Off-state diagnostics with TLE9560/61/62

About this document

Scope and purpose

This application note provides information about the off-state diagnostic features of the TLE9560/61/62.

It should be used in conjunction with the corresponding datasheet, which contains full technical details on the device specification and operation.

Intended audience

Developers working with the TLE956x devices.

Table of contents

1 Introduction

The Motor System IC family (TLE956x) is a multi-half-bridge MOSFET driver, which combines power, communication and supply.
All devices feature a low-dropout voltage regulator with an output current of 250mA/5V. The communication interface incorporates a CAN FD transceiver up to 5Mbit/s according to ISO 11898-2:2016 (including Partial Networking option) and/or LIN transceiver.
All devices are available in a VQFN-48 (7mm x 7mm) package.

The devices offer a wide range of diagnostic features for the bridge driver both in on-state and in off-state. This application note focuses on the off-state diagnostic features of the half-bridge.

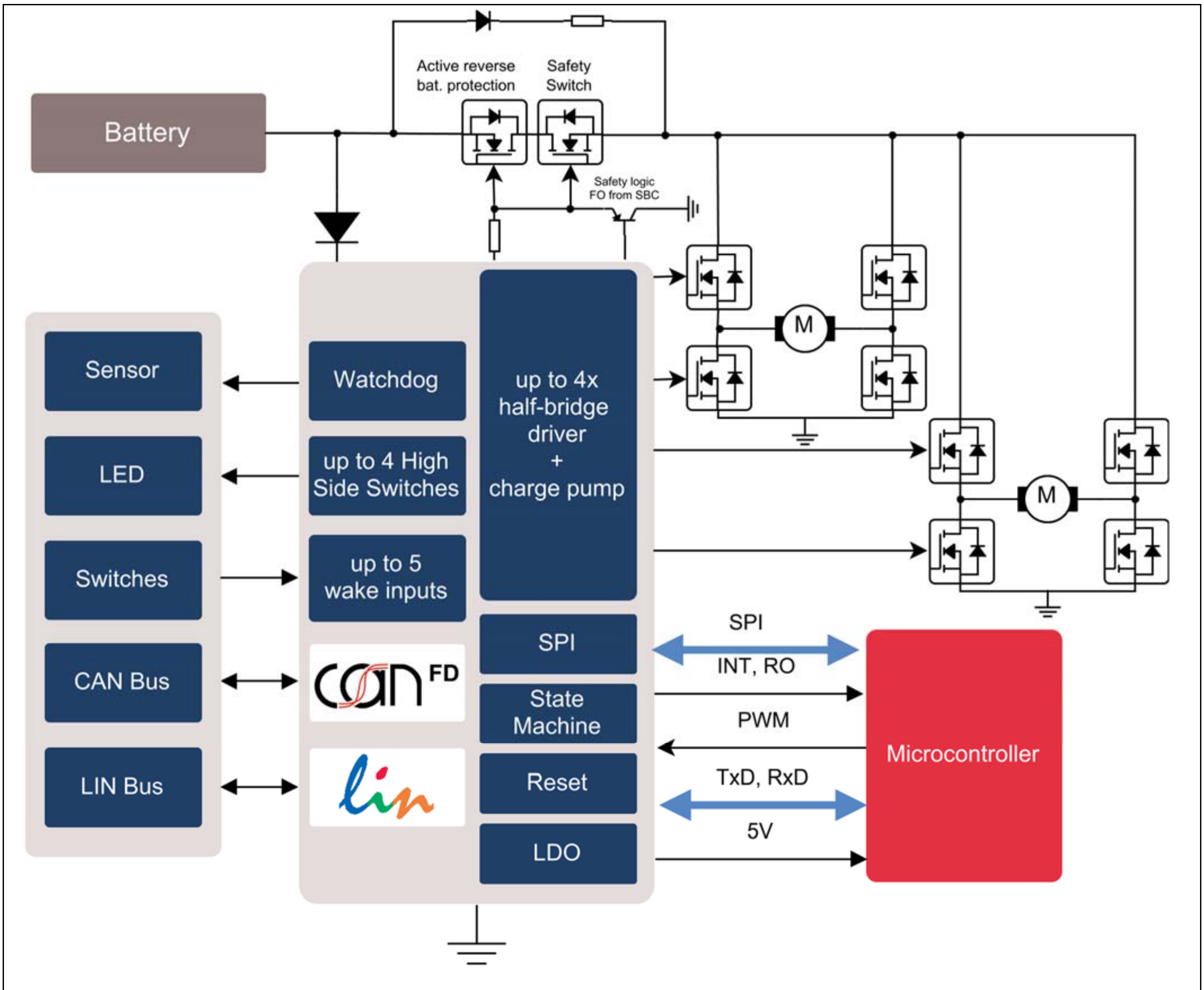

Figure 1 **TLE9560/61/62 block diagram in one of the possible half-bridge configurations**

2 Off-state diagnostic general principles

2.1 Benefits

The off-state diagnostic features (i.e. the MOSFETs are off while the diagnostic is performed) offer several advantages:

- Diagnostic checks can be performed for loads that are infrequently activated
- MOSFET short circuit conditions are detected without the stress inherent to the on-state diagnostic mode (note that the on-state diagnostic is also available TLE956x). For example, the microcontroller can perform an off-state diagnostic right before the activation request of the load. Upon the fault condition, the application software can report the failure and inhibits the load activation, avoiding stress to the MOSFETs

2.2 Required settings

The bridge driver is activated and the associated MOSFETs are off:

- The device is in **Normal Mode**
- The bridge driver is in active mode**: CPEN = 1_B** (charge pump enabled)
- The MOSFETs are actively kept off: **HBxMODE[1:0] = 11_B**
- It is highly recommended to set the drain-source overvoltage threshold ($V_{DSMONTH}$) of the diagnosed half-bridge to its maximum value for a robust diagnostic: **HBxVDSTH[2:0] = 111_B**, $V_{DSMONTH}$ = 2 V typ. (datasheet parameter $V_{DSMONTH7\_CPON}$)*.

*It is recommended to restore the setting of $V_{DSMONTH}$ once the off-state diagnostic is performed for an appropriate MOSFET protection in on-state.

