Hold status) of V_{OUT}. This is different from the conventional bipolar latch method. ZCL detection method has no hysteresis width of the magnetic sensitivity to switch V_{OUT}. Instead, the ZCL detection method can switch V_{OUT} without chattering by using the Hold status. Zero-cross detecting circuit and sensor device is patented by Ablic Inc.

This IC switches V_{OUT} after the output delay time (t_D) from when the magnetic flux density applied to this IC crosses B_Z (from $B > B_{RS}$ to $B < B_Z$ or from $B < B_{RN}$ to $B > B_Z$). When V_{OUT} is switched, this IC starts the Hold status. In the Hold status of V_{OUT}, when the magnetic flux density applied to this IC exceeds B_{RS} or B_{RN}, this IC releases the Hold status (from $B < B_Z$ to $B < B_{RN}$ or from $B > B_Z$ to $B > B_{RS}$).

Figure 15 show the V_{OUT} operation timing when sine wave magnetic flux density is applied to this IC.

(1) $B > B_{RS} \rightarrow B < B_Z$, and after t_D, V_{OUT} = "L" → "H", and Hold status starts

(2) $B < B_Z \rightarrow B < B_{RN}$, and after t_D, Hold status is released, and V_{OUT} = "H" continues

(3) $B < B_{RN} \rightarrow B > B_Z$, and after t_D, V_{OUT} = "H" → "L", and Hold status starts

(4) $B > B_Z \rightarrow B > B_{RS}$, and after t_D, Hold status is released, and V_{OUT} = "L" continues

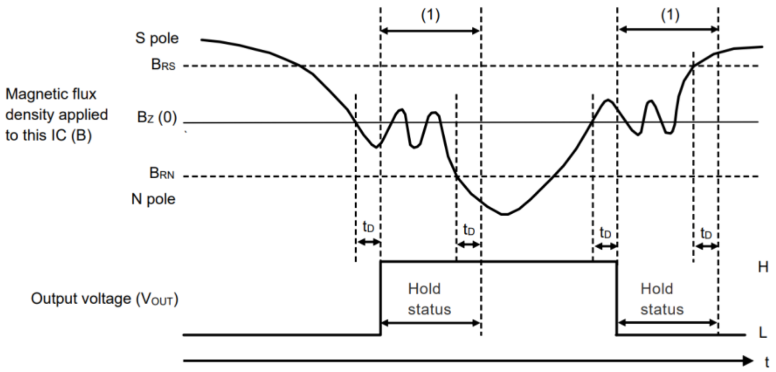


Figure 15. Product with VOUT = "L" at S pole detection.

Users can select the bipolar latch or Zero Crossing Latch detection method for Hall effect latch ICs for motor control and rotation detection, and the unipolar or omnipolar detection method for Hall effect switch ICs for detecting opening, closing and sliding motion (see Fig. 16).

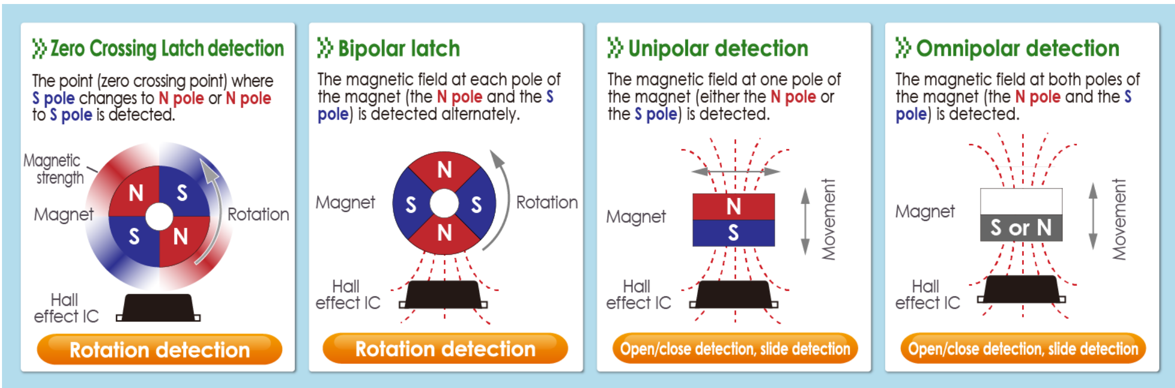


Figure 16. Detection types of Hall effect ICs.

Miniaturization of brushless motors also requires miniaturization of sensors. Thus, three Hall sensors can be placed in one chip and thereby provide three signals with a phase shift of 120° at the output. In this case, the motor configuration implies the use of a dipole switching magnet and the placement of the sensor on the rotor axis (Figure 17).

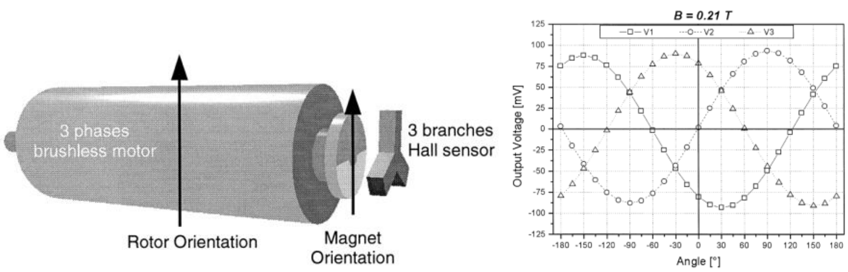


Figure 17. Three branches vertical Hall device mounted as angular position.

In the case of a three-phase motor, the use of a 3D Hall sensor simplifies the application. The angular placement of the Hall sensors of 120° between them ensures the automatic generation of a three-phase control signal, i.e. each Hall sensor corresponds to one of the 3 phases.

In order to determine the angular position of the rotor in all four quadrants, at least two Hall sensors are required. When two Hall sensors are used, it is not necessary to know the amplitude of the magnetic field. Most often, two sensors are placed at a mutual angle of 90°. In this way, the output of one sensor corresponds to a sine signal, and the output of the other sensor to a cosine signal (see Fig. 16).

Modern sophisticated systems use integrated Hall sensor elements with complex analog and digital signal processing within a single device.

