Application Note

Implementing Programmability and Diagnostics With the TMAG5328 Resistor and Voltage Programmable Hall-Effect Switch

TEXAS INSTRUMENTS

ABSTRACT

This application note discusses how the TMAG5328 resistor and voltage adjustable, low-power Hall-effect switch can increase system design flexibility and reduce design time. In addition, the document also discusses how using voltage to adjust the TMAG5328's B_{OP} enables multiple applications. One of these applications is a software programmable Hall-effect switch with microcontroller-less standalone mode, which is done by using a DAC or digital potentiometer with nonvolatile memory. Additionally, the document discusses how sweeping the voltage that sets the B_{OP} can be used to back-calculate the sensed magnetic flux density seen by the TMAG5328. This document also discusses how adding a square wave voltage waveform can help the TMAG5328 implement diagnostics for detecting faults such as TMAG5328 device pin shorts, TMAG5328 device pin disconnections, and when a system's magnet is either too close or too far from the sensor. The magnet out-of-range functionality implemented for diagnostics can also be reused as a magnetic window comparator instead.

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1 Introduction

Many systems require a mechanism to detect the mechanical position between a moving component in the system and a fixed component. Systems that only require a simple binary detection of position are often implemented by placing a magnet on the movable component and a Hall-effect switch on the fixed component (the base). An example of an open/close detection system is the mechanism in refrigerators that detect when the refrigerator's door (the moving component) is open or closed, which determines when to turn ON or OFF the refrigerator light. In Figure 1-1, a magnet is placed on the moving refrigerator door and the Hall-effect switch is placed on a fixed PCB underneath the refrigerator base. In this example, it is assumed that the center of the magnet is directly above the sensing element of the Hall sensor when the refrigerator door is closed.

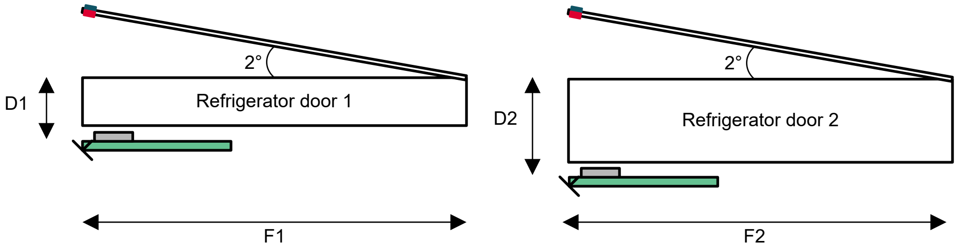

Figure 1-1. Example Open/Close Detection System With Hall-Effect Sensors and Magnet

Table 1-1. Design Parameters for Fridge 1

DESIGN PARAMETER	EXAMPLE VALUE
Hall effect device	TMAG5328A1D
V_{CC}	5 V
Magnet	10 mm cubic N35
D1	7.025 mm
F1	500 mm
Door opening angle	2°
Calculated threshold needed (B_{OP})	7.87 mT
R_{ADJ}	7.87 kΩ

Table 1-2. Design Parameters for Fridge 2

DESIGN PARAMETER	EXAMPLE VALUE
Hall effect device	TMAG5328A1D
V_{CC}	5 V
Magnet	10 mm cubic N35
D2	16.08 mm
F2	500 mm
Door opening angle	2°
Calculated threshold needed (B_{OP})	3.49 mT
R_{ADJ}	3.48 kΩ

Figure 1-2 shows an example output graph of the TMAG5328 omnipolar Hall-effect switch. The device in Figure 1-2 is an omnipolar device, therefore the output responds to both positive and negative magnetic flux densities, which means the device responds the same regardless if the north or south pole of a magnet approaches the device. As the magnet approaches the Hall-effect switch, the magnitude of the sensed magnetic flux density increases. When the applied magnetic flux density exceeds the B_{OP} threshold, the device in Figure 1-2 outputs a low voltage. The output of the device in Figure 1-2 stays low until the magnetic flux density decreases to less than B_{RP}, and then the output drives a high voltage.

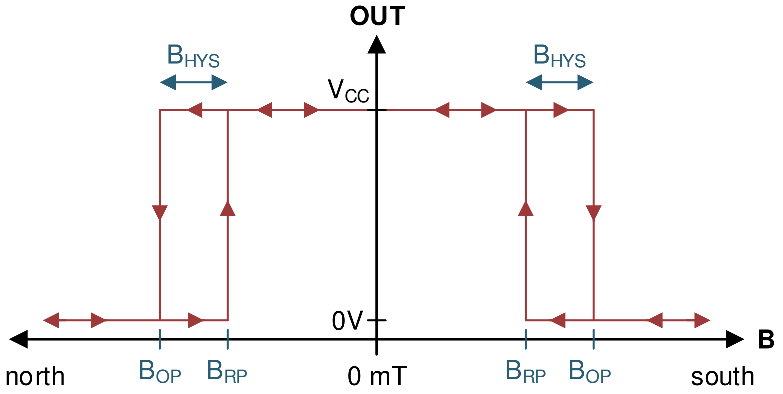

Figure 1-2. Output Graph of the TMAG5328 Omnipolar Switch

1.1 Mapping Switching Distance to Magnetic Flux Density

The relationship between the sensed magnetic flux density and the magnet-to-sensor distance along with the B_{OP} and B_{RP} determine the magnet-to-sensor distance at which the switch changes state. In many cases, the magnet travels in a direct linear path of travel, so distance is often expressed by the direct magnet-to-sensor distance. In Figure 1-1, however, distance is specified by the angle of opening because the refrigerator door opens on a hinge that causes the magnet to move nonlinearly. For Figure 1-1, the magnet-to-sensor distance increases as the angle of opening increases.

Figure 1-3 shows an example graph of how the sensed magnetic flux density varies as the angle of the opened refrigerator door 1 varies. The magnet-to-sensor distances at which the switch changes state depends on the B_{OP} and B_{RP} . If you want to determine the typical distance at which the sensor switches state, find the locations on the Figure 1-3 plot where the sensed magnetic flux density values are equal to the $B_{OP,TYP}$ and $B_{RP,TYP}$ specifications listed in the device data sheet. Alternatively, when determining the worst-case device to device variation for output switching, refer to the $B_{OP,Max}$ and $B_{RP,Min}$ specifications. $B_{OP,Max}$ and $B_{RP,Min}$ account for process variation, temperature and voltage. Designing the system within these bounds will result with consistent operation despite these variables.

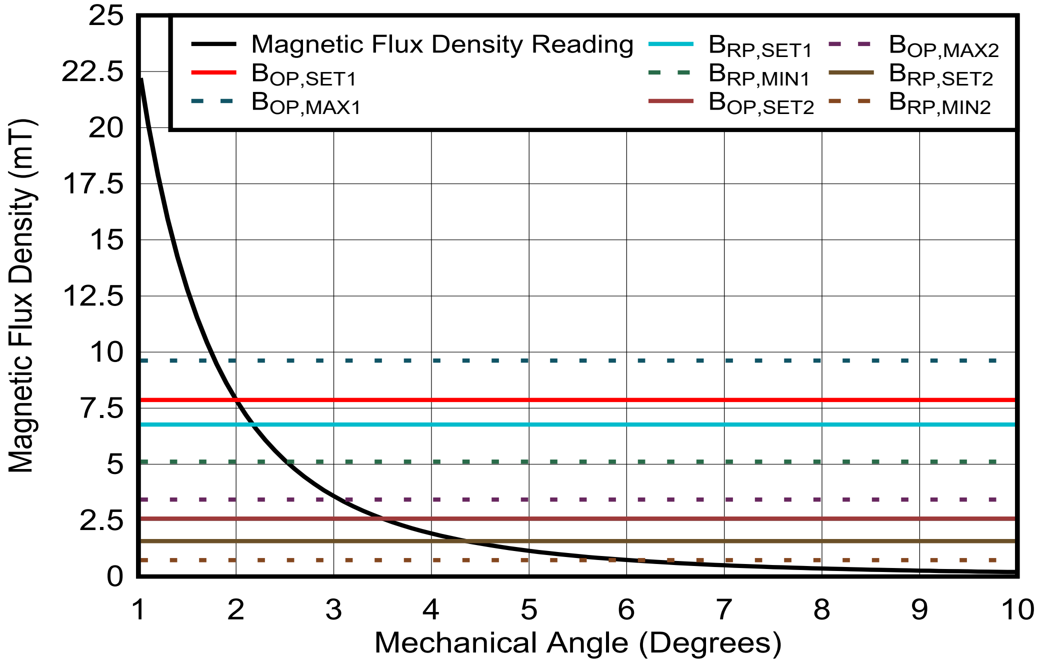

Figure 1-3. Magnetic Flux Density vs Refrigerator Angle of Opening (Refrigerator 1)

As an example, let's say there are two Hall-effect switches with the following specs:

- Switch 1
  - $B_{RP,MIN}$ =5.12 mT
  - $B_{RP,TYP}$ =6.87 mT
  - $B_{OP,TYP}$ =7.87 mT
  - $B_{OP,MAX}$ =9.62 mT
- Switch 2
  - $B_{RP,MIN}$ =0.73 mT
  - $B_{RP,TYP}$ =1.58 mT
  - $B_{OP,TYP}$ =2.58 mT
  - $B_{OP,MAX}$ =3.43 mT

If switch 1 is used in refrigerator 1, the output of switch 1 will be low when the angle of opening for door 1 is ≤1.8°, regardless of variations in process variation, temperature, and voltage. The angle of opening for door 1 is ≤1.8° when the sensed magnetic flux density is greater than the 9.62 mT $B_{OP,MAX}$. However, the typical distance where the output of switch 1 is asserted low would be at 2°, which is when the sensed magnetic flux density equals the device's $B_{OP,TYP}$ value of 7.87 mT. The output of switch 1 will be high when angle of opening for door 1 is ≥2.5°, which is when the sensed magnetic flux density is less than the 5.12 mT $B_{RP,MIN}$. The typical distance where the output of switch 1 is asserted high, however, would be at 2.2°.

