AN4892
Application note

VIPower M0-5 H-bridges - hardware design guide

Introduction

Understanding the behavior of the latest generation VIPower H-bridges for DC motor control in automotive applications can facilitate design and reduce costs.

The M0-5 generation of drivers builds on the knowledge derived from previous generations, with improved robustness functionality and package density. The integration of high side driver (HSD) switch chips and low side driver (LSD) chips in the one package (hybrid approach) pin allows minimization, a reduced component count, improved reliability and the saving of board space.

The combination of logic functions with analog power structures in the silicon allows an intelligence inside the chip which goes beyond simple driving to protection and fault feedback to a microcontroller across wide temperature and battery voltage ranges.

Contents

List of tables

List of figures

1 General concepts in DC motor control

A direct current (DC) motor is based on the interaction between a magnetic field created by the current circulating in the winding of the fixed part (inductor) and the magnetic field created by the current circulating in the moving windings (armature).

A permanent magnet DC (PMDC) motor uses permanent magnets in the inductor.

Figure 1: A PMDC motor

A collector on the armature windings mast carries the unidirectional current from the supply into the varying current of the armature rotating windings via a pair of stationary carbon brushes which are held in little sockets with a spring behind them to push the brushes onto the segments. This guarantees good electrical connection (even though there is a slight resistance across them).

In a rotating motor, the armature windings generate a "back electromotive force" (back-EMF) or reverse voltage nearly equal to the supply voltage when the motor is rotating but not driving anything.

The back-EMF is given by:

$$E_a = k \cdot \omega_m \cdot \Phi$$

…where k is a constant, ωm is the speed of the motor, and Φ is the strength of the magnetic field generated by the field coils or magnets.

The back-EMF is obviously zero when the motor starts from zero speed, so the current drawn by the motor at this moment is very large; this is also true when the motor is stalled.

The torque produced by a permanent magnet or shunt wound motor is given by:

$$T = k_f \cdot \Phi \cdot I$$

…Where k_f is a constant, I is the armature current and Φ is the strength of the magnetic field generated by the field coils or magnets.

The stall torque Ts is the maximum torque that a motor can deliver just as it stalls.

The electrical steady state equation of the motor is:

$$V = E_a + R_a \cdot I$$

…where V is the supply voltage of the motor, E_a is the armature back-EMF, R_a is the resistance of the armature windings and I is the armature current.

The efficiency of a DC motor is defined as the ratio of the output (mechanical) power to the input (electrical) power.

Maximum efficiency normally occurs at a torque less than Ts/2.

Maximum mechanical power occurs at approximately one half of the stall torque.

Performance curves (power, current and efficiency versus torque) are usually given for a specific regulated voltage supply which maintains a constant voltage regardless of torque demand. For such supplies, stall torque and no-load speed remain proportional for different supply voltages.

Figure 2: DC motor characteristic curves
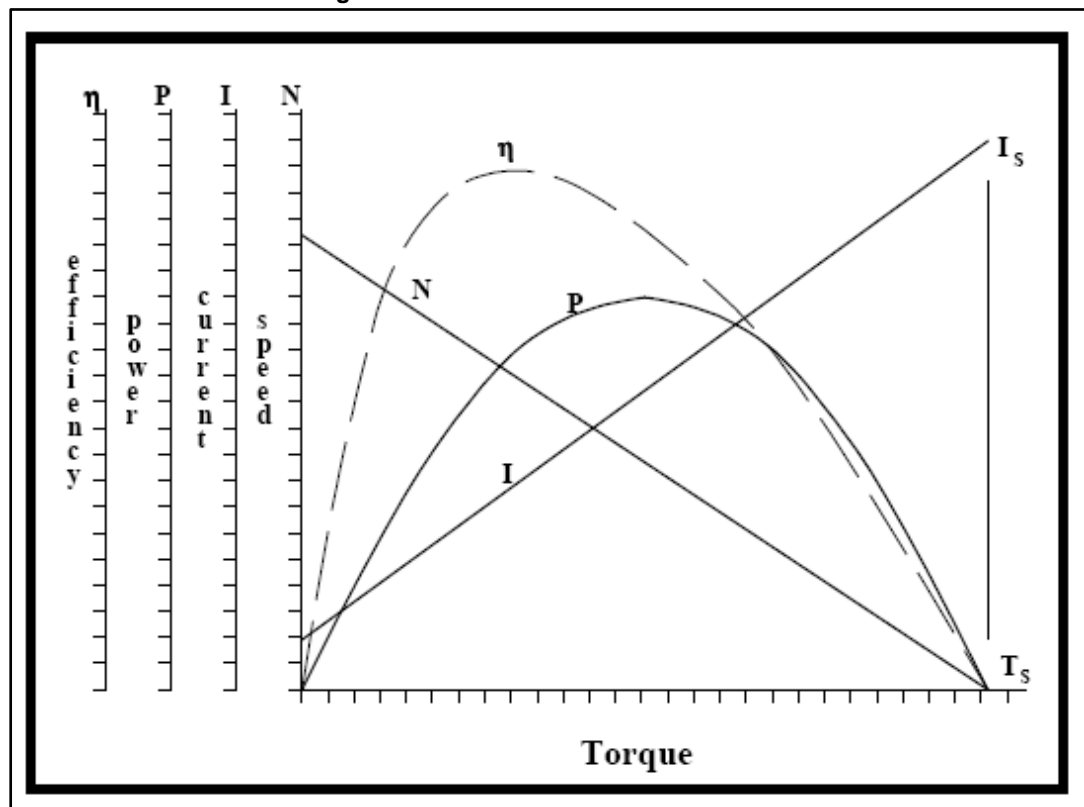
The H-bridge can be used to drive a DC motor in both directions by driving four MOS in the correct sequence to reverse current flow through the motor.