2.3 Detectable failures by the off-state diagnostic

The TLE956x enables the detection of the following fault conditions while the MOSFETs are deactivated:

- Short-circuit between SHx and VBAT
- Short-circuit between SHx and GND
- Open load

SHx designates the output of the half-bridge x, VBAT is the battery voltage

2.4 Theory of operation

Figure 2 and Figure 3 show the block diagram of the gate drivers of one half-bridge.

The following integrated components are used to perform the off-state diagnostic:

- Pull-up diagnostic current (**I_{PUDIAG}**)
- Pull-down diagnostic current (**I_{PDDIAG}**)
- Comparator for the high-side drain-source overvoltage

Note: I_{PUDIAG} is a by-product of the drain-source overvoltage monitoring for each high-side MOSFET. It is automatically activated when the bridge driver is in active mode (CPEN = 1_B and the considered half-bridge is actively kept off: HBxMODE[1:0] = 11_B)

Note: I_{PDDIAG} can be individually activated for each half-bridge only if the bridge driver is activated and the considered half-bridge is actively kept off

By design I_{PDDIAG} > 4.25 x I_{PUDIAG}. Typically I_{PUDIAG} = 400 µA, I_{PDDIAG} = 2200 µA. Background information for this ratio is given in examples of chapter 3 and chapter 4.

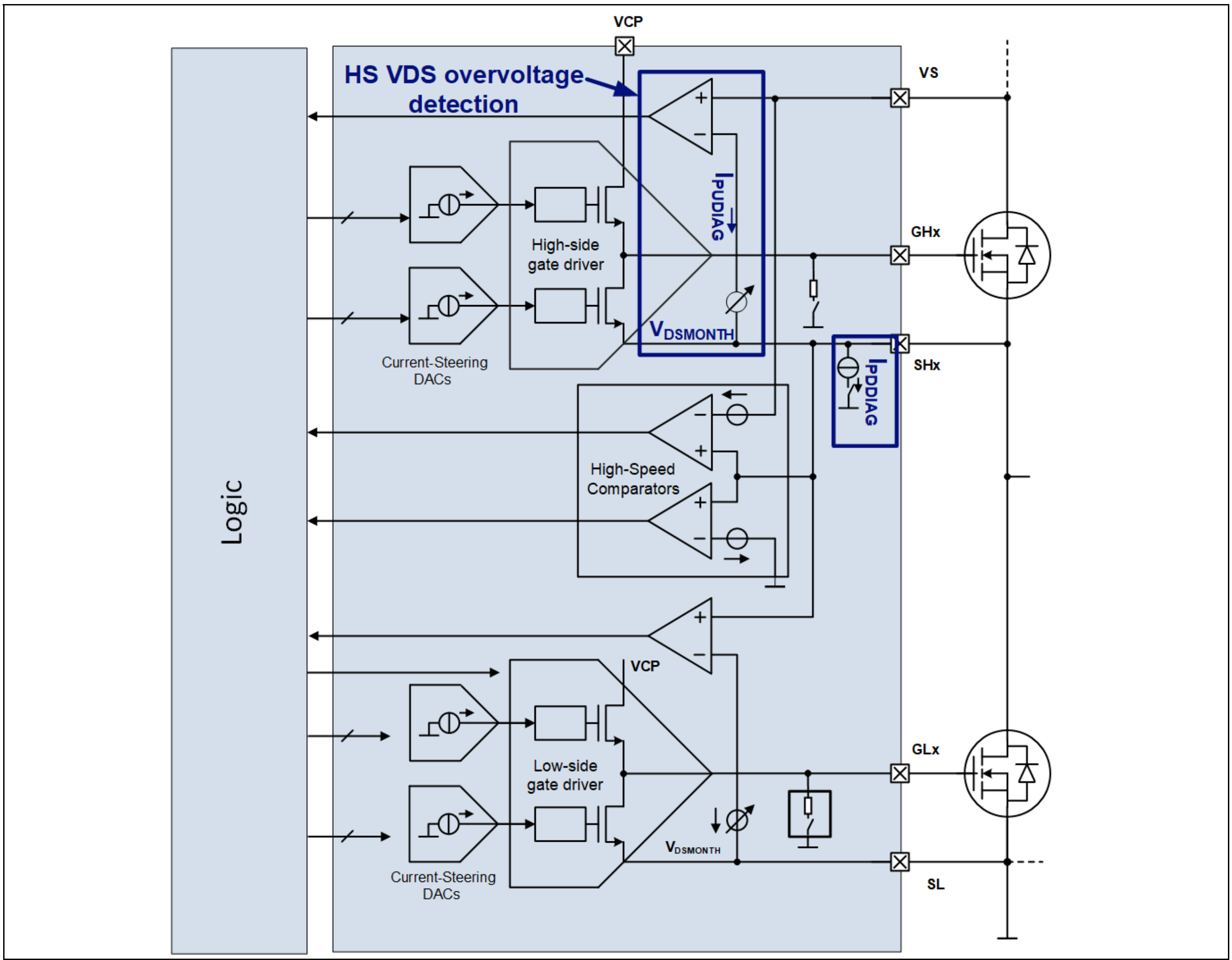

Figure 2 Block diagram of one half-bridge gate driver

The TLE956x determines the voltage at SHx, using the drain-source overvoltage comparators of the high-side MOSFETs. The microcontroller can read the status bits HBxVOUT to determine if V_{SHx} is high or low.

The diagnostic process is controlled by the microcontroller, whose task is:

- To activate and deactivate I_{PDDIAG}, (refer to the control bits HBxIDIAG)
- To read and interpret the status bits HBxVOUT according to the setting of I_{PDDIAG}

2.5 Conventions

The following conditions are equivalent in the rest of this document:

- HBxVOUT = 0: V_{SHx} is low (V_S - V_{SHx} > $V_{DSMONTH}$)
- HBxVOUT = 1: V_{SHx} is high (V_S - V_{SHx} < $V_{DSMONTH}$)

V_S designates the voltage applied to the VS pin. In particular, it is also the drain voltage of the high-side MOSFETs.