If switch 2 is used in refrigerator 2, the typical distance at which the output of switch 2 is asserted low would be at 3.5°. The output would be low at an angle ≤3.1° regardless of variations in process variation, temperature, and voltage. Additionally, the output of switch 2 would be asserted high at 4.4° typically. The output would be asserted high at an angle ≥6.0° regardless of variations. The different switching distances of switches 1 and 2 shows how switching distance is dependent on the B_{OP} and B_{RP} specs of a Hall sensor.

1.2 How to Program BOP of TMAG5328

Most Hall-effect switches have a fixed B_{OP}, which typically imposes design constraints on the placement and specifications of the magnet needed to ensure switching of the Hall-effect sensor at the desired distance. To allow design flexibility, many Hall-effect switches come with multiple device variants with different B_{OP} values; however, there are only a finite number of B_{OP} options available with a Hall-effect switch, which still puts constraints on the placement and specifications of the magnet.

The TMAG5328 Hall-effect switch, on the other hand, has an adjustable B_{OP} that can be programmed anywhere between 2 to 15 mT by applying a voltage or connecting a resistor to the ADJ pin of the device. By following simple formulas, it is easy to calculate what resistor value or voltage value is needed to set up the right B_{OP} value. The hysteresis value of the TMAG5328 is fixed to 1 mT, which results in the B_{RP} value being B_{OP} – 1 mT. As an example, if the B_{OP} is set to 5 mT, the B_{RP} would be set to 4 mT.

To set the B_{OP} of the TMAG5328 using an external resistor, connect the resistor between the ADJ and GND pins of the device. Figure 1-4 shows the relationship between B_{OP} and resistance defined as $B_{OP}(mT) = R_{ADJ}(k\Omega)$. The B_{OP} of the TMAG5328 must be set to a value between 2 mT and 15 mT, R_{ADJ} must be set between 2 kΩ and 15 kΩ.

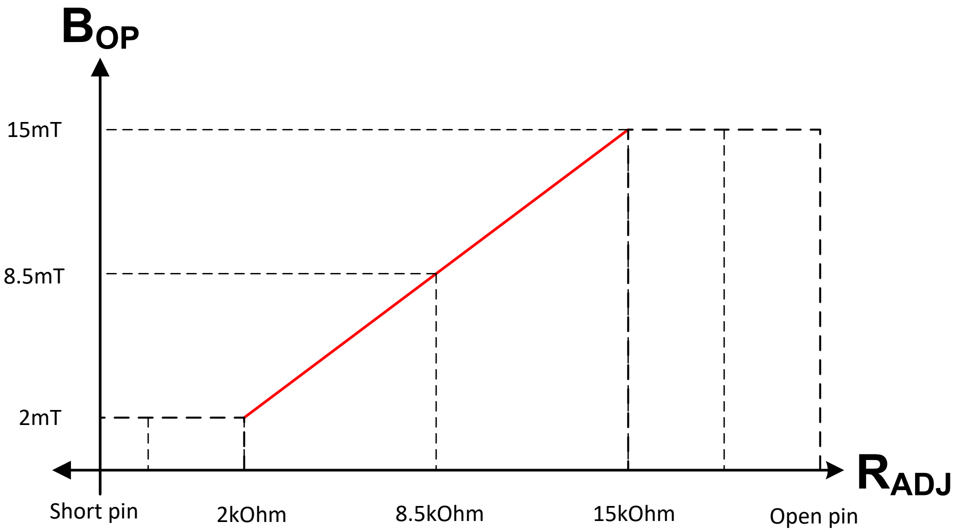

Figure 1-4. B_{OP} vs R_{ADJ}

The other method to setup the B_{OP} is to apply a voltage to the ADJ pin. The relationship between B_{OP} and voltage is defined as B_{OP}(mT)= V_{ADJ}(mV) × 0.0125. To apply a voltage on the ADJ pin, the voltage source must be able to settle within 4 µs after being exposed to a 80-µA current on the ADJ pin. Figure 1-5 shows that the TMAG5328 B_{OP} must be set to a value between 2 mT and 15 mT and the V_{ADJ} must be set between 160 mV and 1200 mV.

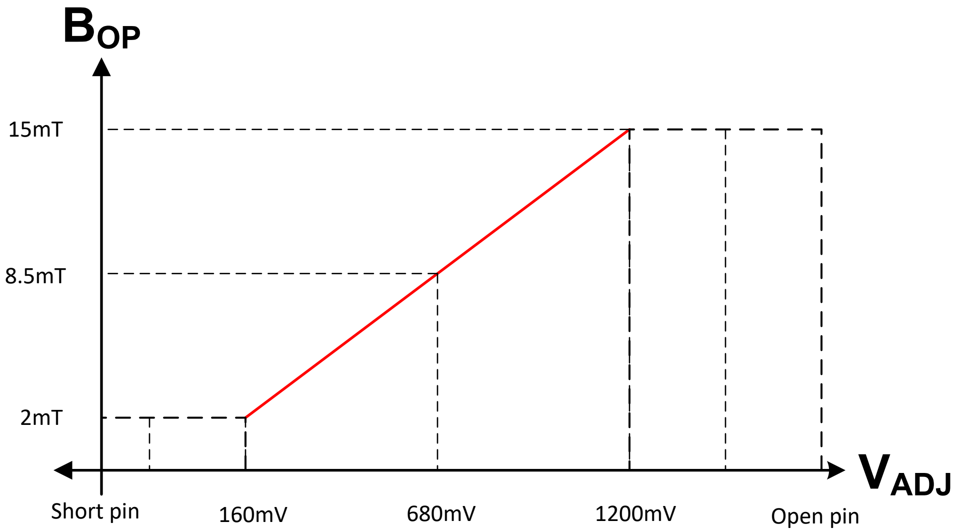

Figure 1-5. B_{OP} vs V_{ADJ}

1.3 Advantages of TMAG5328 Adjustable B_{OP}

The adjustable B_{OP} of the TMAG5328 enables design flexibility that fixed B_{OP} Hall-effect switches cannot provide. The advantages of the TMAG5328 programmable B_{OP} include the following:

- **Design Flexibility**: The magnet-to-sensor distance at which the output of the sensor changes state depends on the B_{OP}, magnet material, and magnet dimensions. The B_{OP} can be adjusted on the TMAG5328, therefore the B_{OP} enables the following capabilities:
  - **Reuse of TMAG5328 device across multiple platforms**: Different hardware platforms often have different requirements for switching distance and magnet specifications. As an example, Figure 1-1 shows two refrigerator designs with different dimensions. If it desired for the switch to assert its output low when the door angle is at 2°, each refrigerator would require a Hall sensor with a different B_{OP}. According to Figure 1-3, the B_{OP} should be set to 7.87 mT so that the output of the switch typically is asserted low at

2°. The output of the Hall-effect switch would typically be asserted high at 2.2° . Figure 1-6 shows that refrigerator 2 requires a $B_{OP,TYP}$ of 3.49 mT for the output of the switch to typically assert low at a door angle of 2°. The output would typically assert high at a door angle of 2.5° with this switch. The TMAG5328 can be reused in both of these refrigerator designs by only changing the voltage or resistor connected to its ADJ pin to produce the necessary B_{OP} for each design. Only using one Hall-effect switch provides better inventory management compared to using two different Hall-effect switches.