The torque of the motor is proportional to the armature current and can be controlled with current chopping (PWM control): an external controller checks the current level by monitoring the voltage of a sense resistor in series with the supply and then drives the appropriate power MOS.

This means that when current does not flow in the sense resistor (which occurs during recirculation), it is not possible to measure the current level and thus limit it. The steady-state speed can be varied simply by applying the appropriate magnitude and polarity of the armature voltage.

Also, the torque is directly proportional to the armature current, which in turn depends on the difference between the applied voltage V and the back-EMF, E_a. You can therefore make the machine develop positive (motoring) or negative (generating) torque by simply controlling the extent to which the applied voltage is greater or less than the back-EMF.

An armature voltage controlled D.C. machine is therefore capable of four-quadrant operation with reference to the numbered quadrants of the torque-speed plane, as shown below.

Figure 3: Operation of a DC motor in the four quadrants of the torque-speed plane
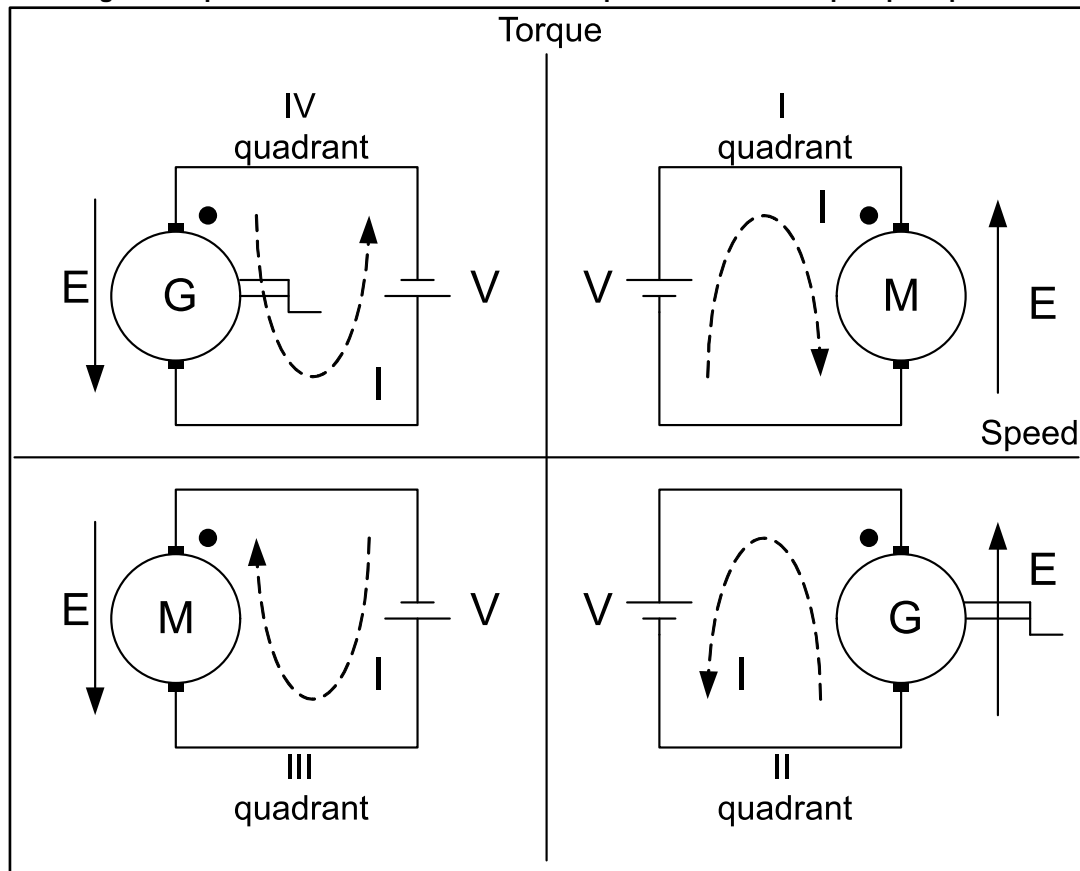
One of the motor terminals is shown with a dot on top in all four quadrants to indicate the sign of the torque and the speed: if the current is flowing in the motor and the back-EMF opposes it, then T>0 and E>0 (i.e., ωm > 0): the operation is motor onwards (I quadrant).

If the current is flowing outside the motor and the back-EMF is in the same direction, then T<0 and E>0 (i.e., $\omega m \square$ > 0): the operation is brake onwards (or generator, II quadrant). In this case, the motor absorbs mechanical energy and gives electrical energy to the supply.

The operation can be with a reversed speed both as motor (T<0, E<0, III quadrant) as well as generator (T>0, E<0, IV quadrant).