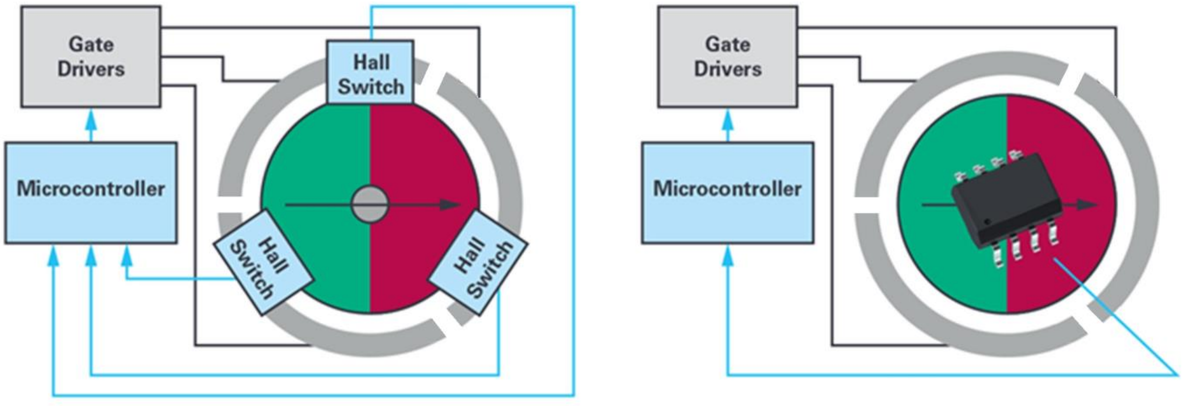


Figure 18. (a) BLDC block commutation control and (b) BLDC sine commutation control.

A simple dipole magnet generates the necessary magnetic field by rotating it perpendicularly. Wide magnetic field sensor configurations allow On Axis (axis end) or Off Axis (axis side) mode of application.

It is not mandatory, but usually BLDC motors are trapezoidal motors by construction and trapezoidal (i.e. six-step) commutation is applied, which usually works with the help of three Hall devices. There is one Hall device that generates UVW signals at its output that correspond to the signals of three spatially spaced Hall sensors. This type of Hall device is usually mounted on-axis (although an off-axis variant is also possible). A commutation magnet is a dipole magnet. When in on-axis configuration, a dipole commutation magnet is always applied.

The distinction between positioning and commutation is important as some motors have multiple control loops: one control loop for commutation and one control loop for positioning. These control loops do not necessarily use the same sensor (see Fig. 19).

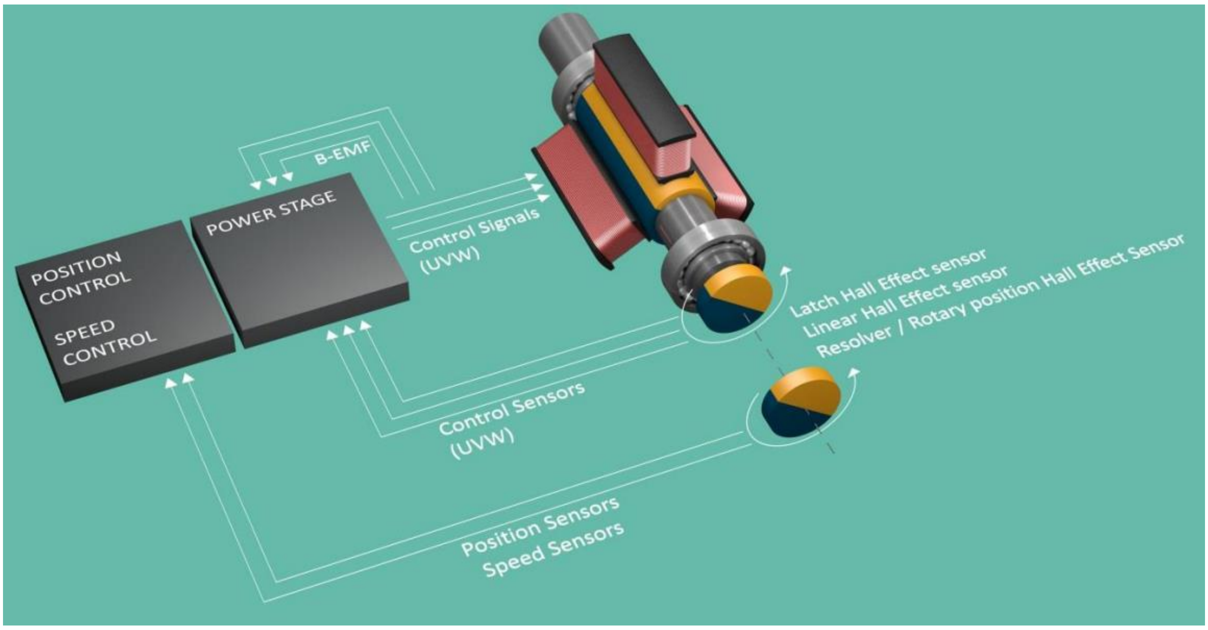


Figure 19: General Building Blocks and communication paths to enable motor commutation and positioning.

Outputs of sensors fed to commutation circuitry. Measurement of shaft angle essential for commutation; that is, application of voltage to stator windings must be synchronized with shaft angle. A sensor is required to give the feedback to the motor control system indicating when the rotor has reached the desired position. If the commutation is done faster or slower than the speed of the rotor, the magnets go out of sync with the magnetic field of the stator. This causes the rotor to vibrate and stop instead of rotating.

Because of all the above, sensors for motor commutation must be fast in order to work in real time, they must perform precise monitoring of the rotor angle and be reliable.

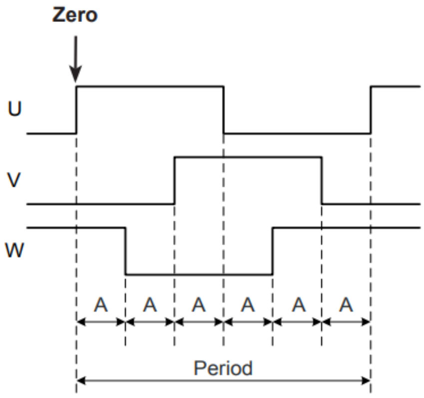
Commutation outputs

On a high-level overview we can talk about 3 different hall-based product categories for motor commutation: latch/switch, linear hall and resolver.

Motor commutation with Latch/Switch

Latch/Switch products are placed in the stator in a multi-IC configuration. They are interesting for trapezoid control of BLDC motors: 3 ICs are used, 1 for each phase. (Described earlier in the section "BLDC Motor Control with Hall Sensors")

UVW outputs can be output as digital signals. The number of signal periods (P) equals number of pole pairs. The timing diagram shows the signals when the position data is increasing. The U signal always starts at zero position regardless the signal period length (see Fig. 20).