- HBxIDIAG = 0: I_{PDDIAG} of HBx is off
- HBxIDIAG = 1: I_{PDDIAG} of HBx is on

3 Off-state diagnostic with one DC motor

This chapter provides examples of off-state diagnostic for a single DC motor configuration.

3.1 Example with a DC motor controlled by two half-bridges

This section gives an example of off-state diagnostic with one DC motor controlled by the half-bridges 1 and 2 (HB1 and HB2).

This sub-chapter analyzes the voltage at SH1/SH2 (noted V_{SH1}/V_{SH2}) in the following test configurations:

- Configuration 1: I_{PDDIAG} HB1 OFF, I_{PDDIAG} HB2 OFF
- Configuration 2: I_{PDDIAG} HB1 ON, I_{PDDIAG} HB2 OFF
- Configuration 3: I_{PDDIAG} HB1 OFF, I_{PDDIAG} HB2 ON

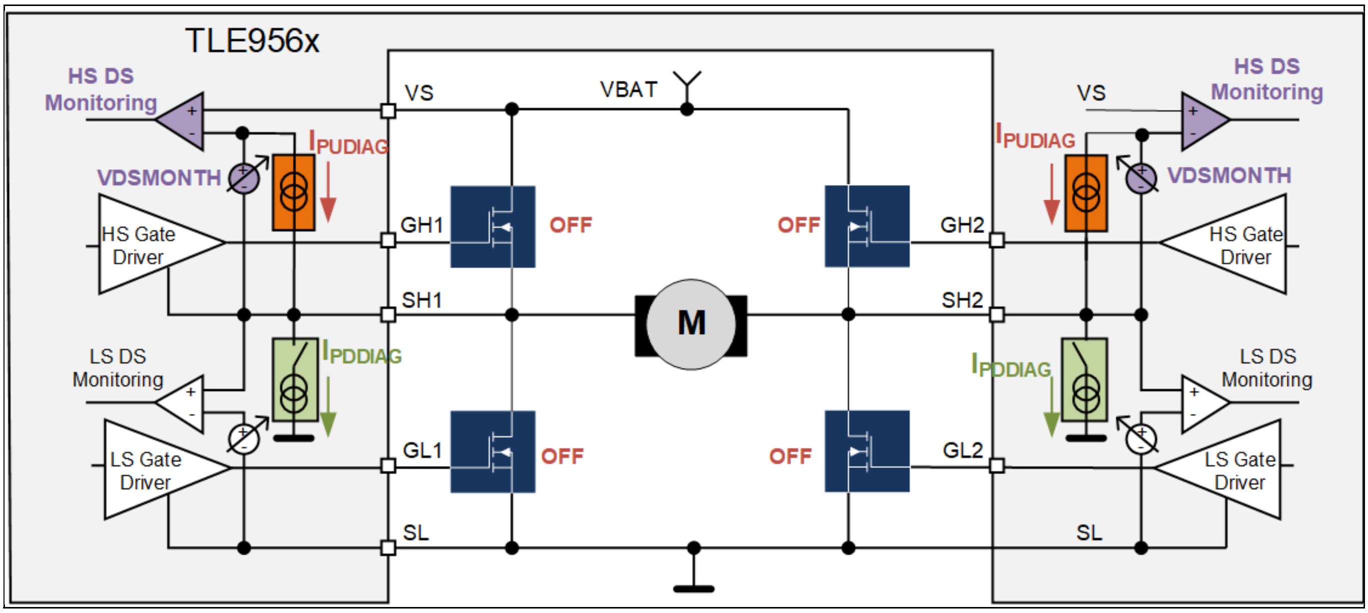

Figure 3 Simplified block diagram with one DC motor controlled by two half-bridges

3.2 Normal load conditions

Configuration 1: I_{PDDIAG} HB1 OFF, I_{PDDIAG} HB2 OFF

In normal conditions, the motor is connected between SH1 and SH2 without any short circuit or open load conditions.

If I_{PDDIAG} of HB1 and HB2 are off, then SH1 and SH2 are pulled up by I_{PUDIAG} of HB1 and HB2 (Figure 4).

V_{SH1} = V_{SH2} = High.

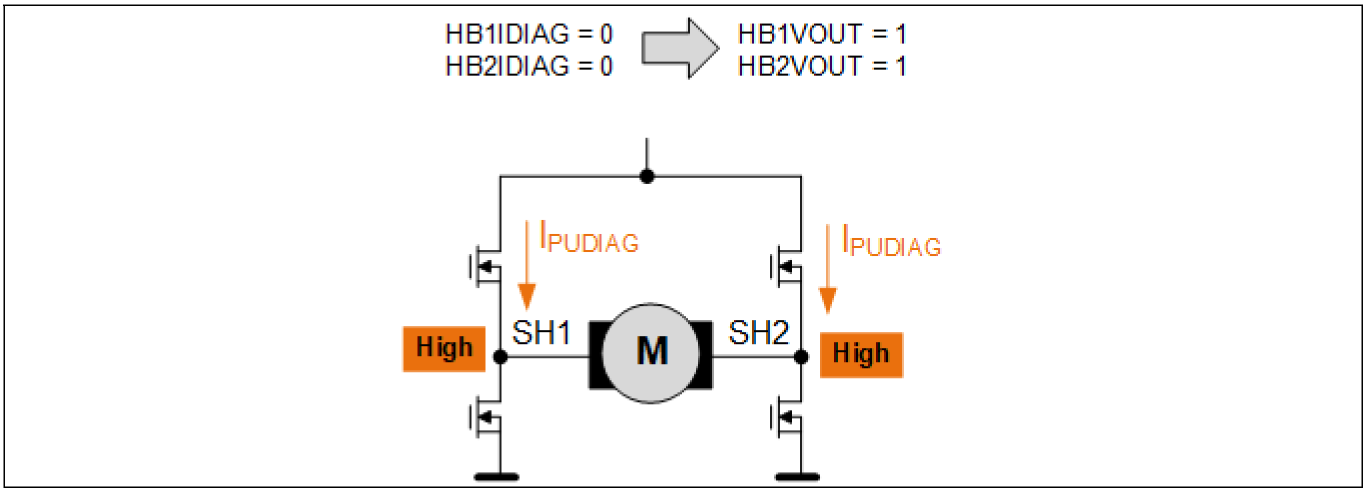

Figure 4 One motor in normal conditions, I_{PDDIAG} HB1/HB2 OFF with normal load

Configuration 2: I_{PDDIAG} HB1 ON, I_{PDDIAG} HB2 OFF

By design I_{PDDIAG} > 4.25 x I_{PUDIAG} so that one pull-down is stronger than two pull-ups. Therefore SH1 is pulled to GND → **V_{SH1} = low**. Refer to Figure 5, left picture.