A set of four transistors in H-bridge configuration allows the independent variation of the voltage and current of the motor and therefore complete operation in the four quadrants. The speed can be varied by varying the voltage applied to the motor.

Figure 4: Four-quadrant, full-bridge converter
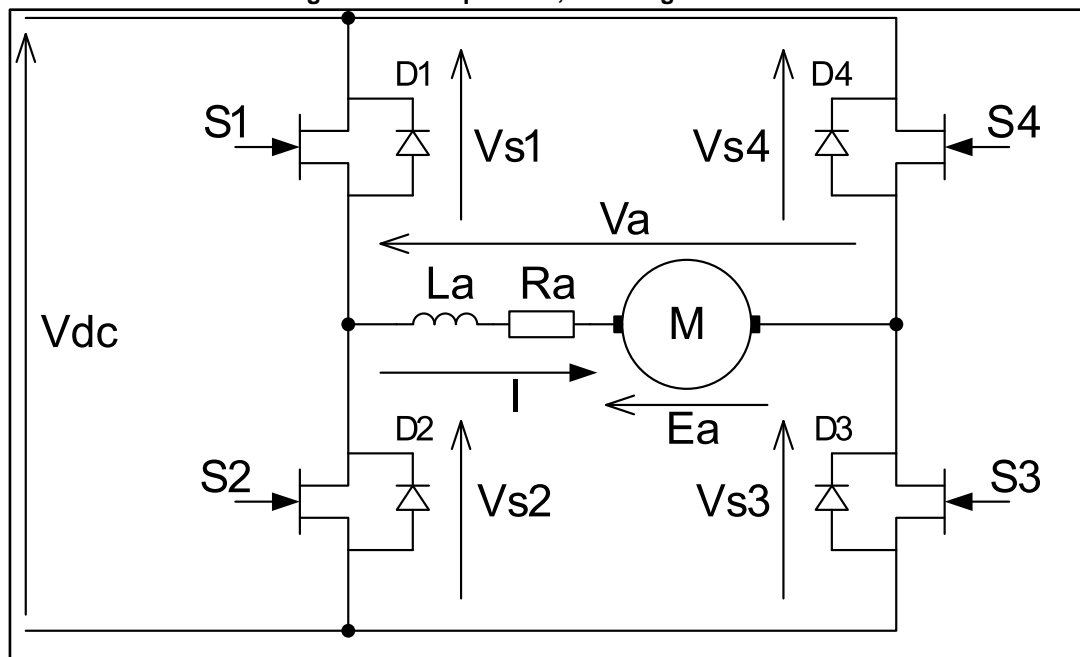
If motoring and regenerating operation are required with both directions of rotation then the full bridge converter of Figure 4 is required. Using this configuration allows the polarity of the applied voltage to be reversed, thus reversing the direction of rotation of the motor. Thus in a full bridge converter the motor current and voltage can be controlled independently. The motor voltage Va is given by:

$$Va = \frac{Vs2 - Vs1 + Vs4 - Vs3}{2}$$

Where Vs1 and Vs2 are controlled by switching S1 and S2, and Vs3 and Vs4 by switching S3 and S4. The usual operating mode for a full bridge converter is to group the switching devices so that S1 and S3 are always on simultaneously (clockwise rotation) and that S2 and S4 are on simultaneously (anticlockwise rotation).

If we have a separately excited DC motor and a DC constant voltage power supply such as a car battery, the speed of the motor does not vary much with the torque applied. If the steady state point is that shown in the figure below, we can significantly decrease the motor speed from ω_1 to ω_2 by adding a series resistor (Rext) to the armature circuit.

Figure 5: Speed regulation with external resistor
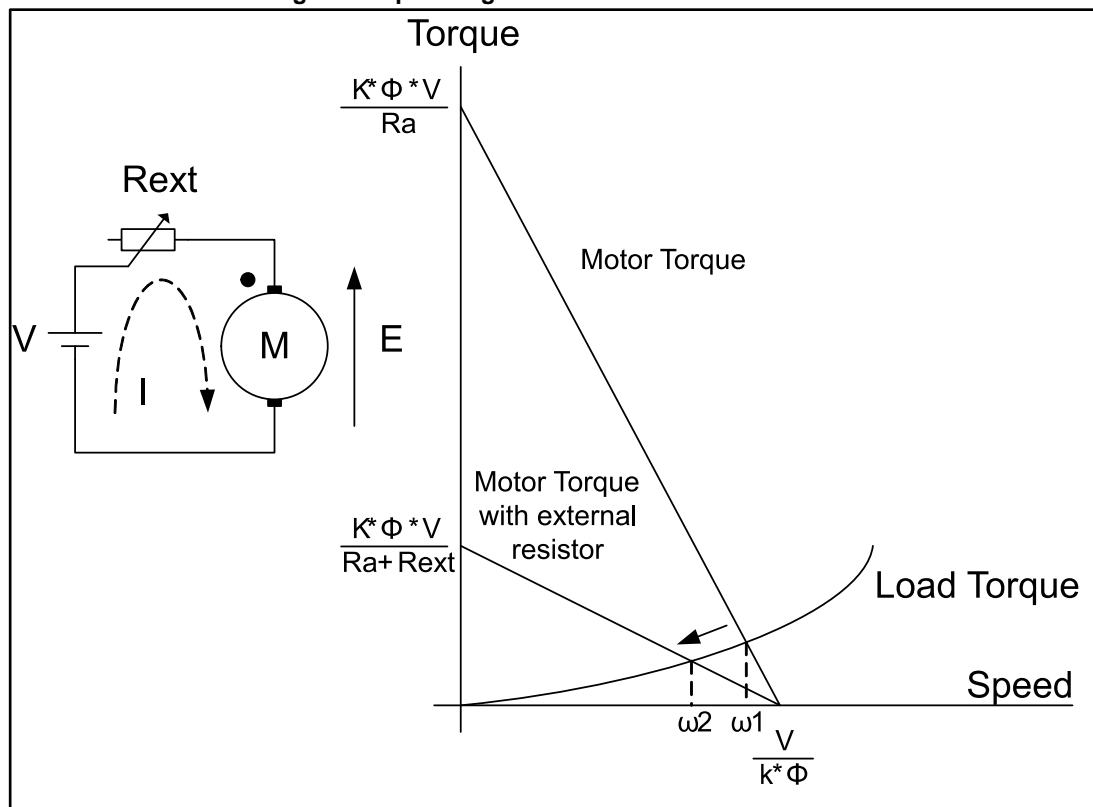
The series resistance also limits the current to start the motor, which can damage the brush contacts of the motor when it is too high. This method increases power dissipation (Joule effect in the resistance) and decreases system efficiency.