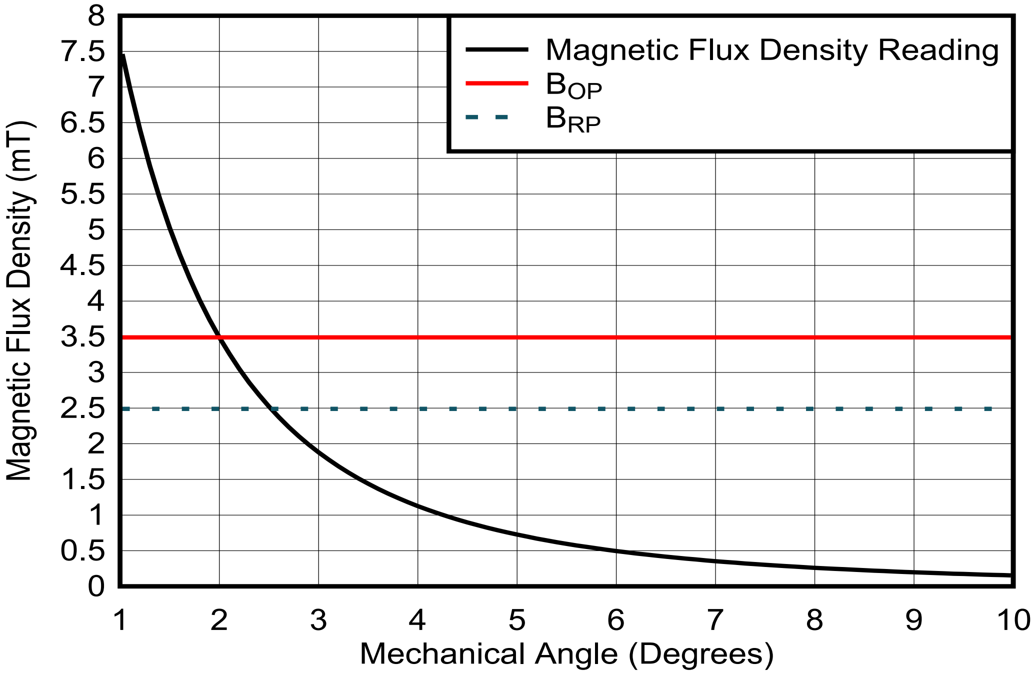

Figure 1-6. Magnetic Flux Density vs Refrigerator Angle of Opening (Refrigerator 2)

– **Easy last minute design adjustments**: If a magnet in a design changes, the magnetic flux density seen by the Hall-effect sensor would also change. The TMAG5328 can easily address the changes in observed magnetic flux density by adjusting its B_{OP} accordingly to reproduce a switching distance that is close to the switching distance before design adjustments. As an example, let's say the magnet in refrigerator 1 of was changed from 10x10x10 to 7x7x7. Figure 1-7 shows that changing the magnet requires a B_{OP} of 3.17 mT for the output to be typically asserted low at 2°. In this case, the output would typically assert high when the door angle is at 2.4°. Alternatively, if the mechanical construction of a design changes in a way that requires a different magnet-to-sensor distance (similar to the two magnet-to-sensor distances in the refrigerators in Figure 1-3), the B_{OP} on the TMAG5328 can also be easily adjusted to meet the new resulting magnet to sensor switching distance requirements.

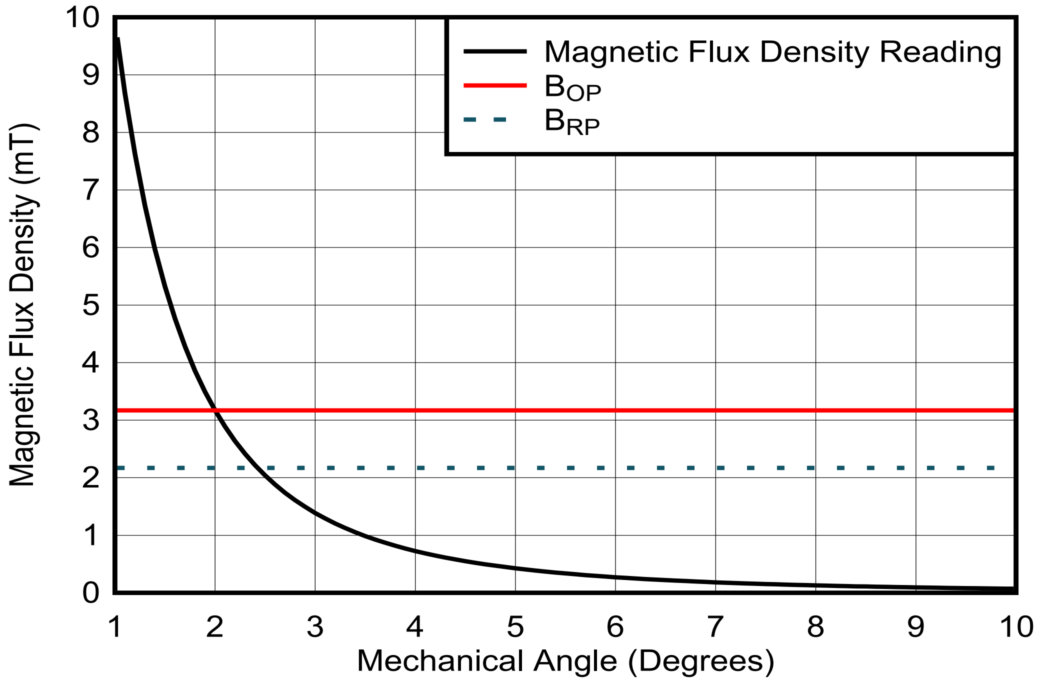

Figure 1-7. Magnetic Flux Density vs Refrigerator Angle of Opening (Refrigerator 1 With Different Magnet)

- **Reduced design time:** To determine if a Hall sensor can be used in a design, prototyping or magnetic simulations are often performed. The adjustable B_{OP} on the TMAG5328 can accelerate both prototyping and magnetic simulations.
  - **Easy and quick prototyping**: In some systems, initial system prototyping is done by placing different Hall-effect switches with different B_{OP} specifications into a system to see how the B_{OP} options affect the desired magnet to sensor switching distances. Testing multiple B_{OP} options with fixed B_{OP} devices require hand soldering then testing multiple devices one by one, which is time consuming. However, because the B_{OP} of the TMAG5328 can be dynamically adjusted, it is not required to solder multiple devices to test B_{OP}. To test a specific B_{OP} with the TMAG5328, only the corresponding voltage must be applied to the ADJ pin of the device, which accelerates prototyping time. After determining the voltage that produces the desired B_{OP}, the final system can use a DAC to generate this voltage to recreate the desired B_{OP}. Alternatively, the voltage can be converted to a resistor value that produces the same B_{OP} so that the final system only requires a TMAG5328 and resistor.
  - **Reduced simulation time:** Magnetic simulations are used to determine the relationship between magnetic flux density sensed by the device and distance, similar to the relationship shown in Figure 1-3, Figure 1-6, and Figure 1-7. Depending on the utilized magnetic simulator, it could take a long time to run a simulation. Performing these types of magnetic simulations commonly require multiple simulation iterations, where the selected magnet, magnet-to-sensor distances, and B_{OP} can be iteratively adjusted until the desired switching behavior can be guaranteed. Having an adjustable B_{OP}, loosens design constraints, which reduces the time it takes to perform simulations to find a viable solution, thereby reducing time to market. As an example, let's say that the conditions for Refrigerator 1 in Figure 1-3 are first simulated to determine the relationship in Figure 1-3. If only a 3.17 mT B_{OP} Hall sensor is available instead of the 7.87 mT B_{OP} needed to produce the 2° switching distance for the given magnet, the designer can try using a different magnet to see if using a different magnet helps meet their requirements. It could take a few simulation iterations to find that using a 7x7x7 magnet can produce the desired B_{OP}. However, if the TMAG5328 was used, the B_{OP} could be set to the 7.87 mT B_{OP} needed for the first simulation, thereby preventing the wasted time performing the additional simulation iterations.
- **Enables new applications not typically available with fixed B_{OP} sensors:** The adjustable B_{OP} of the TMAG5328 allows the device to be used for the following purposes:
  - **Determining the sensed magnetic flux density seen by the switch:** Omnipolar Hall-effect switches typically only provide information on whether the absolute value of the sensed magnetic flux density is

greater than B_{OP} or less than B_{RP} **.** The TMAG5328, on the other hand, also enables a method to estimate the sensed magnetic flux density seen by the device, assuming that it is within the 2 to 15 mT range. The sensed magnetic flux density seen by the device can be determined by connecting a voltage source to the ADJ pin, setting the ADJ pin to 1.2 V, and then gradually decreasing the voltage until the output is asserted low. The voltage at which the output switches state can be converted to units of mT to estimate the magnetic flux density seen by the device. Section 2 provides more information on how to determine the sensed magnetic flux density seen by the switch.

- **Implementing a programmable Hall-effect switch with microcontroller-less standalone mode:** A DAC with nonvolatile memory (NVM), such as the DAC43701 or TPL1401, can be paired with the TMAG5328 to create a programmable Hall-effect switch implementation. In this implementation, the DAC output is connected to the TMAG5328 output so that the DAC output voltage sets the B_{OP} of the TMAG5328. A microcontroller is only needed to initially configure the DAC nonvolatile memory to automatically generate the voltage needed to implement the desired B_{OP}. After the DAC is configured, the microcontroller is no longer needed in the system. The DAC will automatically drive the TMAG5328 to create the desired B_{OP}, even after subsequent system power ON or reset events. Instead of relying on applying a specific condition on the device's VCC pins, this programmable Hall-effect switch implementation uses the DAC communication interface (SPI, I2C, and so forth) to program the switch, which makes it easier to program or dynamically change the B_{OP}. The DAC communication interface often can support multiple devices on the same interface, therefore multiple DAC+switch systems can be connected to the same bus for faster programming. Section 3 provides more information on how to use the DAC with NVM for implementing a programmable Hall-effect switch.
- **Implementing diagnostics:** A square wave can be applied to the TMAG5328 to implement diagnostics for detecting faults such as TMAG5328 device pin shorts, TMAG5328 device pin disconnections, and when a system's magnet is either too close or too far from the sensor. The magnet out-of-range functionality implemented for diagnostics can also be reused as a magnetic window comparator instead. Section 4 provides more details on this.