SH2 is also pulled to GND by I_{PDDIAG} of HB1 via the motor windings → **V_{SH2} = low**.

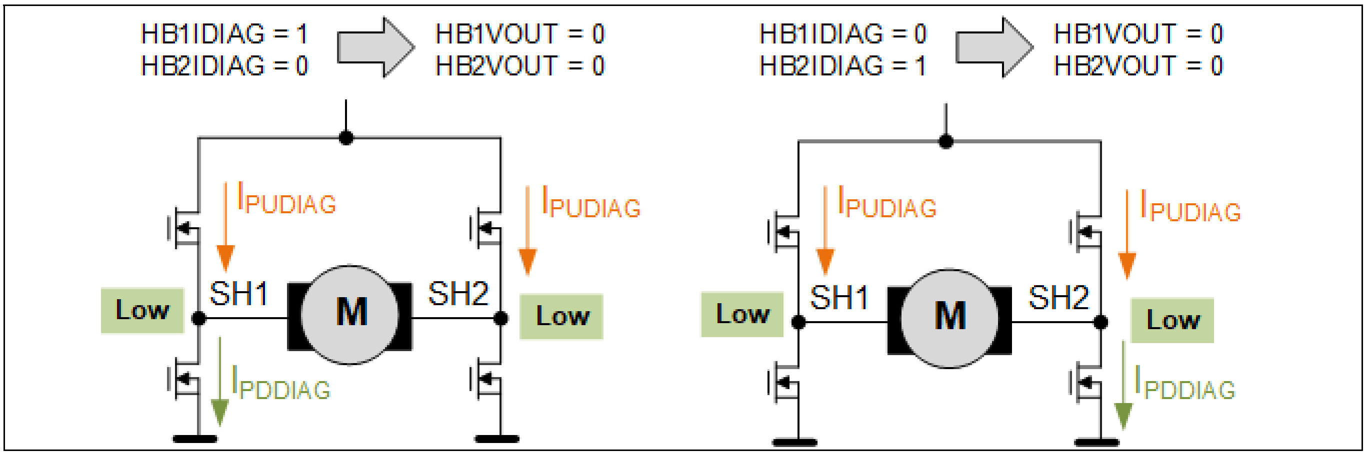

Figure 5 One motor in normal conditions with one pull-down diagnostic current on

When the pull-down and pull-up diagnostic currents of a half-bridge are activated, it results in a net pull-down current which is equal to I_{PDDIAG} - I_{PUDIAG} (in the considered half-bridge).

In the case shown on Figure 5, the net pull down current is I_{PDDIAG} – 2 x I_{PUDIAG}.

Note: When capacitors are connected to SHx (e.g. ESD capacitors placed on the PCB, or filter capacitors located in the motors), these capacitors are charged / discharged by the sum of the diagnostic currents resulting from each half-bridge. Therefore, the application must take into consideration this charge / discharge times for a valid determination of the voltage level at the SHx pins

Configuration 3: I_{PDDIAG} HB1 OFF, I_{PDDIAG} HB2 ON

This configuration is equivalent to Configuration 2, with HB2 pull-down activated instead of HB1.

V_{SH2} = low. Refer to Figure 5, right picture.

SH1 is pulled down by I_{PDDIAG} of HB2 via the motor → **V_{SH1} = low**.

Table 1 summarizes the results obtained in normal conditions.

Table 1 Truth table with normal load conditions

Configuration	I_{PDDIAG} HB1	I_{PDDIAG} HB2	V_{SH1}	V_{SH2}
1	OFF	OFF	HIGH	HIGH
2	ON	OFF	LOW	LOW
3	OFF	ON	LOW	LOW

3.3 Short circuit to VBAT

A short circuit between SH1 and VBAT results in **V_{SH1} = high**, independently from the activation of I_{PDDIAG}.

SH2 is pulled up by the short circuit via the motor windings: **V_{SH2} = high**.

Similarly, a short circuit of SH2 to VBAT results in **V_{SH1} = V_{SH2} = high**, independently from the activation of I_{PDDIAG}.

Table 2 and Figure 6 summarize the results obtained with a short circuit of one output to VBAT.