The alternative is to vary the supply voltage at the nominal flux of the motor Φ. When the supply voltage is varied continuously from -Vn_max to +Vn_max, the driving torque curve is shifted in a very wide range (*Figure 6: "Speed regulation by supply voltage variation"* gives a slight range of voltage variation).

Figure 6: Speed regulation by supply voltage variation
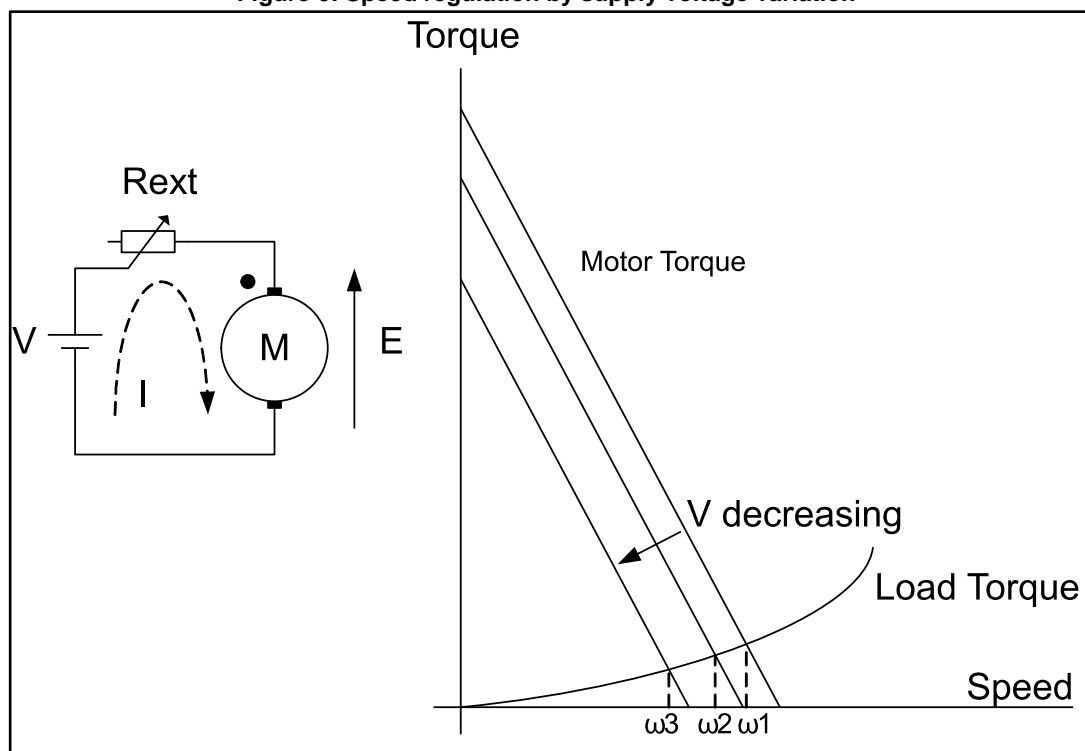
Whenever a higher speed is required, we must weaken the flux because we cannot increase the supply voltage. We know that the speed of the motor at zero torque is given by:

$$\omega_{m0} = \frac{V_{nmax}}{K \cdot \varphi}$$

The speed is therefore in inverse proportion to the flux. This method is complicated and only implemented in DC motor drives requiring precise torque regulation.

Returning to the speed variation issue, the most common method to vary the speed or the torque with a constant DC power supply is to "chop" the DC voltage via pulse width modulation (PWM) signals driving the Power MOSFETs of the H-bridge. PWM allows control of the average current delivered to the motor by switching the transistors on and off in rapid succession.