2 Determining Sensed Magnetic Flux Density Seen by TMAG5328

To estimate the magnetic flux density sensed by the TMAG5328, connect a DAC or other voltage source to the TMAG5328 ADJ pin and follow the procedure below:

1. Configure the DAC output code to provide 1.2 V to the ADJ pin of the TMAG5328. This ADJ voltage would result in $B_{OP,TYP}$ = 15 mT , $B_{RP,TYP}$ = 14 mT, and $B_{RP,MIN}$ = 11.65 mT.
2. Verify that the output of the TMAG5328 is high. If the TMAG5328 output is not asserted high, the sensed magnetic flux density is too large to be determined by this technique, which might occur if the sensed magnetic flux density is greater than $B_{RP,MIN}$ = 11.65 mT.
3. Reduce the DAC output voltage (V_{DAC}) a step size of one LSB (V_{LSB}).
4. To ensure that the new BOP is set, wait for a time period at least greater than the TMAG5328 sampling period. The TMAG5328 has a sampling time of 50 ms, therefore you need a delay of at least 50 ms. To account for part-to-part variation in sampling time, a 100-ms delay can be used, which is much larger than the maximum sampling time expected from the TMAG5328.
5. Read the TMAG5328 output:
    a. If the TMAG5328 output has switched low, the sensed magnetic flux density in units of mT is equal to V_{DAC} (in units of mV) × 0.0125.
    b. If the TMAG5328 output is high and V_{DAC} - V_{LSB} > 0.16 V, continue from step 3.
    c. If the TMAG5328 output is high and V_{DAC} - V_{LSB} ≤ 0.16 V, the sensed magnetic flux density is less than 2 mT, which is too low for this technique to determine the sensed magnetic flux density.

The more DAC steps there are between the 0.16 V to 1.2 V V_{ADJ} operating range of the TMAG5328 and the higher the DAC accuracy, the more accurate the estimate of the sensed magnetic flux density. However, using more DAC steps results in a longer execution time for estimating the sensed magnetic flux density. In the TMAG5328EVM, the DAC43701 DAC is used to determine the magnetic flux density sensed by the TMAG5328. The DAC43701 is an 8-bit DAC that is configured to use a 0 V to 1.82 V range. From this 0 V to 1.82 V range, 144 of the possible 256 DAC codes can be used with the TMAG5328 because these codes fall within the 0.16 V to 1.2 V V_{ADJ} range of the TMAG5328. The DAC43701 is pin-to-pin compatible with the 10-bit DAC53701, therefore the DAC53701 can replace the DAC43701 on the EVM to allow 584 usable codes within the 0.16 V to 1.2 V V_{ADJ} range of the TMAG5328. Using the DAC53701 can enable a slightly more precise estimate of the sensed magnetic flux density than the DAC43701; however, the more codes that are used for determining the sensed magnetic flux density, the longer it takes for the procedure to run. If 100 ms is spent at each DAC code between the 0.16 V to 1.2 V V_{ADJ} range of the TMAG5328, it would take about 14.4 seconds to iterate through all the DAC43701 codes and 58.4 seconds to iterate through all the DAC53701 codes.

Figure 2-1 shows a logic analyzer screenshot when this procedure was conducted using the TMAG5328 and DAC43701 devices on the TMAG5328EVM. In Figure 2-1, the *Timer ISR* plot shows a pulse every time the DAC output changes, the *TMAG5328 OUTPUT* plot shows the state of the TMAG5328 OUT pin across time, and the *DAC Output Voltage* plot measures the DAC output voltage across time. In Figure 2-1, the output is asserted low at V_{DAC} = 0.702 V, which indicates that the sensed magnetic flux density is approximately 8.78 mT. The time it takes for this procedure to run depends on how large the sensed magnetic flux density is, where larger magnetic flux densities result in shorter execution times. In the example below, the procedure completed in about 6 to 7 seconds.

Figure 2-1. Logic Analyzer Screenshot of Procedure for Determining Sensed Magnetic Flux Density

3 Implementing a Software-Programmable Hall-Effect Switch With Microcontroller-Less Standalone Mode

The TMAG5328 can be made into a software-programmable Hall-effect switch by connecting a software-programmable voltage source with nonvolatile memory to the TMAG5328 ADJ pin. The voltage source could be a DAC or digital potentiometer. Figure 3-1 shows the TMAG5328EVM which specifically uses the DAC43701 8-bit DAC with nonvolatile memory to turn the TMAG5328 into a software-programmable Hall-effect switch. The devices are nearly pin-to-pin compatible, therefore the DAC43701 DAC can be replaced with the higher-resolution DAC53701 DAC or the TPL1401 digital potentiometer (DPOT).

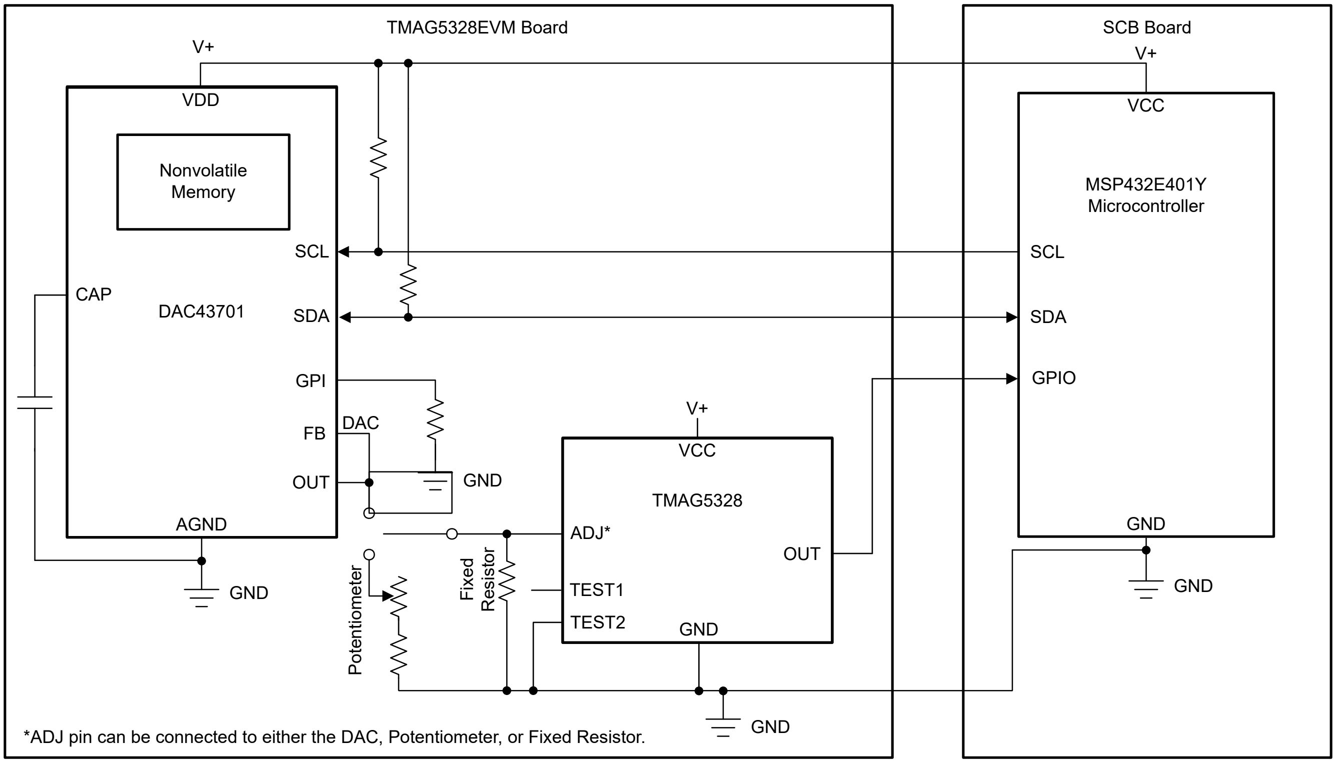

Figure 3-1. TMAG5328EVM Block Diagram

The nonvolatile memory on these DAC/DPOT devices can be programmed to initialize the device to a user-defined output voltage every time the system is powered ON or when another type of RESET event occurs. The output of the DACx3701 or TPL1401 drives the ADJ pin of the TMAG5328, therefore the TMAG5328 B_{OP} will also be automatically programmed after the system is powered ON. A microcontroller, which on the EVM is on a second PCB called the Sensor Controller Board (SCB), is only necessary to initially program the DAC nonvolatile memory. After the DAC nonvolatile memory is programmed to automatically output a voltage to create the user-defined B_{OP}, the microcontroller is no longer needed. Only the DAC/DPOT and TMAG5328 devices are needed to ensure that the B_{OP} settings are maintained.