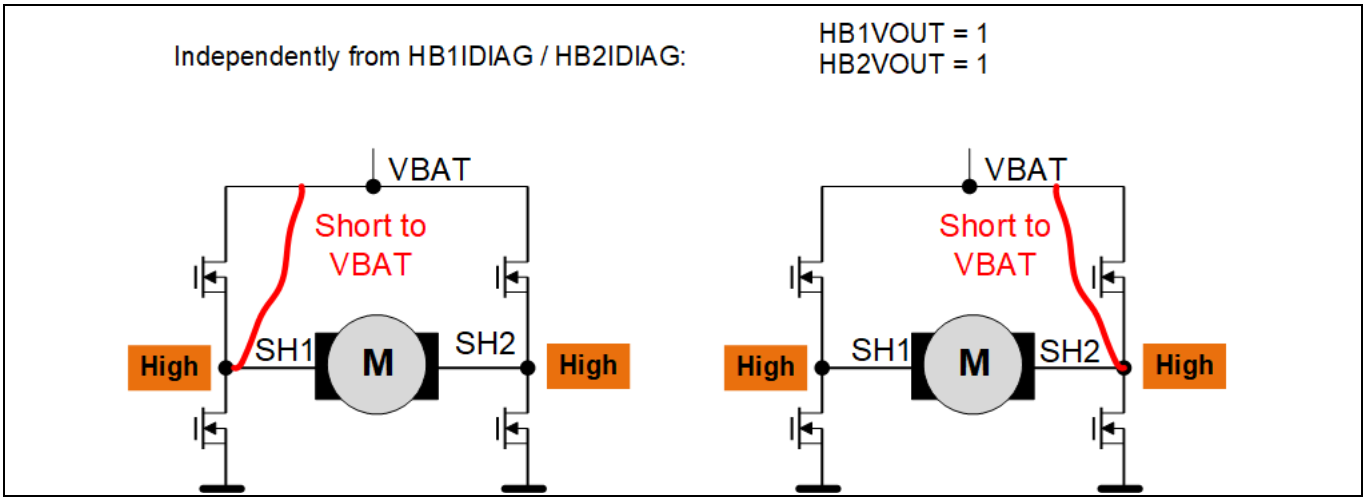

Figure 6 Short circuit to VBAT

Table 2 Truth table with a short circuit to VBAT

Configuration	I_{PDDIAG} HB1	I_{PDDIAG} HB2	V_{SH1}	V_{SH2}
1	OFF	OFF	HIGH	HIGH
2	ON	OFF	HIGH	HIGH
3	OFF	ON	HIGH	HIGH

3.4 Short circuit to GND

A short circuit between SH1 and GND results in **V_{SH1} = low** even if I_{PDDIAG} are deactivated.

SH2 is pulled down by the short circuit via the motor windings. **V_{SH2} = low**.

Similarly, a short circuit of SH2 to GND results in **V_{SH1} = V_{SH2} = low**, independently from the state of I_{PDDIAG}.

Table 3 and Figure 7 summarize the results obtained with a short circuit of one output to GND.

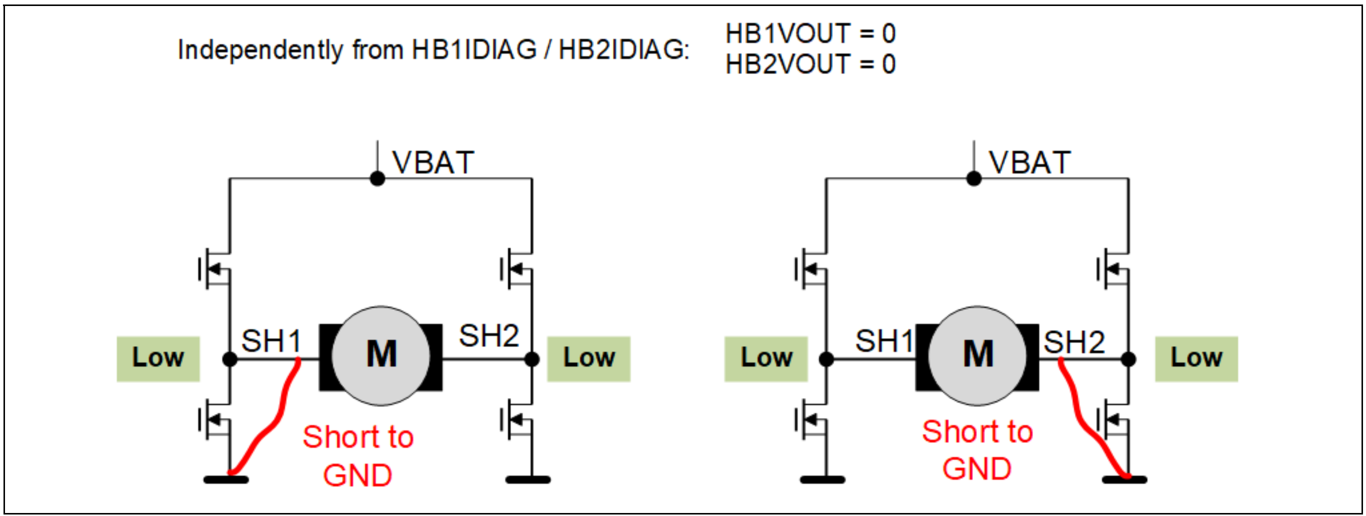

Figure 7 Short circuit to GND

Table 3 Truth table with a short circuit to GND

Configuration	I_{PDDIAG} HB1	I_{PDDIAG} HB2	V_{SH1}	V_{SH2}
1	OFF	OFF	LOW	LOW
2	ON	OFF	LOW	LOW
3	OFF	ON	LOW	LOW

3.5 Open load – SH1 is disconnected

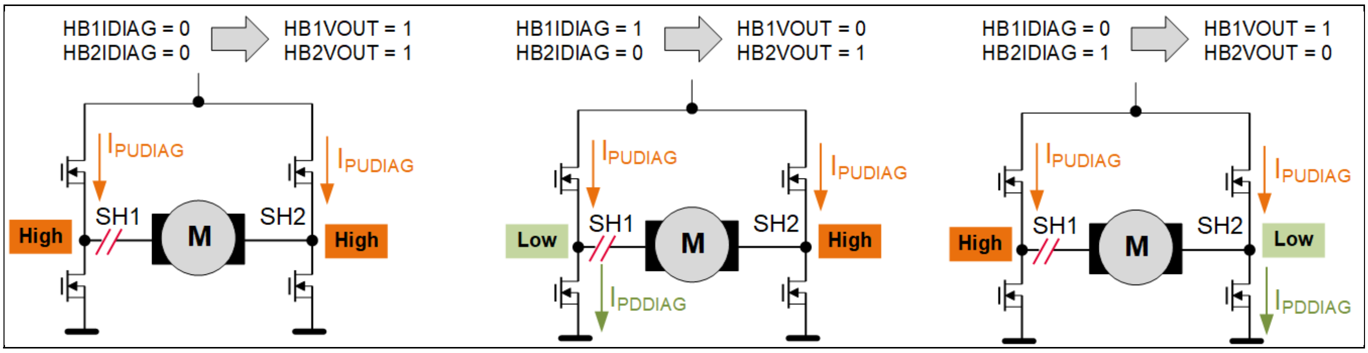

Figure 8 One motor – Diagnostic result with an open load at SH1

Configuration 1: I_{PDDIAG} HB1 OFF, I_{PDDIAG} HB2 OFF

SH1 and SH2 are pulled up by their respective pull-up diagnostic current: **V_{SH1} = V_{SH2} = high**

Configuration 2: I_{PDDIAG} HB1 ON, I_{PDDIAG} HB2 OFF

SH1 is pulled down by I_{PDDIAG} HB1: **V_{SH1} = low**

Due to the motor disconnection at SH1, SH2 is pulled up by I_{PUDIAG} HB2: **V_{SH2} = high**

Configuration 3: I_{PDDIAG} HB1 OFF, I_{PDDIAG} HB2 ON

SH1 is pulled up by I_{PUDIAG} HB1: **V_{SH1} = high**

SH2 is pulled down by I_{PDDIAG} HB2: **V_{SH2} = low**

Table 4 summarizes the results obtained in case of open load.