The motor is switched on and off thousands of times a second with the duty cycle controlling how much current is delivered to the motor. The switching is so fast that it appears to the motor (due to its inductance) that it is receiving a steady voltage. Therefore, the motor's output torque or the speed can be varied smoothly by controlling the duty cycle of the PWM signal.

In general, to achieve optimum efficiency in a PWM motor drive at the highest practical frequency, the motor should have an electrical time constant, t_a
(t_a = armature inductance (La)/armature resistance (Ra)) close to the duration of the applied waveform T. Consequentially, these low inductance, low inertia motors also exhibit very fast response with quite high torque.

Electrical time constants in the order of 100 µs allow these motors to be used with switching rates as high as 100 kHz, with typical drive circuits being operated at 10 kHz. Thus an appropriate choice of switching frequency and motor inductance ensures a high average motor current during each switching pulse.

Motor current control, and hence torque control, is achieved with a fixed frequency by varying the width of the applied pulsed waveforms, and hence the duty cycle.

A practical example of torque control is a motor driving a power window in a car, which requires an inrush current up to 40 A to be started. This may stress the driver and the motor, so it is advisable to limit the inrush current by applying a PWM to the driving transistors over the first tens of milliseconds with an increasing duty cycle (see *Figure 7: "Example DC motor soft start"*).

While the varying duty cycle (from 0% to 100%) clearly delays the starting of the motor, the resulting current curve is very smooth, like that of a simple inductive load. This operation is commonly known as a soft start.

The operating frequency should be not below 20 kHz in order to avoid motor noise.

Figure 7: Example DC motor soft start
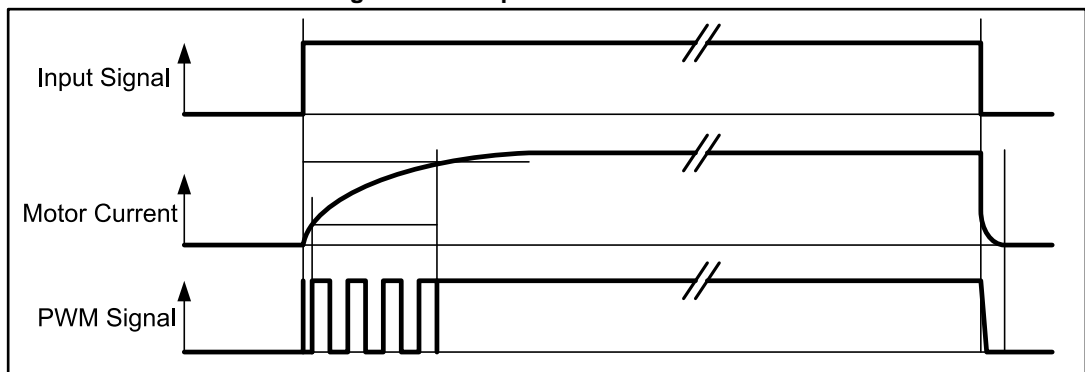
MOSFETs are preferred in half or full bridges due to their fast switching response and outstanding low resistance in linear mode compared to BJT transistors. P-MOSFETs can be used as high side switches of half or full bridges and N-MOSFETs for the low side switches.

A P-MOSFET switch has about three times the resistance of an N-MOSFET with the same dimensions, so N-MOSFETs with an integrated charge pump are normally adopted as high side switches. The charge pump needed to properly turn the N-MOSFET limits the PWM frequency on the high side switches (as already mentioned, this can be 20 kHz). For this reason, PWM is commonly applied to low side switches only.

1.1   DC Motors and main automotive applications

DC Motors are used in the automotive field for managing power up to 400W. While high reliability and robustness are required for the harsh automotive environment, motors must also be small and light to reduce car weight and consequently CO_2 emissions. Motors must also work with higher currents to produce suitable torque.

DC motors are traditionally built with wound electromagnets both on rotors and stator. There are three types of wound field DC motor:

- series wound: the field winding is in series with the armature winding; this produces a high torque, low speed motor
- shunt wound: the field winding is in parallel with the armature winding; this produces a low torque, high speed motor
- compound wound: the field winding is partly in parallel and partly in series; this produces a more balanced motor with a steady speed over a range of loads.

The most common type of DC motor used in cars is, however, the permanent-magnet DC motor (PMDC). They do not have a field winding on the stator frame, but rely on permanent

magnets to provide the magnetic field against which the rotor field interacts to produce torque. Compensating windings in series with the armature may be used on large motors to improve commutation under load.

Permanent-magnet motors are convenient in miniature motors to eliminate the power consumption of the field winding, and high energy magnets made with neodymium or other strategic elements may be used to minimize overall weight and size.

The table below indicates the approximate loads generally used in motor vehicle applications, all of which use PMDC types.

Table 1: Common Automotive DC motors characteristics

Application	Stall current (A)	Stall torque (Nm)	Current at max efficiency (A)	Max efficiency (%)	Max power (W)
Mirror adjuster	0.2	4.2	0.08	45.0	0.5
Heating HVAC	0.3	7.6	0.1	59.0	0.7
Headrest adjusters	1.3	37.0	0.7	62.0	3.9
Washer pump	14	61.0	2.8	61.0	41.0
Headlamp washer	40	190.0	7.0	65.0	127.0
Child safe lock	4.5	32.0	0.7	63.0	11.5
Door lock	12.0	268.0	1.9	66.0	33.0
Seat adjustment	15.0	456.0	2.9	62.0	45.0
Power window	30.0	418.0	5.6	61.0	77.0
Electric parking brake	100.0	624.0	13.0	67.0	260.0

In the last 20 years, the semiconductor component used for driving, protecting and controlling DC Motors in automobiles has increased immensely compared to traditional solutions based on electromechanical devices, due to:

- technology: as semiconductor technology advances, component costs are lowered;
- competition: carmakers increasingly use electronics for competitive advantage;
- reliability: semiconductor reliability improves remarkably with each new generation.