Fgure 20. Timing diagram – Commutation.

Table 1. UVW outputs.

Pole	A	Period	Pole pairs[1]
2	60°	360°	one
4	30°	180°	two
6	20°	120°	three
8	15°	90°	four
10	12°	72°	five
12	10°	60°	six
14	8.57°	51.42°	seven
16	7.50°	45°	eight

UVW Hysteresis A hysteresis larger than the output noise is introduced on the UVW output to avoid any spurious transitions (see Figure 21).

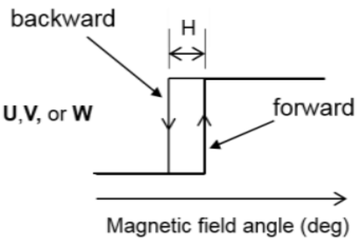


Figure 21: Hysteresis of the UVW signal.

Advantages

- Suitable for long wire applications.
- Compatible with hall switches.
- Cost.

Limitations

- Lower output resolution than ABI.
- 3 output lines required.
- Read only

[1] Number of pole pairs equals number of periods per revolution.

Motor commutation with Linear Hall

A linear Hall effect sensor can be used to replace the Hall latch sensors. Using multiple sensors in quadrature provides absolute rotor angle with high angle resolution. Their analog output makes it possible to calculate, with a dedicated algorithm, a much more accurate rotor position. This makes them not only suitable for detecting the motor commutation point but also for an accurate position control (see Figures 22 and 23).

Two linear hall sensors placed at a 90° magnetic phase shift can also be used as a sine cosine angle sensor. The angle α is calculated from the acous tangent of *sin* over *cos*.

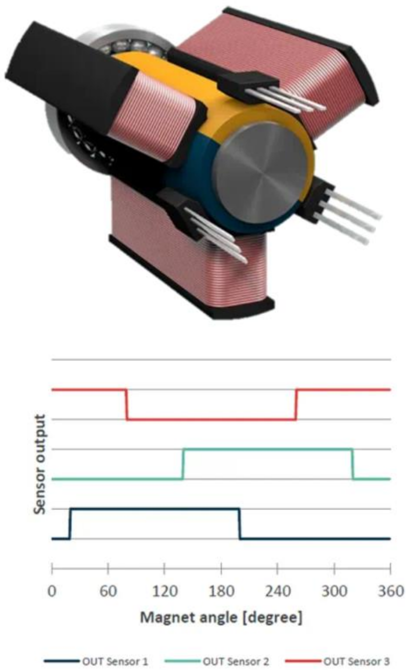


Figure 22: Setup with 3 sensors.

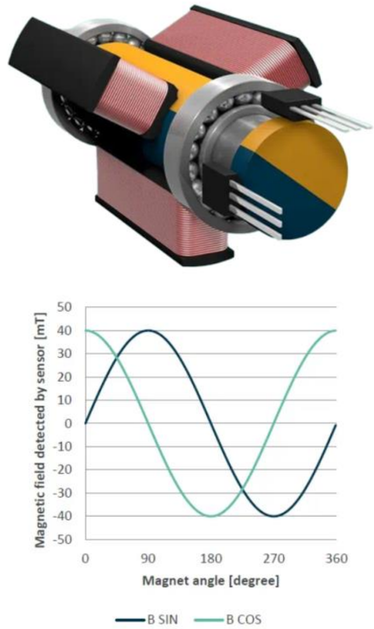


Figure 23: Setup with 2 sensors.

The mathematical Clarke transformation converts a three-phase system to a two-phase orthogonal system (see Figure 24).

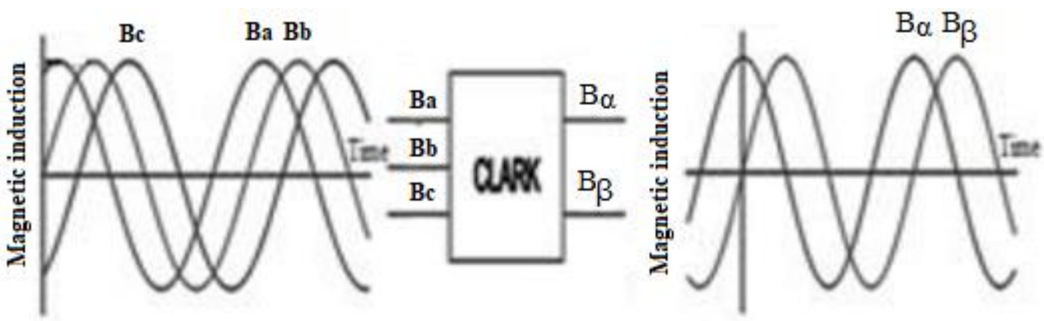


Figure 24. Direct Clarke transformation.

The modification from a two-phase orthogonal α, β frame to a three-phase system is done using the inverse Clarke transform (see Figure 25):

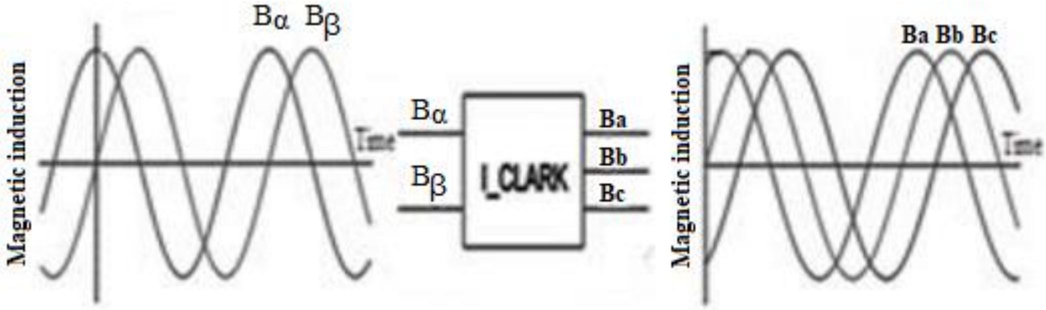


Figure 25. Inverse Clarke transformation.

Motor commutation with Magnetic Resolver (Analog sine/cosine)

Magnetic Resolvers, also known as resolvers or motor resolvers, are fast IC solutions which provides ratiometric analog sine-cosine outputs (see Figure 26). These outputs are representative of the rotor magnetic flux and thus can be used to detect the motor position. The latest generation can be placed either on-axis (End of Shaft) or off-axis (Though Shaft) (see Figures 27 and 28).