In-system calibration can also be supported by following the procedure below:

1. Configure the system so that the magnet-to-sensor distance is at the desired distance for the TMAG5328 output to switch from high to low.
2. Follow the procedure in Section 2 to determine the V_{ADC} value that causes the TMAG5328 output to switch from high to low.
3. Store step 2’s V_{DAC} value into the DAC nonvolatile memory.

In-system calibration allows the user to obtain their desired system functionality when magnet placement or manufacturing tolerance can vary greatly from device to device.

Instead of relying on applying a specific condition on the VCC pins of a device, this calibration scheme uses the DAC I2C interface to program the switch, which makes it easier to program. This approach does not require an additional power supply circuit to program the Hall-effect switch. The I2C interface of the DAC allows software-based modification of the B_{OP}, which can enable in-field upgrades of an already deployed unit without performing hardware modification. In addition, four DAC43701 devices can be put on the same I2C bus. If the programming micrcocontroller has multiple I2C interfaces, then more than four systems can be programmed at the same time, thereby further reducing the time needed to perform mass calibration.

The TMAG5328EVM supports this in-system calibration technique. The TMAG5328EVM's Quick Start Video shows an example of this in-system calibration technique by using the head-on linear displacement 3D print attachment.

4 Implementing Diagnostics and a Magnetic Window Comparator

A square wave voltage waveform on the ADJ pin of the TMAG5328 can help a user detect under certain conditions when the TMAG5328 pins have been disconnected or shorted to other pins. This technique for implementing diagnostics works by applying a square wave on the TMAG5328 ADJ pin, which allows the pin to alternate the B_{OP} and B_{RP} of the TMAG5328 in a way to also create a square wave output on the TMAG5328 OUT pin. You can use a DAC to create the square wave, or you can use another voltage output circuit to create a voltage waveform that alternates between two voltages somewhere within the 0.16 V and 1.2 V. During the diagnostic check, a microcontroller can check to confirm the TMAG5328 OUT pin changed state after the ADJ pin square wave changed state. If the TMAG5328 OUT pin does not change state after the ADJ square wave changes state, a fault may have occurred.

The high and low voltage values of the square wave create two B_{OP} values that alternated between. When the high voltage of the square wave is applied to the ADJ pin, it creates a larger B_{OP}, which is referred to as $B_{OP,HIGH}$. It also results in a new B_{RP}, which is referred to as $B_{RP,HIGH}$. If the sensed magnetic flux density in the system (B_{System}) is less than $B_{RP,HIGH}$, the TMAG5328 output is asserted high when the high portion of the square wave is applied to the ADJ pin. When the low voltage of the square wave is applied to the ADJ pin, it creates a smaller B_{OP}, which is referred to as $B_{OP,LOW}$. If B_{System} is greater than $B_{OP,LOW}$, the TMAG5328 output is asserted low when the low portion of the square wave is applied to the ADJ pin. Consequently, the produced square wave on the TMAG5328 output should change state after the square wave on its ADJ pin switches from high to low or low to high.

In addition to detecting signal shorts and disconnections, this technique also implements a magnetic window comparator that detects when the sensed magnetic flux density is either greater than $B_{OP,HIGH}$ or less than $B_{RP,LOW}$. If the high voltage value of the square wave is selected so that $B_{RP,HIGH}$ is larger than the maximum magnetic flux density reading expected in the system and the low voltage of the square wave is selected so that $B_{OP,LOW}$ is less than the minimum magnetic flux density reading expected in the system, the window comparator can potentially detect when there is a fault due to the system's magnet being either too close or too far from its normal range of positions.

For this diagnostic technique to properly function, you must meet the following constraints:

- $B_{OP,LOW} \geq 2$ mT (this means that the low output voltage of the square wave must be ≥ 0.16 V)
- $B_{OP,HIGH} \leq 15$ mT (this means that the high output voltage of the square wave must be ≤ 1.2 V)
- $B_{OP,LOW} \leq B_{System}$ (this is needed to ensure that the TMAG5328 output is asserted low when the low portion of the square wave is applied)
- $B_{System} \leq B_{RP,HIGH}$ (this is needed to ensure that the TMAG5328 output is asserted high when the high portion of the square wave is applied)
- The square wave pulse width duration, referred to as t_{OP}, must be greater than the TMAG5328 period of magnetic sampling. This requirement ensures that the TMAG5328 has enough time to update its B_{OP} based on the voltage provided to the ADJ pin. For example, as the TMAG5328 period of magnetic sampling is 50 ms, using a value of t_{OP} = 100 ms is more than sufficient to meet this requirement.

Figure 4-1 shows a visual representation of these constraints.

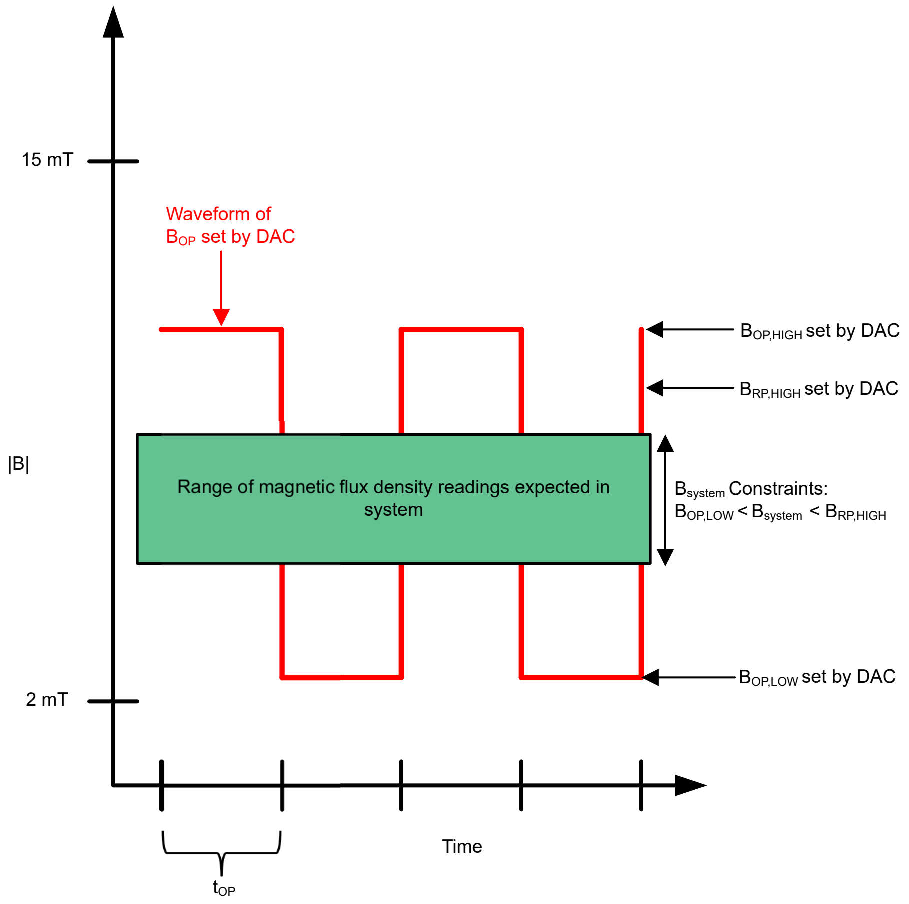

Figure 4-1. Constraints for Diagnostic Implementation

4.1 Conducting Diagnostic Tests With TMAG5328EVM and Head-On Linear Displacement 3D Print

This diagnostic technique was tested on the TMAG5328EVM by loading firmware on the EVM's microcontroller that would generate a timer interrupt every 100 ms. In the firmware, the DAC produces a square wave that alternates between 0.68 V (the low state) and 1.04 V (the high state), which creates a $B_{RP,HIGH}$ value of 12 mT and a $B_{OP,LOW}$ value of 8.5 mT. The head-on linear displacement attachment was connected to the TMAG5328 and configured so that the TMAG5328 sees a magnetic field between 8.5 mT to 12 mT.

In the timer interrupt service routine, the TMAG5328 output is first read. If the DAC output voltage is at 1.04 V, the TMAG5328 OUT pin should be high. If the DAC output voltage is currently at 0.68 V, the TMAG5328 OUT pin should be low. If the TMAG5328 OUT pin is not in the correct state, a fault has occurred, which is logged by the microcontroller.

After checking the state of the TMAG5328 OUT pin, the microcontroller configures the DAC to switch to 1.04 V if the TMAG5328 OUT pin is currently at 0.68 V or switch to 0.68 V if the TMAG5328 OUT is currently at 1.04 V. The TMAG5328 output is checked at the next timer interrupt, which gives the TMAG5328 enough time to update its B_{OP}.

Figure 4-2 below shows the expected waveform on the TMAG5328 OUT pin when no faults are present. Due to the OUT pin changing states, the LED connected to the TMAG5328EVM would blink at a frequency equal to the frequency of the DAC square wave (approximately 5 Hz).