Improvements in silicon technologies have led highly integrated power, driving and control circuitry in a single chip, as well as drastic reductions in silicon area. This avoids the use of many components to perform the same function, allowing overall space saving and, in many cases, cost effective solutions. Innovative packages have also brought significant improvements to thermal dissipation and, consequently, power management.

There are many automotive applications where it is necessary to drive bi-directional DC motors and therefore use a complete H-bridge. An H-bridge is obtained using two switches connected to the (battery) positive voltage (high-side drivers) and two switches connected to ground (low-side drivers) in a typical "H" configuration.

Figure 8: "Window lift motor driven by relays" shows a conventional bi-directional DC motor application schematic, suitable for car window lifts or seat positioning, for example. The following list of basic components are used:

- a double relay switch with relevant drivers (SA, SB, DA, DB) in order to drive the motor in clockwise and anticlockwise mode
- a low side Power MOSFET for PWM driving (S)

- a freewheeling diode for re-circulation mode (D)
- an optical shift encoder in order to control the motor shaft angular position (or use an end point switch)
- a protection fuse on the battery line
- a filtering capacitor (C)
- a microcontroller

Figure 8: Window lift motor driven by relays
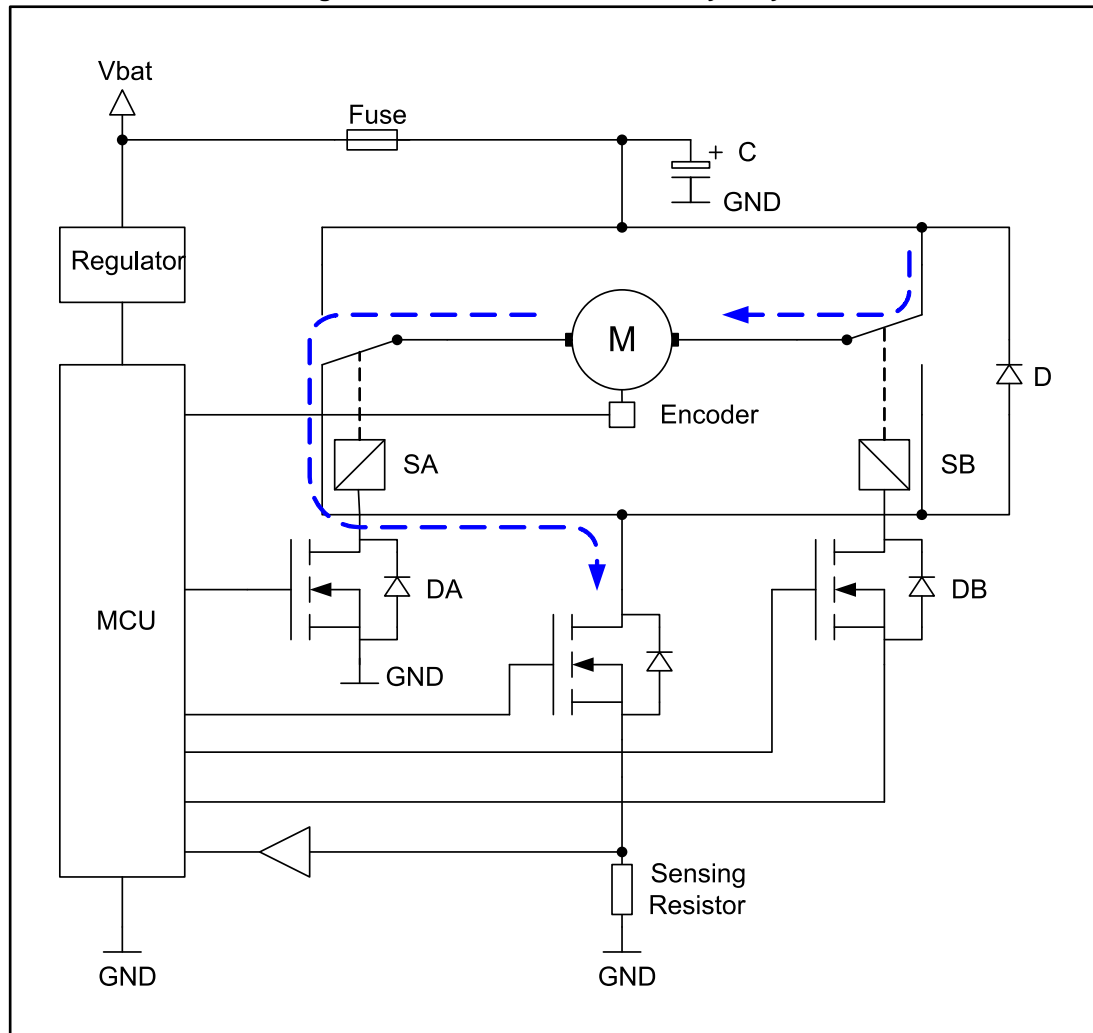
Speed or torque control to detect obstacles is especially necessary for safety (like anti-pinch in window lifts) in automotive applications. To achieve it, the following methods are normally used:

1. an external sensing resistor connected to GND to feed the motor current back to a microcontroller and thus its torque
2. an effect HALL sensor mounted on the motor to detect and feed back to the microcontroller a given speed variation during the motor rotation.