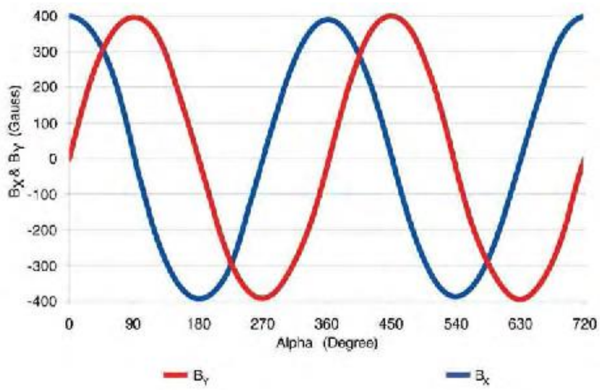


Figure 26: Sine Cosine output example.

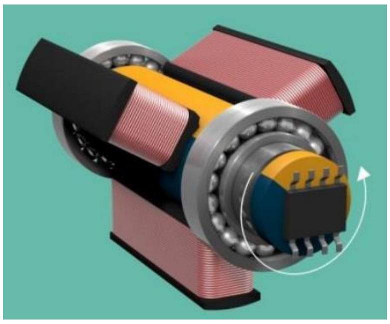


Figure 27: End of shaft.

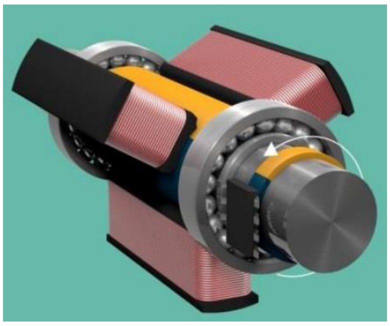


Figure 28: Through shaft

Advantages

- Easy to integrate with most microcontrollers.
- Suitable for long distance wires.
- Low latency.

Limitations

- When operating with a differential and/or dual-die sensor, more signal lines are required.
- Poor interference resistance.
- Requires differential signal lines for robustness.

One IC sensor with several different output protocols

Modern Hall devices can generate different types of output switching signals, and for direct application in ECM these are (UVW) outputs and differential sine/cosine outputs (see Figure 29).

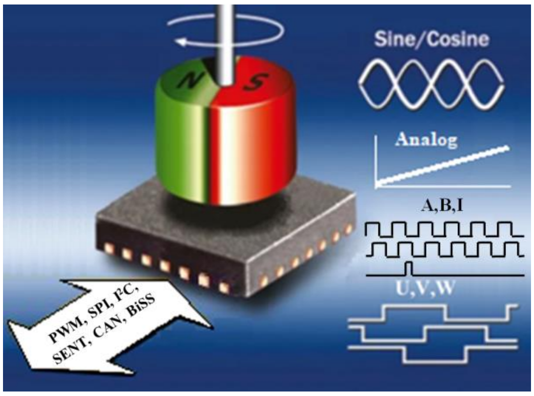


Figure 29. Modern sensors have a system-on-chip (SoC) architecture that includes: Hal element front end, digital signal processing to calculate the angular position information, and multiple output formats: PWM, SPI, I2C, SENT, CAN, BiSS, and either motor commutation (UVW), sine/cosine, or encoder outputs (A, B, I).

The UVW output emulates the three Hall switches usually used for the block commutation of a three-phase electric motor.

If the number of pole pairs of the motor exceeds the number of pole pairs of the target magnet, some sensors can generate more than one UVW cycle per revolution. It does this by dividing the digital angle into the required number of commutation steps per 360° revolution.

There are sensors that can support both on-axis and off-axis installation. Compared with the application in the shaft, which needs to occupy an end face of the motor shaft, the off-shaft installation method is more flexible and more suitable for robot joints, AGV hub motors and other applications.

Encoder outputs

Incremental Output Interface (ABI or ABZ)

Incremental output mode in the form of quadrature A/B and index outputs emulate an optical or mechanical encoder. The A and B signals toggle with a 50% duty cycle (relative to angular distance, not necessarily time) at a frequency of 2N cycles per magnetic revolution, giving a cycle resolution of (360 / 2N) degrees per cycle. The pulses emitted from the A and B outputs are quadrature-encoded, meaning that when the incremental encoder is moving at a constant velocity, the A and B waveforms are square waves and there is a 90 degree (¼ of the cycle period) phase difference between A and B. The "I" (or "Z") signal is an index pulse that occurs once per revolution to mark the zero (0) angle position. One revolution is shown in Figure 30.

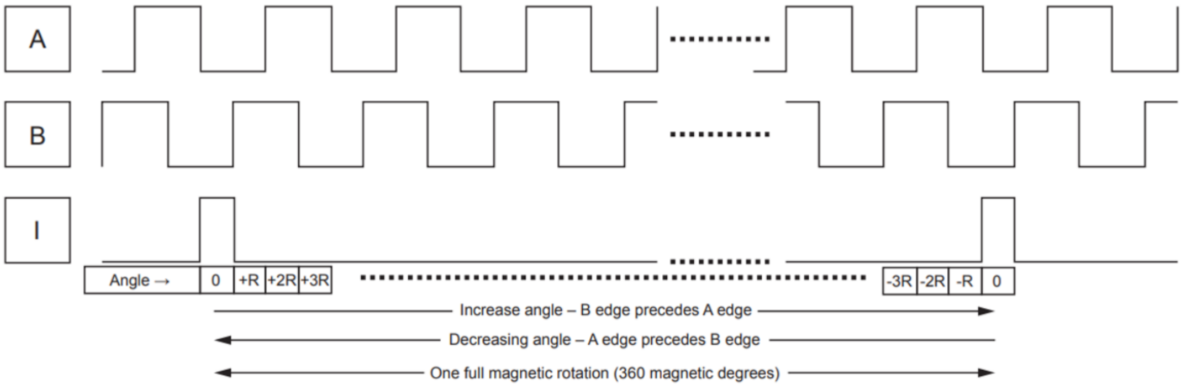


Figure 30: ABI output protocol.

Advantages

- Can output the absolute angle.
- Suitable for long wire applications.
- Can apply angle hysteresis to moderate jitter.
- Offers higher resolution than UVW.
- Compatible with encoders.

Limitations

- Three output lines required in most applications (sometimes the user can omit some).
- Protocol does not show an absolute position prior to seeing the index pulse.
- Read only.