Table 4 Truth table open load - SH1 or SH2 is disconnected

Configuration	I_{PDDIAG} HB1	I_{PDDIAG} HB2	V_{SH1}	V_{SH2}
1	OFF	OFF	HIGH	HIGH
2	ON	OFF	LOW	HIGH
3	OFF	ON	HIGH	LOW

3.6 Open load – SH2 is disconnected

Similarly a motor disconnection at SH2 shows the same result as for a motor disconnection at SH1. Refer to Figure 9. Therefore, Table 4 is valid for an open load, independently from the location of the disconnection.

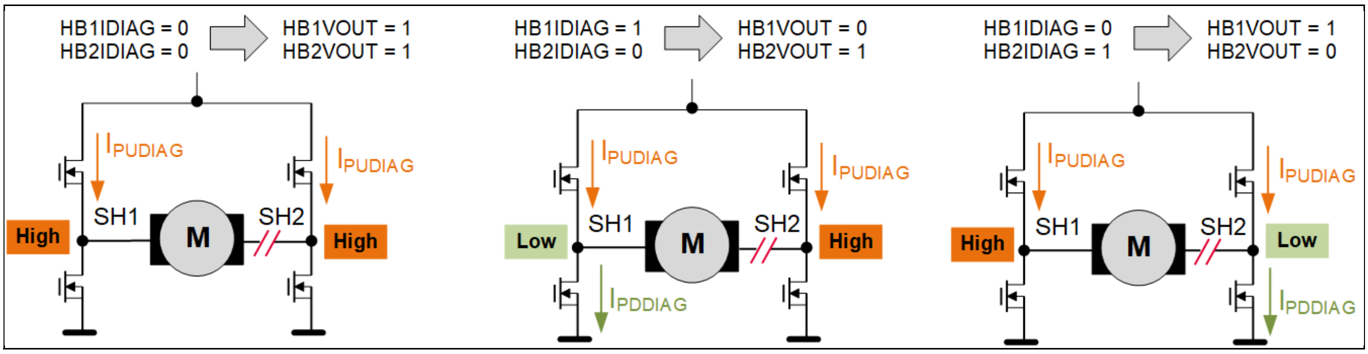

Figure 9 One motor – Diagnostic result with an open load at SH2

3.7 Summary of the off-state diagnostic

Compiling the results from Table 1, Table 2, Table 3 and Table 4, we see that the test configuration 1 and the test configuration 2 are sufficient to detect and distinguish between a normal load condition, a short circuit to VBAT/GND, and an open load. Refer to Figure 10:

- **V_{SH1} and V_{SH2} = high in Configuration 2 is characteristic for a short circuit of one of the outputs to VBAT**. The short circuit to VBAT prevents the pull-down diagnostic current to pull SH1/SH2 to GND.
- **V_{SH1} and V_{SH2} = low in Configuration 1 is characteristic for a short circuit of one of the outputs to GND**. The short circuit to GND prevents the pull-up diagnostic currents to pull SH1/SH2 to VBAT.
- **V_{SH1} = Low and V_{SH2} = high in Configuration 2 is characteristic for an open load condition**. The motor disconnection prevents one pull-down diagnostic current to pull both SH1 and SH2 to GND at the same time.

Load conditions	Configuration	I_{PDDIAG} HB1	I_{PDDIAG} HB2	V_{SH1}	V_{SH2}	
Normal conditions	1	OFF	OFF	HIGH	HIGH	
	2	ON	OFF	LOW	LOW	
Short to VBAT	1	OFF	OFF	HIGH	HIGH	
	2	ON	OFF	HIGH	HIGH	→ Short to VBAT
Short to GND	1	OFF	OFF	LOW	LOW	→ Short to GND
	2	ON	OFF	LOW	LOW	
Open load	1	OFF	OFF	HIGH	HIGH	
	2	ON	OFF	LOW	HIGH	→ Open load

Figure 10 Differentiation between normal load, short to VBAT, short to GND and open load with one motor

4 Off-state diagnostic with two cascaded motors

This chapter provides hints about the off-state diagnostic with two cascaded motors controlled by three half-bridges (Figure 11).

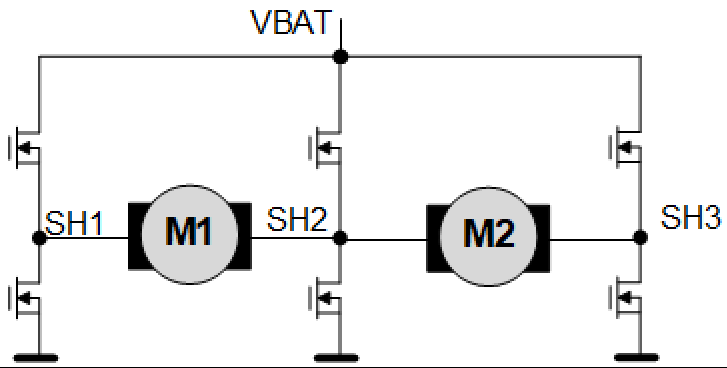

Figure 11 Two cascaded DC motors Summary of the off-state diagnostic

The proposed principle for the off-state diagnostic consists of analyzing V_{SHx} when all pull-down diagnostic currents are deactivated, and when two out of three pull-down diagnostic currents are activated.

Note: An off-state diagnostic activating one pull-down out of three is also possible, considering that I_{PDDIAG} > 4.25 x I_{PUDIAG}. Consequently, one single pull-down is stronger than the sum of three pull-ups. However, the net pull-down current in normal conditions is I_{PDDIAG} - 3 x I_{PUDIAG} (compared to 2 x I_{PDDIAG} - 3 x I_{PUDIAG} if two pull-down currents are activated). Therefore the net discharge current is lower and the settling time for discharging output capacitors is longer.