A rubber ring wrapping the upper edge of the window is also used and a force sensor signals the microcontroller when an obstacle is present. This method requires fine calibration of the rubber ring during the final testing in the car manufacturing plant.

The traditional approach has the following drawbacks:

- limited lifetime.
- clicking noise in the car
- space requirements

Finally, the alternative current sensing resistor causes a voltage drop on the battery line which must be minimized.

The semiconductor smart power approach is shown below with the following basic external components:

- an N-MOSFET on the battery line as a reverse battery protection switch
- resistors on microcontroller I/O
- pull up resistors (R_{pu}) on the diagnostic pins
- current sensing resistor (without any need for power adaptation)
- a filtering capacitor (C)
- The suitable H-bridge VN5H019A-E for windows lift (this particular device has an embedded charge pump (CP) pin which can directly drive the external N-MOSFET)
- microcontroller

Figure 9: Window lift motor driven by VNH5019A-E
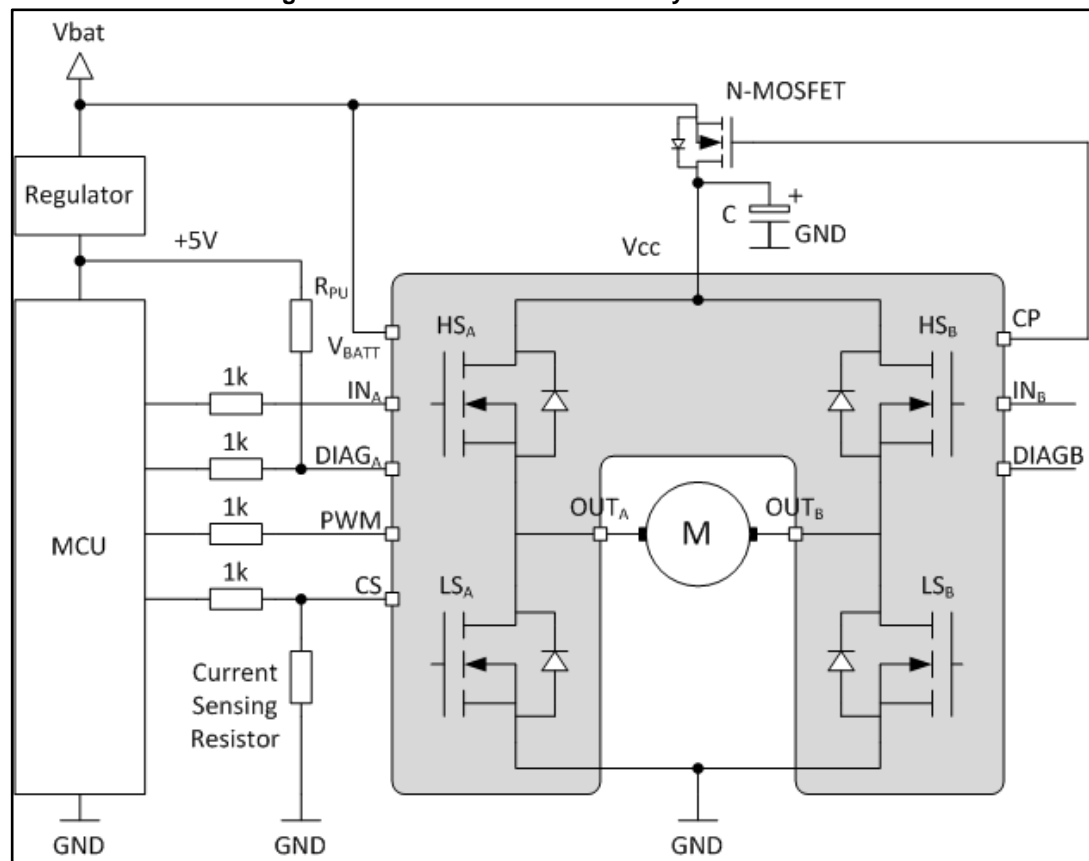
The power package hosts three separate chips (one double HSD chip and two LSD chips). The heat can be dissipated through three bottom slugs directly on the printed circuit board. The device has several embedded protection features of the latest generation VIPower H-bridges, including overload, short circuit and overvoltage protection and precise current sensing which removes the need for a sense resistor connected to the Power GND.

As already mentioned, the component count is heavily reduced and the overall system performance and reliability is clearly improved.

2 VIPower H-bridge features

The VIPower H-bridges are intended to drive a wide range of automotive DC motors. The devices incorporate a dual monolithic high-side driver and two low-side switches. Both families are designed using STMicroelectronics' proprietary VIPower™ M0 technology that allows the integration of a Power MOSFET with an intelligent signal/protection circuitry on the same die.