Analog Output

In modern magnetic sensors, the angle is calculated in the digital part, and then the signal is converted into an analog signal (see Figure 31). Analog protocol outputs a linear analog signal between a max and min value proportional to the magnetic field. While in quiescent state, no field is applied, the output voltage equals half of the supply voltage, then under an applied magnetic field the output voltage either increases or decreases linearly depending on the magnet's polarity. This output protocol is illustrated in Figure 32, were the output is converted into a percentage based off the supply voltage. Voltage values beyond the upper or lower limits represent diagnostic regions.

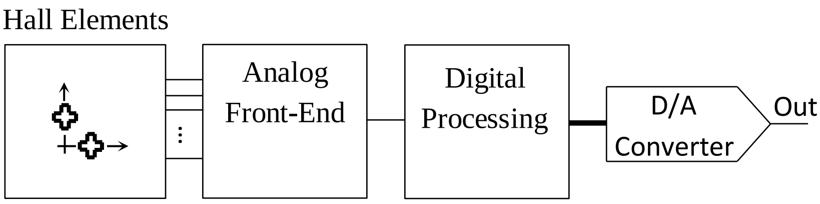


Figure 31. Functional blocks of magnetic angle sensor with analog output.

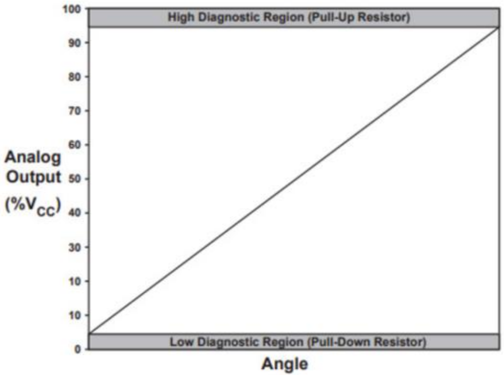


Figure 32: Analog output.

Advantages

- Fast.
- Limited circuitry required.
- Simple output.
- Compatibility between analog sensor often is simple.
- Only one output wire required.

Limitations

- Sensor not capable of outputting additional information.
- Limited amount of information transferred.

PWM Protocol

PWM is an output protocol option for a multitude of angular sensors. It converts the output voltage amplitude to a sequence of constant-frequency binary pulses, with a duty cycle directly proportional to the angle of applied magnetic field. The duty cycle for some sensors has limits at 5% and 95% DC corresponding to 0° and 360° respectively. Figure 33 displays the PWM output waveform and corresponding magnetic field angle. For each PWM period, the output is high for the first 5% and low for the last 5%. The middle 90% segment of the wave is a linear interpolation of the desirable signal output, depending on whether it is an angle or linear sensor.

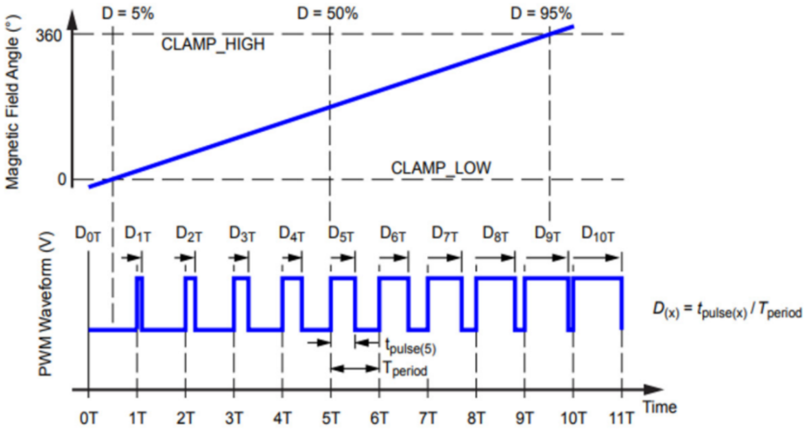


Figure 33: PWM output waveform and magnetic field angle.

Advantages

- Well-established and simple protocol for microcontrollers.
- Allows easy conversion to analog.
- Only one data wire required.
- Well suited for long wire applications.

Limitations

- Limited amount of information transmitted, e.g. error information.
- Low resolution.
- Low throughput.
- Limited signal verification.

SPI Protocol

Serial Peripheral Interface (SPI) is a de facto standard (with many variants) for synchronous serial communication, used primarily in embedded systems for short-distance wired communication between integrated circuits. SPI uses a master–slave architecture, described here with the terms "main" and "sub", where one main device orchestrates communication with some number of peripheral (sub) devices by driving the clock signal and chip select signal(s) (see Figure 34).

Devices that use the SPI interface require four signal lines to communicate. Communication lines are illustrated in Figure 35.

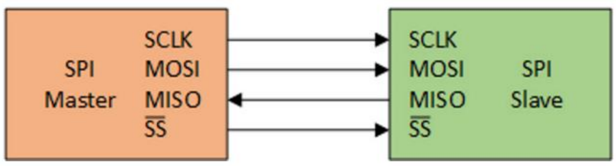


Figure 34: Basic SPI bus example.

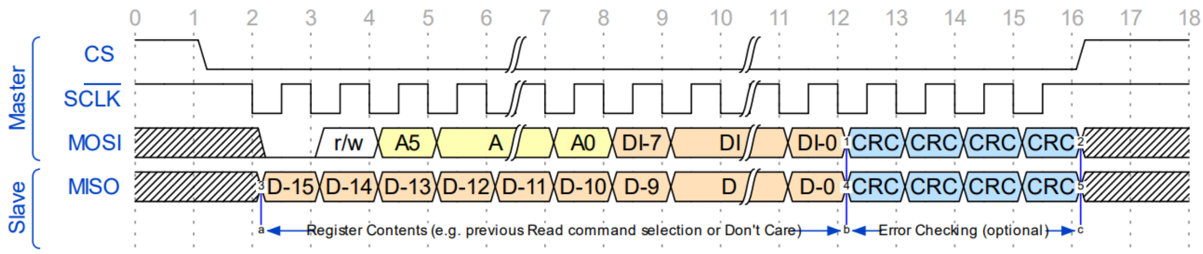


Figure 35: SPI communication example.

Advantages

- Flexible communication that allows read/write (full duplex) to/from the device's memory map.
- High throughput: All Allegro SPI devices support clock frequencies up to 10 MHz.
- Easy to use and integrate with microcontrollers.
- Flexibility for the number of bits transferred.
- Multiple slave devices can be connected on one SPI bus.