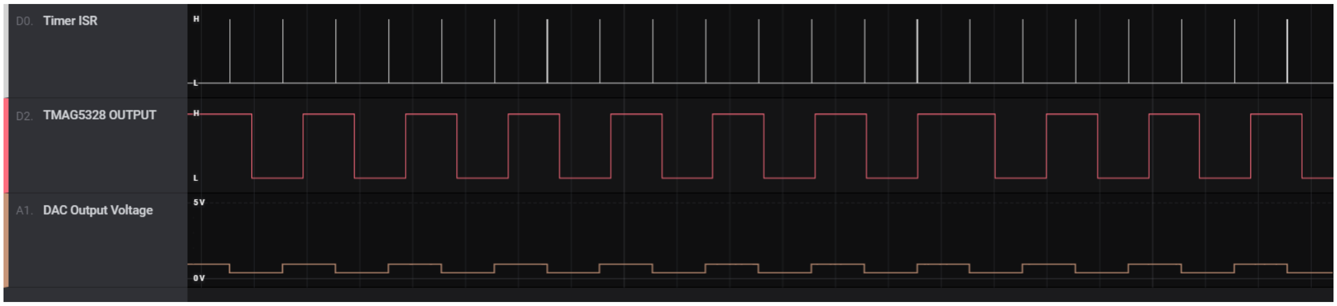

Figure 4-2. Logic Analyzer Screenshot of TMAG5328 OUT Pin When No Faults Present During Diagnostic Testing

4.1.1 Magnet Out-of-Range Testing (Magnetic Window Comparator Testing)

The out-of-range test provides an alert when the observed magnetic flux density is outside the system's range of expected magnetic flux density readings. Out-of-range fault detection was specifically tested on the TMAG5328EVM by adjusting the position of the inner screw of the head-on linear displacement 3D print, as shown in Figure 4-3.

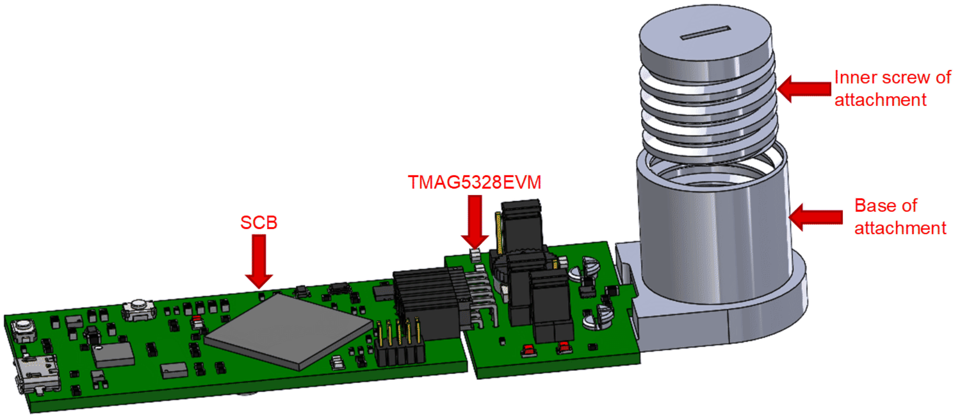

Figure 4-3. TMAG5328EVM Connected to Head-On Linear Displacement 3D Print

In its initial state, the inner screw of the attachment, which has an embedded magnet, was placed so that the sensed magnetic flux density of the TMAG5328 was between 8.5 mT to 12 mT. The inner screw of the 3D print was screwed into the outer base until the sensed magnetic flux density was greater than 12 mT. Figure 4-3 shows the resulting logic analyzer screenshot, which shows that the TMAG5328 OUT pin is asserted low even when the DAC is in the high state. A square wave is no longer present on the TMAG5328 OUT pin, which means this diagnostic technique detected when the magnetic flux density was greater than 12 mT due to the magnet being too close. This scenario was also correctly logged by the EVM's microcontroller as a fault condition.

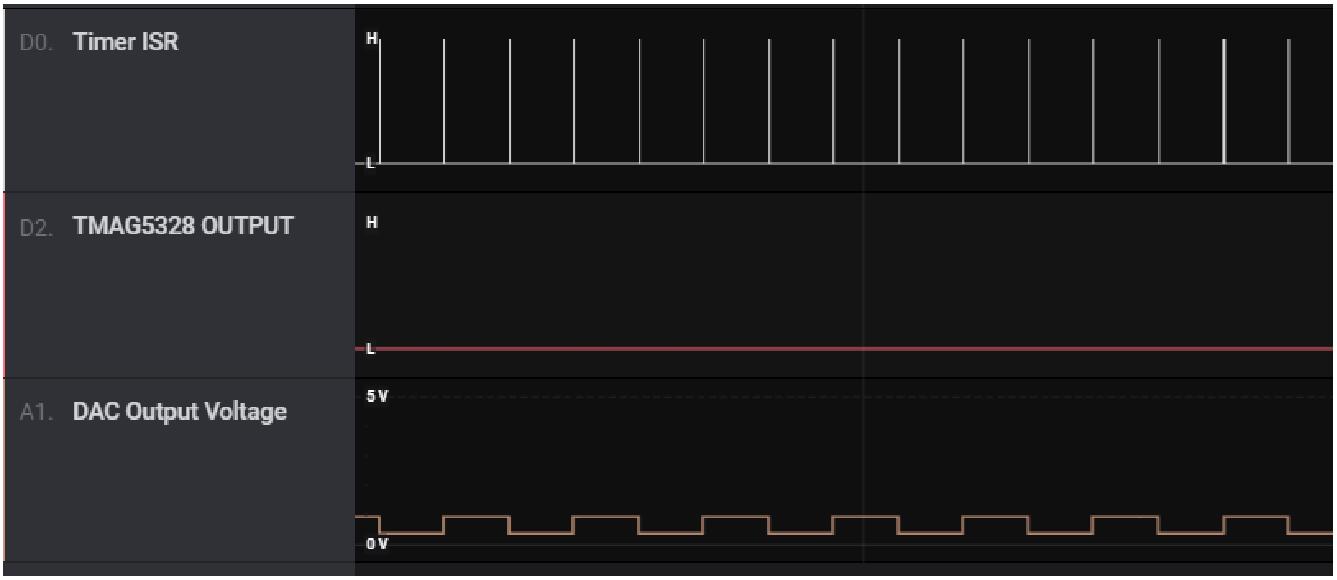

Figure 4-4. Logic Analyzer Screenshot of TMAG5328 OUT Pin When Magnet is Too Close (Sensed Magnetic Flux Density > $B_{RP,HIGH}$)

Next, the inner screw of the 3D print was unscrewed until the sensed magnetic flux density was back to being between 8.5 mT to 12 mT, which resulted in a square wave appearing onto the TMAG5328 OUT pin again like it was in Figure 4-2. The inner screw was further unscrewed until the sensed magnetic flux density was less than 8.5 mT. Figure 4-5 shows the resulting logic analyzer screenshot from the sensed magnetic flux density being less than 8.5 mT. Figure 4-5 shows that the TMAG5328 OUT pin is asserted high even when the DAC is in the low state. A square wave is no longer present on the TMAG5328 OUT pin, which means this diagnostic technique detected when the magnetic flux density was less than 8.5 mT due to the magnet being too far or no longer present in the system. Additionally, the microcontroller was able to correctly to log this as a fault event.