The results are summarized in Figure 12.

Load conditions	Configuration	I_{PDDIAG} HB1	I_{PDDIAG} HB2	I_{PDDIAG} HB3	V_{SH1}	V_{SH2}	V_{SH3}	
Normal conditions	1	OFF	OFF	OFF	HIGH	HIGH	HIGH	
	2	ON	ON	OFF	LOW	LOW	LOW	
	3	OFF	ON	ON	LOW	LOW	LOW	
	4	ON	OFF	ON	LOW	LOW	LOW	
Short to VBAT	1	OFF	OFF	OFF	HIGH	HIGH	HIGH	
	2	ON	ON	OFF	HIGH	HIGH	HIGH	
	3	OFF	ON	ON	HIGH	HIGH	HIGH	Short to VBAT
	4	ON	OFF	ON	HIGH	HIGH	HIGH	
Short to GND	1	OFF	OFF	OFF	LOW	LOW	LOW	Short to GND
	2	ON	ON	OFF	LOW	LOW	LOW	
	3	OFF	ON	ON	LOW	LOW	LOW	
	4	ON	OFF	ON	LOW	LOW	LOW	
Open load MOTOR1	1	OFF	OFF	OFF	HIGH	HIGH	HIGH	
	2	ON	ON	OFF	LOW	LOW	LOW	
	3	OFF	ON	ON	HIGH	LOW	LOW	Open load Motor 1
	4	ON	OFF	ON	LOW	LOW	LOW	
Open load MOTOR2	1	OFF	OFF	OFF	HIGH	HIGH	HIGH	
	2	ON	ON	OFF	LOW	LOW	HIGH	
	3	OFF	ON	ON	LOW	LOW	LOW	Open load Motor 2
	4	ON	OFF	ON	LOW	LOW	LOW	
Open load MOTOR1 and MOTOR2	1	OFF	OFF	OFF	HIGH	HIGH	HIGH	
	2	ON	ON	OFF	LOW	LOW	HIGH	
	3	OFF	ON	ON	HIGH	LOW	LOW	
	4	ON	OFF	ON	LOW	HIGH	LOW	Open load Motor 1 and Motor 2

Figure 12 Differentiation between normal load, short to VBAT, short to GND and open load with two cascaded motors

The test configurations 1, 2, 3 are sufficient to differentiate a normal load condition from the considered failures.

The detailed analysis of the V_{SHx} in the different load conditions are shown in Figure 13, Figure 14, Figure 15, Figure 15 and Figure 16.

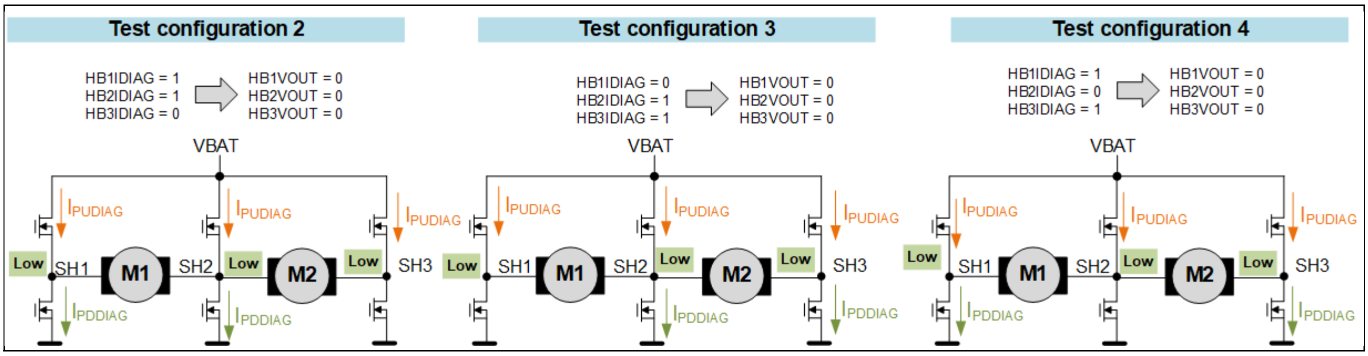

Figure 13 Diagnostic result with two cascaded motors in normal load conditions

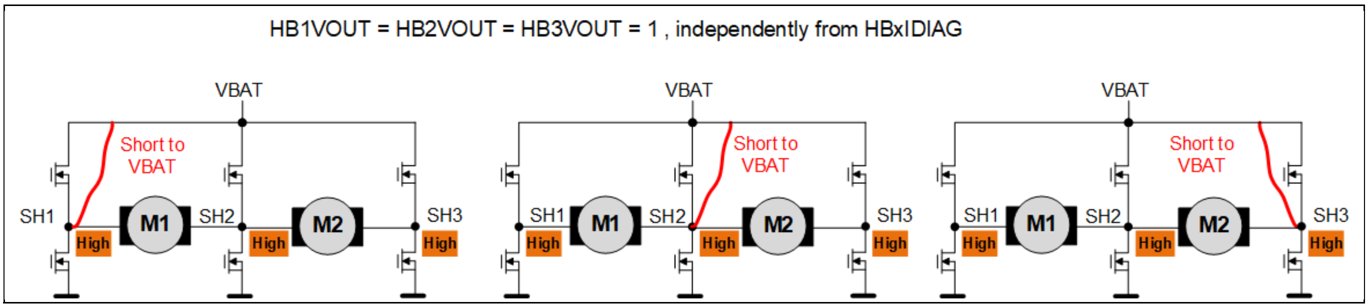

Figure 14 Diagnostic result with two cascaded motors with a short circuit to VBAT