Limitations

- Requires four data signal wires.
- Only handles short distances compared to other protocols.
- Supports just one master device.

I²C Protocol

I²C (**Inter-Integrated Circuit,** alternatively known as **I2C** or **IIC**) is a synchronous bus which provides a full duplex interface between two or more devices. Only two communication wires with respective pull-up resistors are required for this protocol. Typical voltages used are 3.3 V or 5 V, but other voltages are permitted. Some sensors supports voltages down to 1.8 V (see Figure 36).

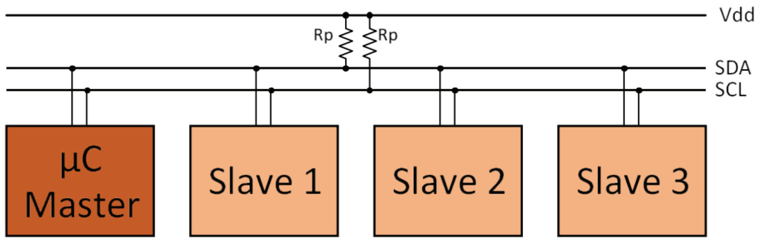


Figure 36: Basic I2C bus example.

I²C communication is composed of several steps outlined in the following sequence as shown in Figure 37.

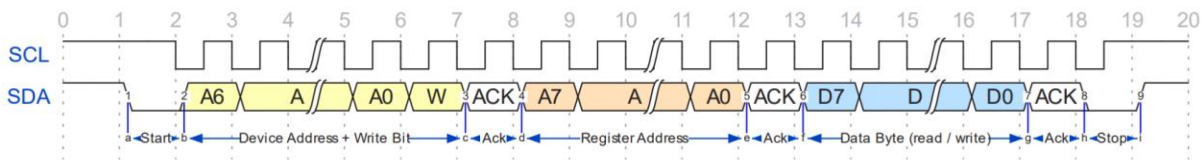


Figure 37: I2C transmission example.

Advantages

- Flexible communication to read and write (full duplex).
- Can handle multiple slave and multiple master devices on one I²C bus.
- Only requires two signal wires.
- Easy to use/integrate. Most microcontrollers support I²C in hardware and/or via software.

Limitations

- Throughput is lower than SPI.
- I²C supports up to 5 Mbit/s (only unidirectional) but most devices support just 0.4 or 1 Mbit/s (bidirectional).
- Only handles shorter distances compared to other protocols.
- Slave number can be limited by address conflicts.
- Communication is not as stable as other protocols, especially in noisy environments.

SENT

SENT (Single Edge Nibble Transmission) protocol is a point-to-point scheme for transmitting signal values from a sensor to a vehicle controller. It is intended to allow for transmission of high resolution data with a low system cost. The SENT protocol is a commonly accepted automotive protocol for highly efficient transfer of sensor data along intravehicular communications networks and is standardized by the Society of Automotive Engineering in publication SAE-J2716.

A SENT message is a series of nibbles. Each nibble is an ordered pair of a low-voltage interval followed by a high-voltage interval. The low interval is defined as 5 SENT ticks, as shown in Figure 38. The high interval contains information and is variable in duration to indicate the data payload of the nibble.

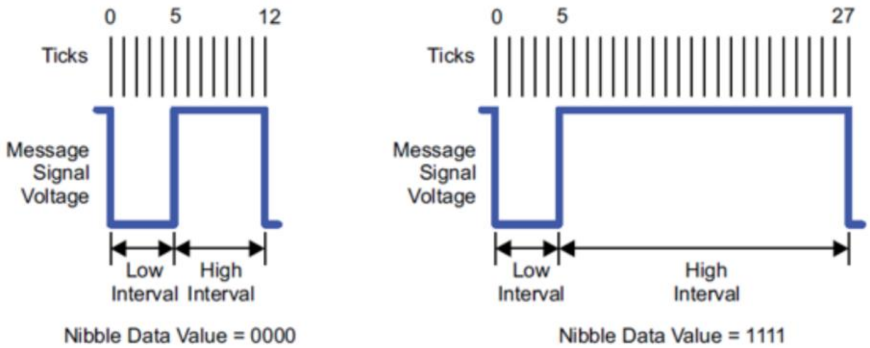


Figure 38: General SENT nibble composition.

The duration of a nibble is expressed in clock ticks and the period of a tick can be defined by the user. The duration of the nibble is the sum of the low-voltage interval plus the high-voltage interval (see Table 2). The slew rate of the falling edge can be adjusted within specific EEPROM parameters of the sensor. The nibbles of a SENT message are arranged in the following required sequence (see Figure 39):

Table 2: SENT nibble composition and value

Quantity of Ticks			Binary (4-bit) Value	Decimal Equivalent Value
Low Voltage Interval	High Voltage Interval	Total		
5	7	12	0000	0
5	8	13	0001	1
5	9	14	0010	2
…	…	…	…	…
5	21	26	1110	14
5	22	27	1111	15

The SENT protocol is a one-way, asynchronous voltage interface which requires three wires: a signal line (low state < 0.5 V, high state > 4.1 V), a supply voltage line (5 V) and a ground line. SENT uses pulse-width modulation to encode four bits (one nibble) per symbol.

The basic unit of time in SENT is called a tick, where a tick can be between 3 - 90 µs, at the sender's option. Each message is preceded by a calibration pulse with a high period of 56 ticks for framing and calibration of tick length. After the calibration pulse, each nibble is transmitted with a fixed-width low signal, followed by a variable-length high period. The low-period is 5 (or more) ticks in length, while the high period can vary, for a total time between falling edges of between 12-27 ticks (representing nibbles ranging from 0-15).