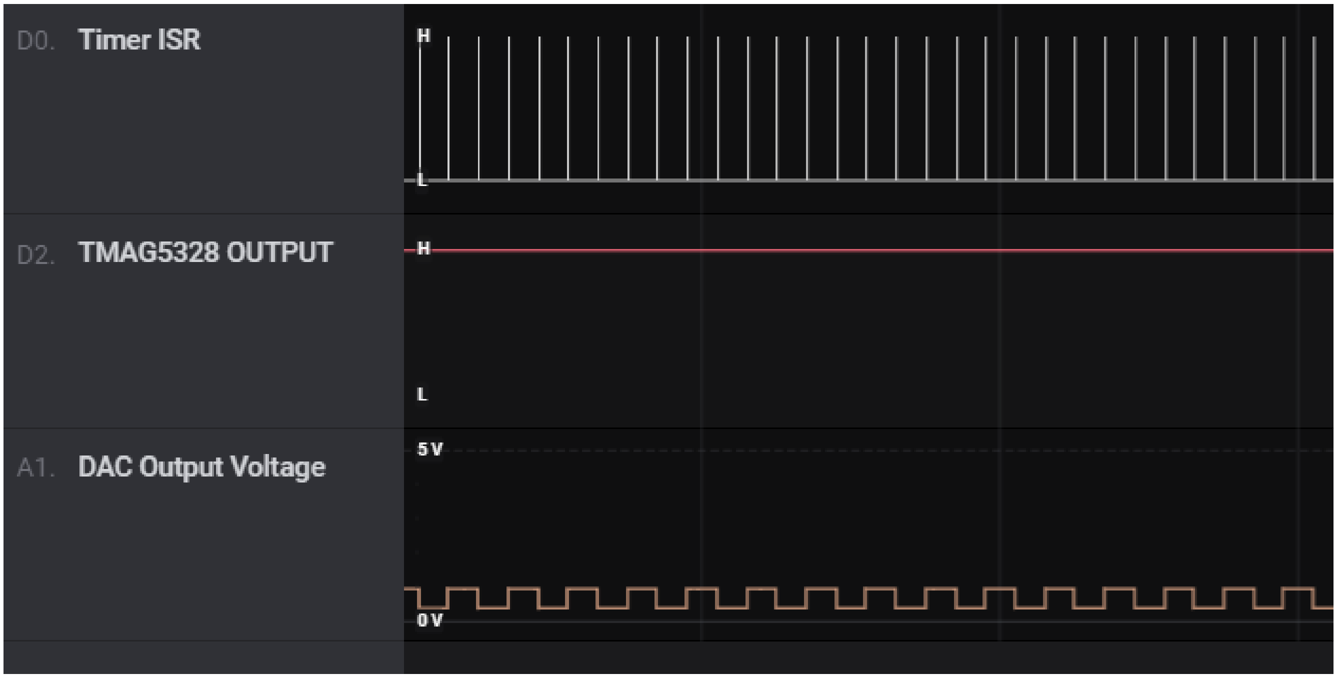

Figure 4-5. Logic Analyzer Screenshot of TMAG5328 OUT Pin When Magnet is Too Far (Sensed Magnetic Flux Density < $B_{OP,LOW}$)

This out-of-range test can also potentially detect if there is an external magnetic field present in the system that is causing the TMAG5328 device to see a magnetic flux density reading it should not normally observe.

After conducting the out-of-range test, the screw component of the 3D print was screwed back into the base so that the magnetic flux density was between 8.5 mT to 12 mT again so that the other faults can be detected.

4.1.1.1 Signal Disconnections

This diagnostic technique was also tested by disconnecting the TMAG5328 ADJ pin from the DAC, disconnecting the TMAG5328 VCC pin from the power supply, and disconnecting the TMAG5328 OUT pin from the OUT signal probed by the logic analyzer and microcontroller.

When the ADJ pin was disconnected from the DAC, the output of the TMAG5328 was either asserted low (Figure 4-6) or high (Figure 4-7). In both cases, the TMAG5328 OUT pin did not have a square wave with frequency equal to the DAC voltage frequency, which would indicate that a fault occurred.

Figure 4-6. Logic Analyzer Screenshot of TMAG5328 OUT Pin When ADJ Pin Disconnected and TMAG5328 OUT Pin is Low

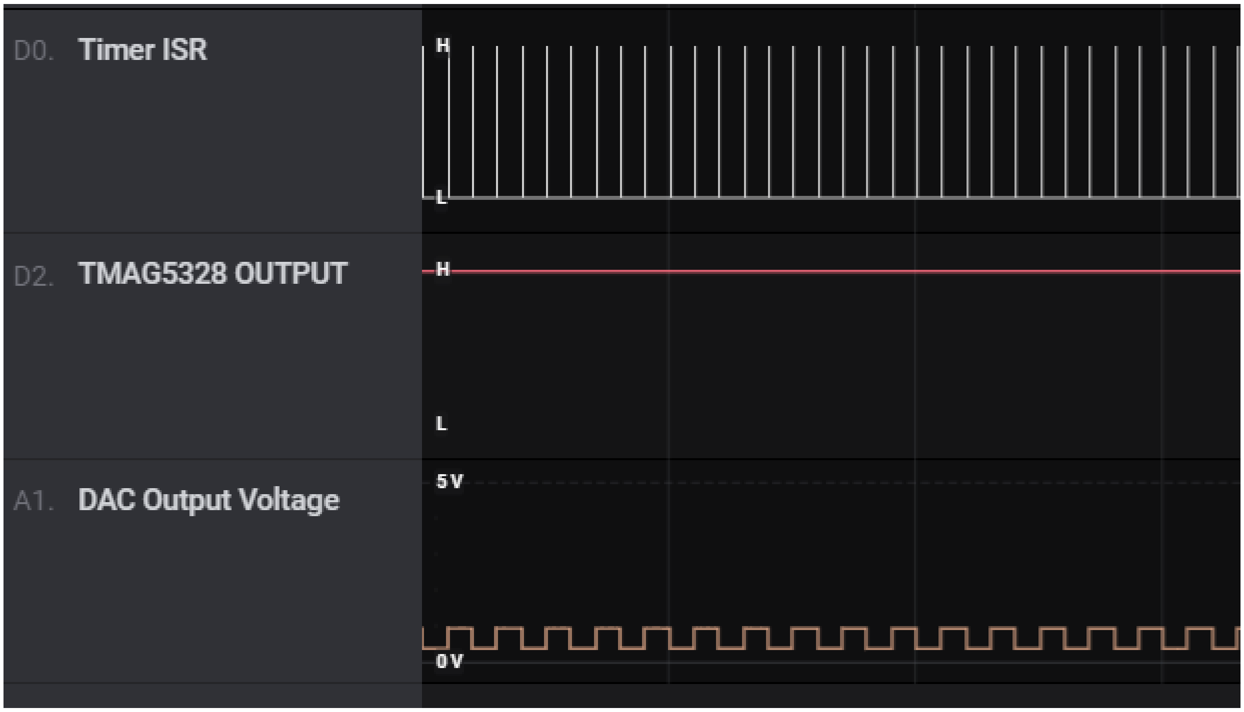

Figure 4-7. Logic Analyzer Screenshot of TMAG5328 OUT Pin When ADJ Pin Disconnected and TMAG5328 OUT Pin is High

When VCC was disconnected from the TMAG5328, the OUT pin was observed low, as shown in Figure 4-8. This was logged by the EVM's microcontroller as a fault event.

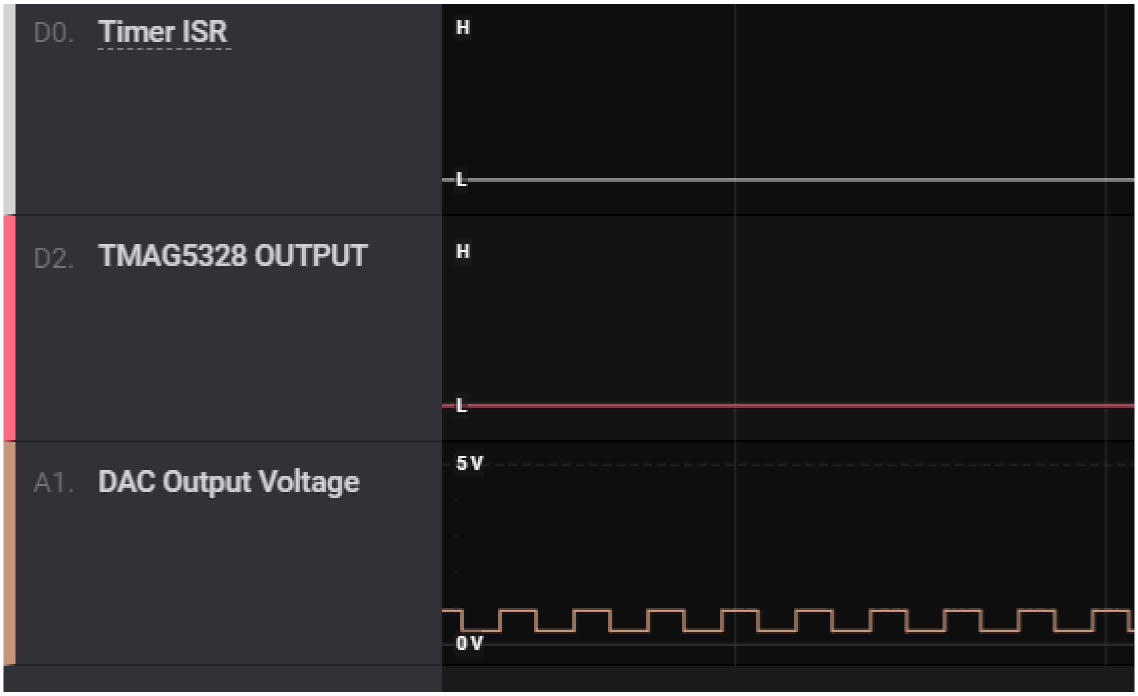

Figure 4-8. Logic Analyzer Screenshot of TMAG5328 OUT Pin When VCC Disconnected

Similarly, the OUT pin was also observed low when the TMAG5328 OUT pin was disconnected, as shown in Figure 4-9. As a result of the OUT pin being stuck low, the EVM's microcontroller also logged this as a fault event.