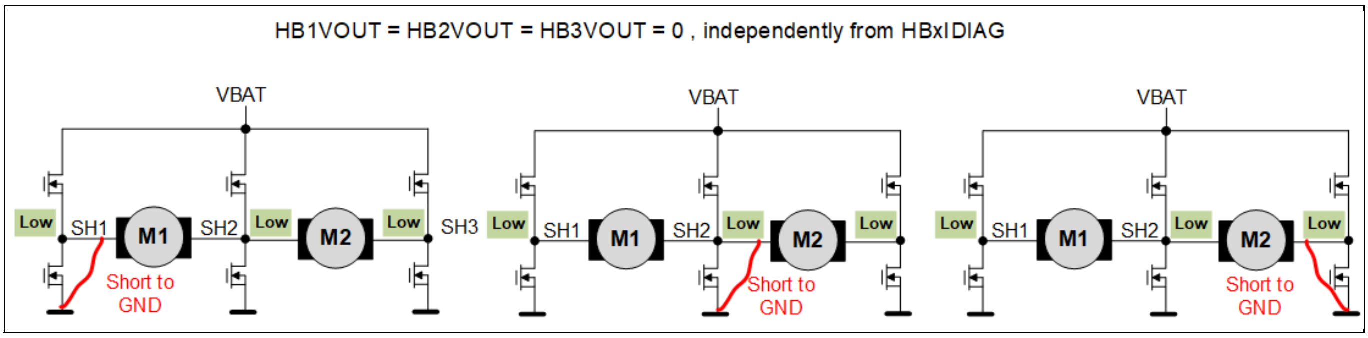

Figure 15 Diagnostic result with two cascaded motors with a short circuit to GND

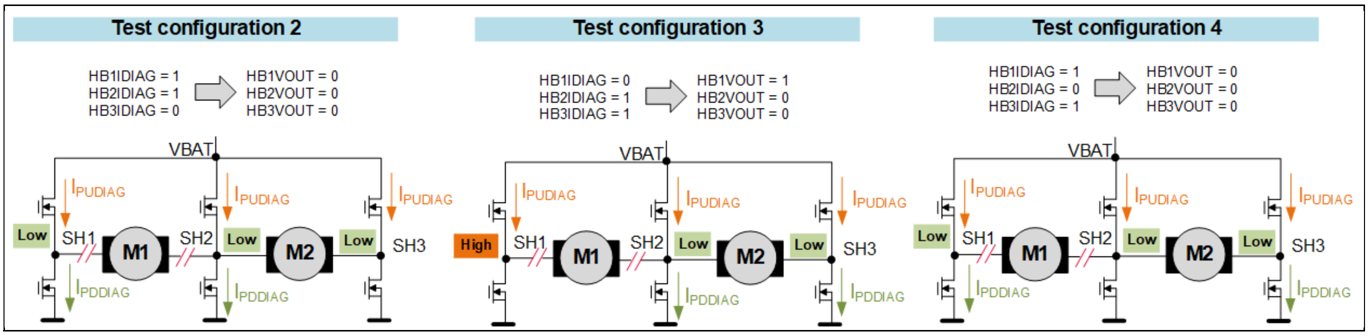

Figure 16 **Diagnostic result with two cascaded motors – Open load for motor 1**

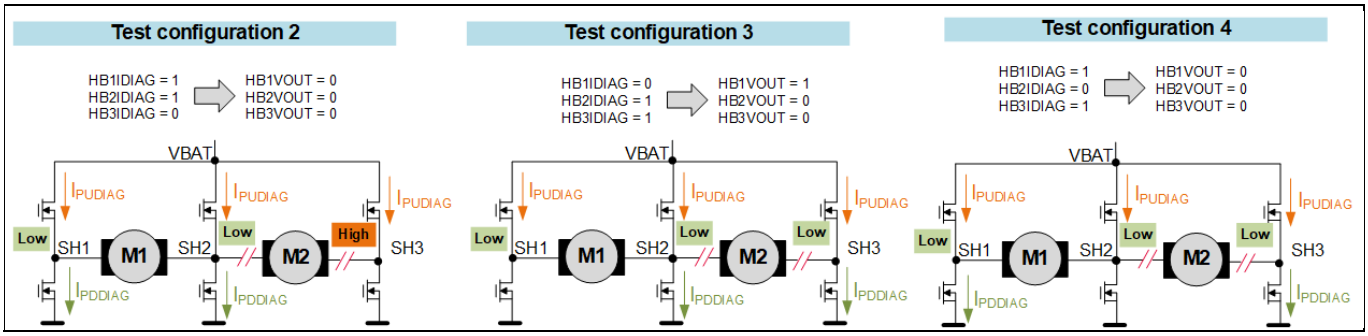

Figure 17 **Diagnostic result with two cascaded motors – Open load for motor 2**

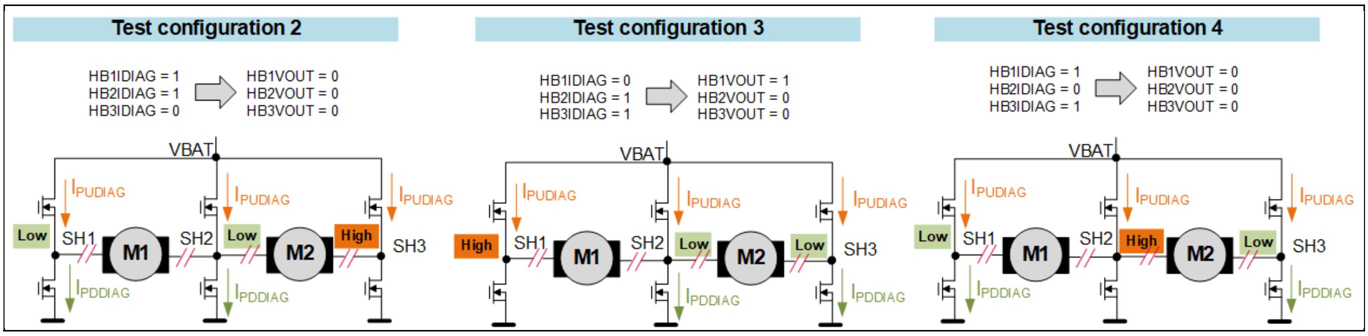

Figure 18 **Diagnostic result with two cascaded motors – Open load for motor 1 and motor 2**

Revision history

Document version	Date of release	Description of changes
0.1	2020-05-07	First draft

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Edition 2020-05-08

Published by

Infineon Technologies AG

81726 Munich, Germany

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Document reference