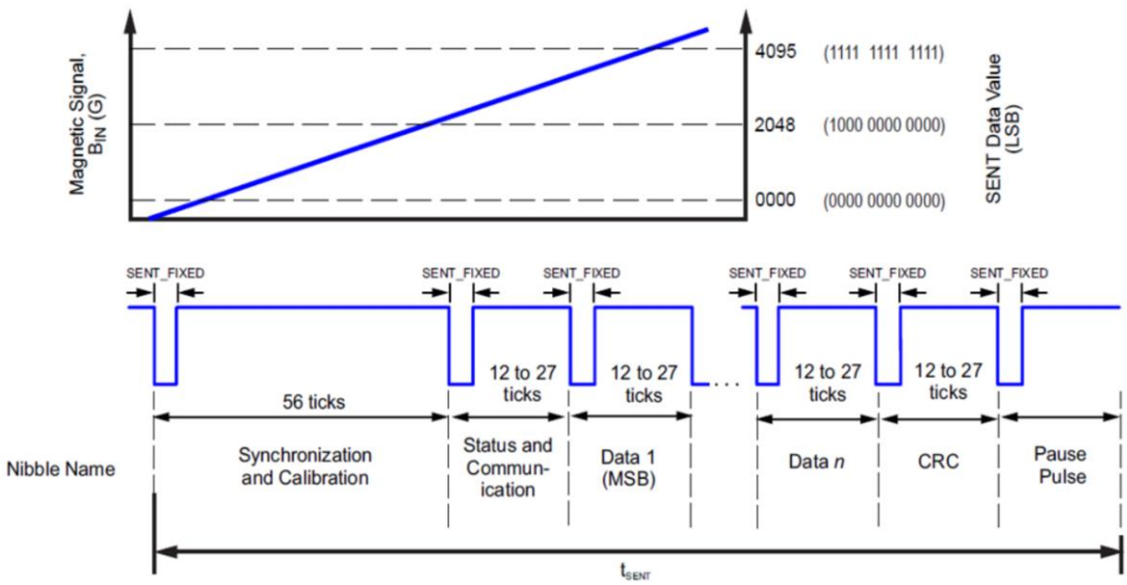


Figure 39: General format for SENT message.

Advantages

- Optimized for harsh environments.
- Requires just one data line.
- High resolution (12 or 16 bit) data.
- Additional information channels available, e.g. for device temperature or serial number.
- Output information is programmable.
- Low cost.
- Supported by many microcontrollers.

Limitations

- Not as easy to implement as SPI or I^2C.
- Low throughput (typically 1 kHz data rate).

CAN bus Protocol

A controller area network (CAN bus) is a vehicle bus standard designed to allow microcontrollers and devices to communicate with each other. It is a message-based protocol, designed originally for multiplex electrical wiring within automobiles to save on copper, but it can also be used in many other contexts. For each device, the data in a frame is transmitted serially but in such a way that if more than one device transmits at the same time, the highest priority device can continue while the others back off. Frames are received by all devices, including by the transmitting device (see Figure 40).

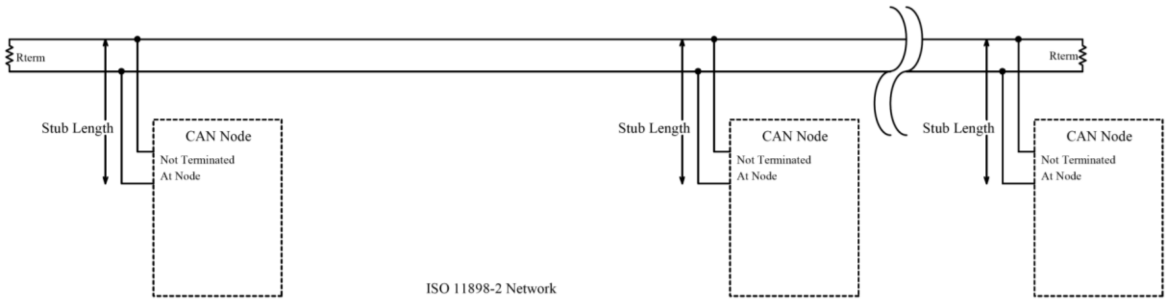


Figure 40. High-speed CAN bus. ISO 11898-2.

Physical organization

CAN is a multi-master serial bus standard for connecting electronic control units (ECUs) also known as nodes (automotive electronics is a major application domain). Two or more nodes are required on the CAN bus to communicate. A node may interface to devices from simple digital logic e.g. PLD, via FPGA up to an embedded computer running extensive software. Such a computer may also be a gateway allowing a general-purpose computer (like a laptop) to communicate over a USB or Ethernet port to the devices on a CAN bus.

All nodes are connected to each other through a physically conventional *two-wire bus*. The wires are a twisted pair with a 120 Ω (nominal) characteristic impedance.

This bus uses differential wired-AND signals. Two signals, CAN high (CANH) and CAN low (CANL) are either driven to a "dominant" state with CANH > CANL, or not driven and pulled by passive resistors to a "recessive" state with CANH ≤ CANL. A 0 data bit encodes a dominant state, while a 1 data bit encodes a recessive state, supporting a wired-AND convention, which gives nodes with lower ID numbers priority on the bus.

Bit timing

All nodes on the CAN network must operate at the same nominal bit rate, but noise, phase shifts, oscillator tolerance and oscillator drift mean that the actual bit rate might not be the nominal bit rate. Since a separate clock signal is not used, a means of synchronizing the nodes is necessary. Synchronization is important during arbitration since the nodes in arbitration must be able to see both their transmitted data and the other nodes' transmitted data at the same time. Synchronization is also important to ensure that variations in oscillator timing between nodes do not cause errors.

Synchronization starts with a hard synchronization on the first recessive to dominant transition after a period of bus idle (the start bit). Resynchronization occurs on every recessive to dominant transition during the frame. The CAN controller expects the transition to occur at a multiple of the nominal bit time. If the transition does not occur at the exact time the controller expects it, the controller adjusts the nominal bit time accordingly.

The adjustment is accomplished by dividing each bit into a number of time slices called quanta, and assigning some number of quanta to each of the four segments within the bit: synchronization, propagation, phase segment 1 and phase segment 2 (see Figure 41).

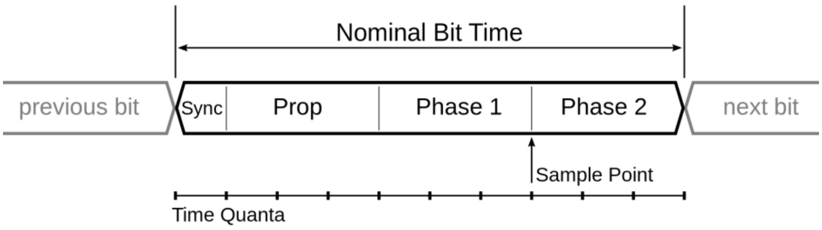


Figure 41. An example CAN bit timing with 10 time quanta per bit

The number of quanta the bit is divided into can vary by controller, and the number of quanta assigned to each segment can be varied depending on bit rate and network conditions.