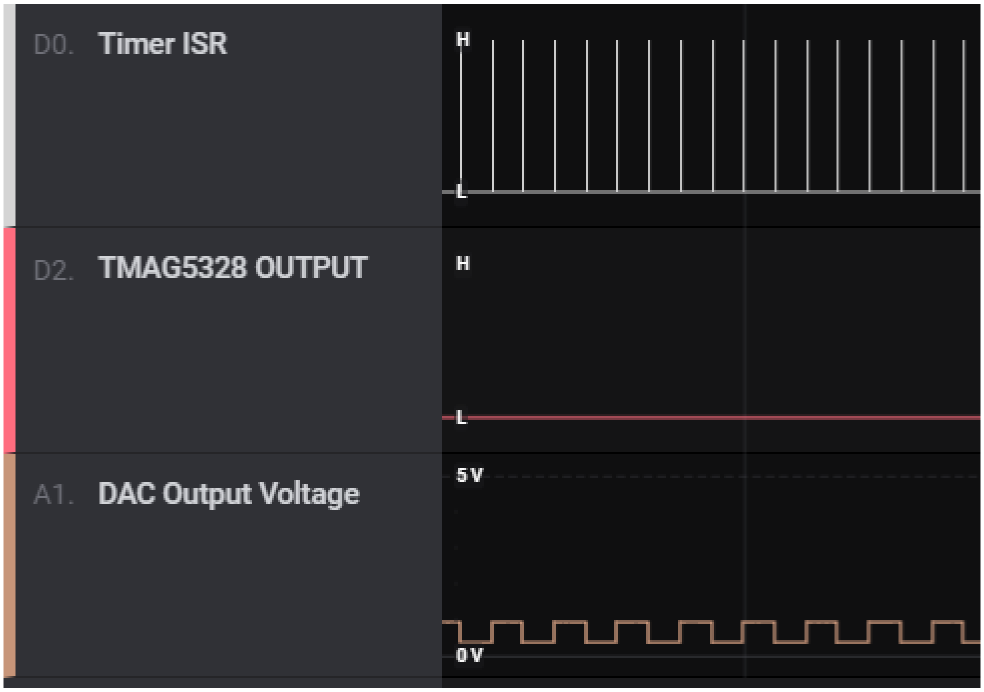

Figure 4-9. Logic Analyzer Screenshot When OUT Pin Disconnected

The TMAG5328 OUT pin did not have a square wave after VCC or OUT were disconnected, therefore this technique was able to detect these signal disconnection faults.

4.1.1.2 Signal Shorts

This diagnostic implementation was tested when the TMAG5328 OUT pin was shorted to GND and shorted to VCC. When the TMAG5328 OUT pin was shorted to GND, the OUT pin stayed low, as shown in Figure 4-10. Shorting the TMAG5328 OUT pin to VCC caused the OUT pin to stay high, as shown in Figure 4-11. For both signal shorts, a square wave was no longer available on the TMAG5328 OUT pin, so the EVM's microcontroller was able to log these events as faults.

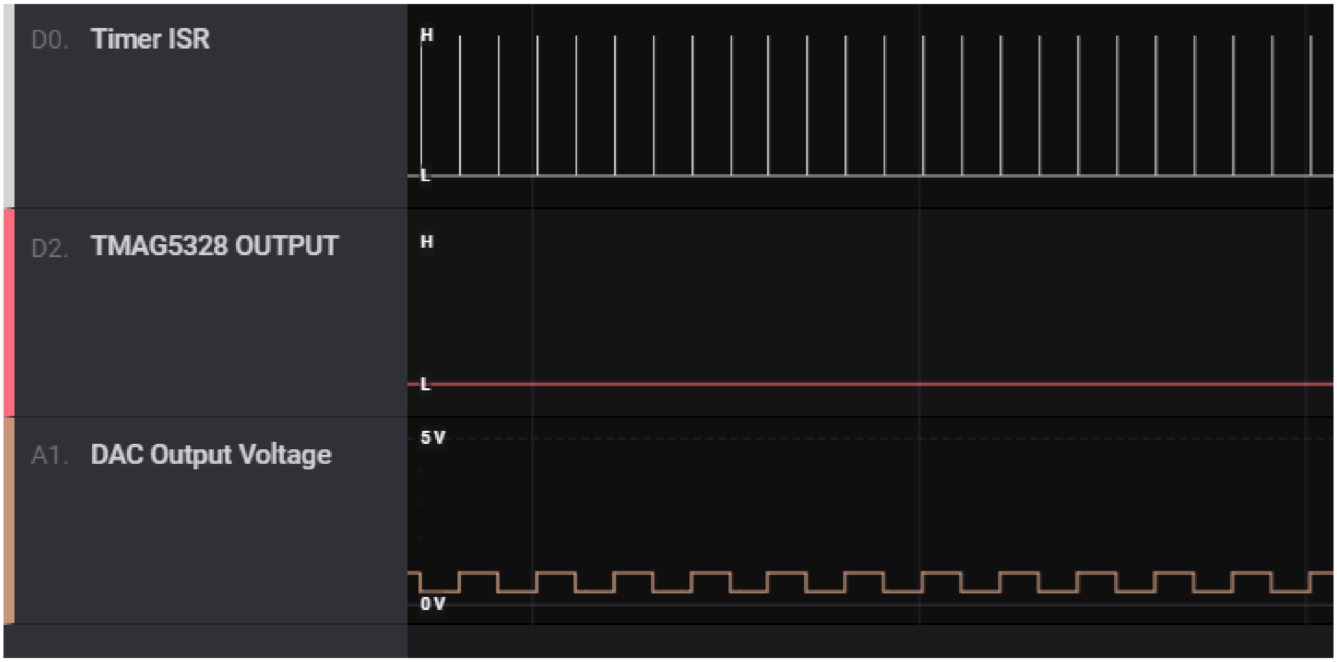

Figure 4-10. Logic Analyzer Screenshot of TMAG5328 OUT Pin When it is Shorted to GND

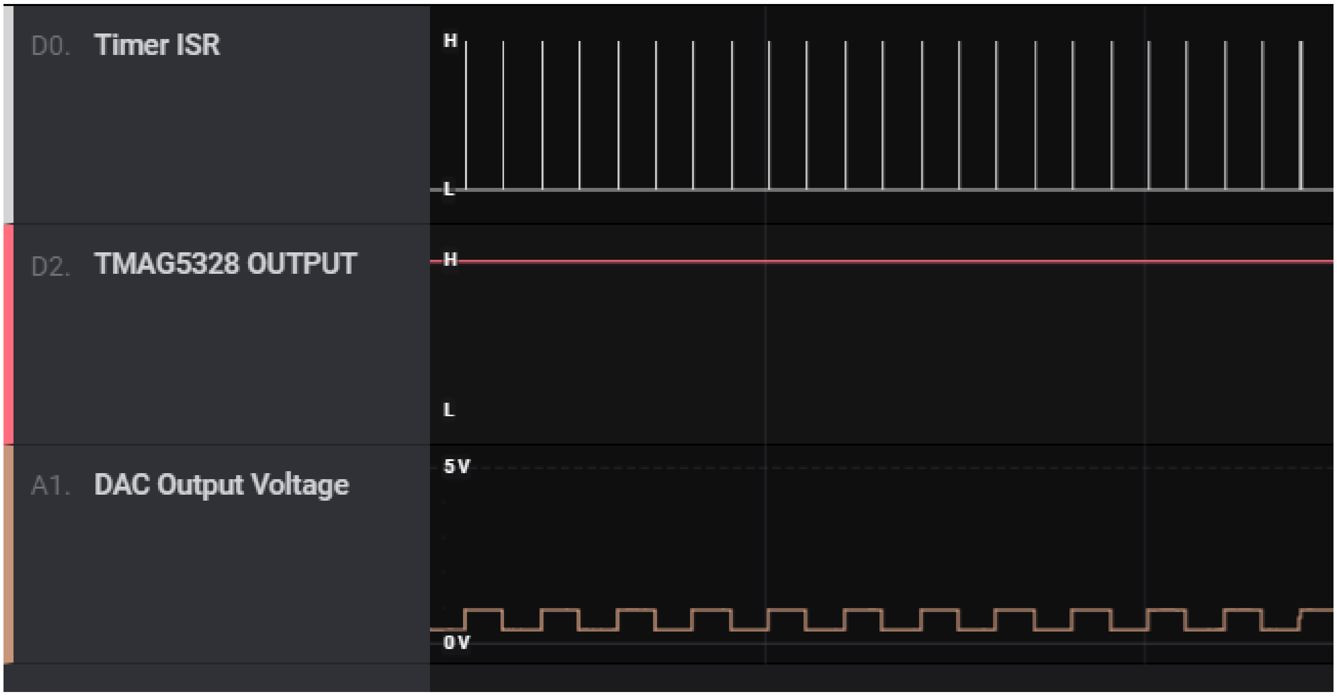

Figure 4-11. Logic Analyzer Screenshot of TMAG5328 OUT Pin When it is Shorted to VCC

5 Summary

By connecting the TMAG5328 to a DAC with nonvolatile memory, a software programmable Hall-effect switch with microcontroller-less standalone mode can be implemented. Using a DAC also enables backcalculating the magnetic flux density seen by the device. In addition, the DAC can be configured to implement diagnostics on the TMAG5328 to detect TMAG5328 pin shorts, TMAG5328 pin disconnections, and magnet out of range faults. These applications as well as the other applications of the TMAG5328 adjustable B_{OP} increases system design flexibility and reduces design time.

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