A transition that occurs before or after it is expected causes the controller to calculate the time difference and lengthen phase segment 1 or shorten phase segment 2 by this time. This effectively adjusts the timing of the receiver to the transmitter to synchronize them. This resynchronization process is done continuously at every recessive to dominant transition to ensure the transmitter and receiver stay in sync. Continuously resynchronizing reduces errors induced by noise, and allows a receiving node that was synchronized to a node that lost arbitration to resynchronize to the node which won arbitration.

Advantages

- It allows 1Mbps data rate. CAN FD (flexible data rate) version supports more than this speed i.e. supports 2+Mbps. CAN FD will support more bandwidth which is eight times more than standard CAN bus.
- It is used to reduce wiring in various automotive applications. Due to less complex interface, it is widely used across various industries.
- It saves overall cost and time due to less and simple wiring as well as use of flash programming.
- Standard CAN protocol supports 8 bytes while CAN FD protocol supports 64 bytes in the data field part.
- Supports auto retransmission of lost messages.
- It works in various electrical environments without any issues.
- The protocol supports different error detection capabilities such as bit error, ack error, form error, CRC error and stuff error.

Limitations

- Though maximum number of nodes are not specified for the network. It supports upto 64 nodes due to electrical loading.
- It supports maximum length of 40 meters.
- It is likely to have undesirable interactions between nodes.
- It incurs more expenditure for software development and maintenance.
- CAN driver must produce atleast 1.5V across typical 60 Ohm.
- Network should be wired in topology which limits stubs as much as possible.
- In order to reduce signal integrity issues such as reflections CAN bus should be properly terminated at both the ends with resistors.
- Node removal requires use of termination resistors of 120 Ohm value at appropriate places on the CAN bus.

BiSS Interface

BiSS is an **open source** digital interface for sensors and actuators. The interface features high-speed bidirectional communication, and is implemented on simple hardware (compatible with industry standard SSI). It is suitable for real-time data acquisition and provides safety features like CRC protected transmission (see Figure 42).

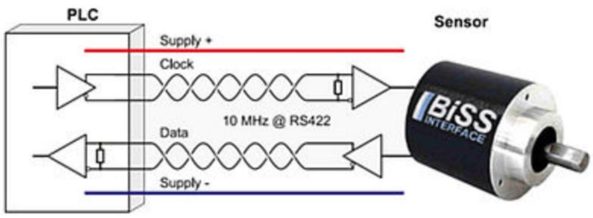


Figure 42. Basic BiSS interface example.

The BiSS interface was introduced by iC-Haus as an open-source interface in 2002. iC-Haus wanted to achieve a fast bidirectional sensor/actuator communication standard that remained compatible with the established SSI (Synchronous Serial Interface) standard. Throughout almost 20 years, BiSS adoption has increased constantly, currently approaching 600 licensed device manufacturers, including industry leaders like Balluff, Baumer, Danaher Motion, Kübler, Hengstler, Hohner, Pepperl+Fuchs, Renishaw, Schneider Electric, Yaskawa, Yuheng Optics, and many others.

Features and Advantages

BiSS interface is a dedicated, real-time sensor/actuator interface as opposed to a general-purpose field bus. The main features of the BiSS interface are listed below:

- Open source

Unlike many proprietary interfaces in the market, BiSS is completely open source. This enables different manufacturers to create products with the same interface, increasing compatibility between different vendors. This is an advantage not only for the manufacturer that has direct access to a full featured and high quality interface, but also for the consumer who does not stay limited to the product and price monopoly of one manufacturer.

- Fast serial synchronous communication using two unidirectional signals

BiSS is a serial interface which reaches high speed transmissions, usually up to 10 MHz over long lines using standard RS422 transceivers or up to 100 MHz along short distances with LVDS connections.

• Bidirectional

BiSS offers permanent bidirectional mode (continuous operation, no mode change necessary) with BiSS-C allowing also both sensor and actuator communication on the same channel using only two additional lines.

• Line delay compensation

Industrial applications require the communication to work reliably even through long cables in noisy environments. BiSS interface is suitable for such applications, offering compensation of line delays and thus achieving high speeds even over long distances.

• Safety features

The BiSS interface fulfills safety application demands, offering additional errors and warning messages from the sensor to the controller and up to 16-bits CRC protection for the transmitted data.

• Bus capability

Some applications require synchronized data acquisition of multiple sensors, for example: multi-axis motion control. BiSS interface offers bus capability, reducing considerably the complexity of the controller by connecting all the sensors in a chain, linked to one data channel at the controller.

• Device description

The BiSS interface provides an electronic identification of a device, making easy Plug-and-Play connection possible. Through the use of standardized descriptions inside EDS (Electronic DataSheet, information written inside the device's memory), XML files or standard BiSS Profiles, all the parameters of the device can be loaded directly by the controller, which can adapt its own settings to the connected device. BiSS licensed manufacturers receive a unique Manufacturer ID, allowing them to identify its own products in the market.

The BiSS protocol frame is represented by the diagram below:

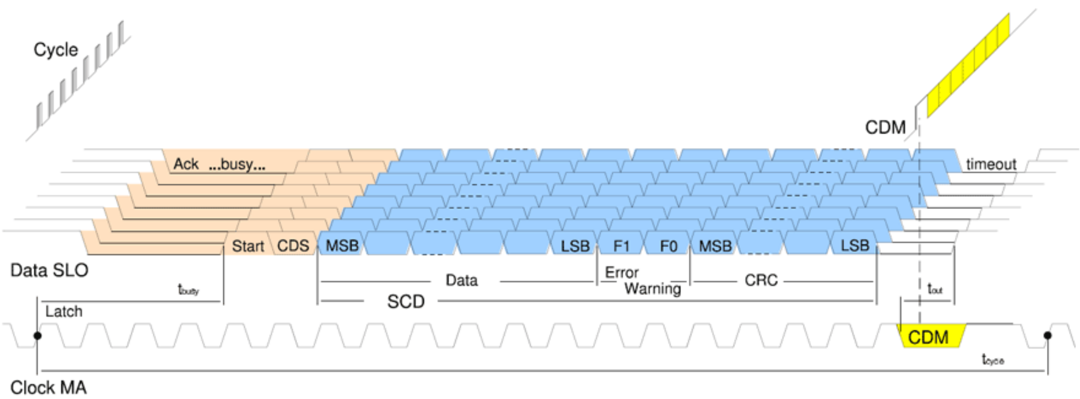


Figure 43. The BiSS protocol frame example.

In the BiSS communication, the controller requesting the data (controlling the operation) is called the BiSS Master, while the sensor providing the acquired data is the BiSS Slave (an actuator is also considered a slave receiving data from a BiSS Master).