The main bridge categories are:

1. VN5770AKP and VN5772AK in an S0-28 full plastic package: the H-bridges feature an independent input for each PMOS gate (for a total of four IN pins to drive the motor in all possible directions)
2. VNH5200AS (in SO-16N), VNH5180A, VNH5050A (in PowerSSO-36 triple pad) and VNH5019A (in MultiPowerSO-30): the H-bridges only have two IN pins to drive the motor in all possible directions.

2.1 Main common VN577x and VNH5xxx features

Analogue current sense: the current sense block delivers a current proportional to the load current according to a known K ratio. The current delivered by the current sense circuit can be easily converted to a voltage through an external sense resistor connected on the CS pin, thus allowing continuous load monitoring and detection of abnormal conditions (see *Section 4: "Description of diagnostic"*).

Over-temperature: in case of overload/short to ground, the junction temperature rises until the thermal protection is triggered. It shuts down the concerned driver (HSD or LSD) as soon as the internal junction reaches 150 °C (minimum threshold). Normal operation is resumed when the junction temperature decreases about 7 or 15°C:

- VN577X: the overtemperature fault is signaled through the CS pin in the dual HSD or by the status or input pin in the LSD (see *Section 2.4: "VN577X features"*).
- VNH5XXX: the overtemperature fault is signaled through the ENx/DIAGx pin and the device is latched off.

Current limitation: the current is limited by the HSD driver to the current limitation value (in the VN577X, this is present in the HSD as well as in the LSD). In the VN5HXXX, the LSD features a shutdown current instead. The current limitation occurrence does not trigger a diagnostic flag.

Power limitation: (VNH5XXX, VN577x): in case of short to ground, as soon as the HSD junction temperature increases about 60 °C versus the temperature inside the control circuitry, the power limitation control is triggered, limiting the temperature gradient and shutting down the PMOS. This is followed by a subsequent turn on with a certain temperature hysteresis. The Power limitation occurrence does not trigger a diagnostic flag.

Undervoltage shutdown: the internal circuitry shuts down the device as soon as the voltage decreases below a certain threshold. The undervoltage occurrence does not trigger a diagnostic flag.

2.2 VNH5XXX features

The VNH5XXX are full-bridge motor drivers. The three dice (one double high side and two low sides) are assembled in triple-pad packages on electrically isolated lead frames. The block diagram of VNH5XXX H-bridge motor driver with analog current sense is shown below.

Figure 10: VNH5XXX block diagram
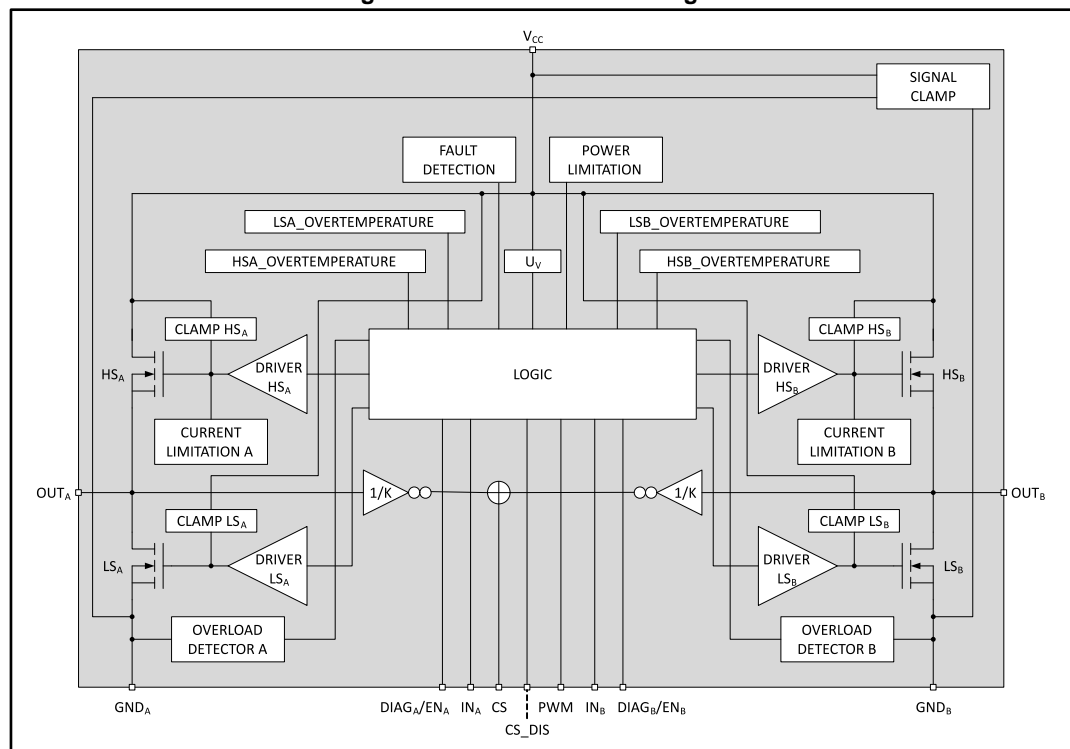
The VNH5XXX family includes the following devices:

1.   VNH5200AS in SO-16N plastic package with $R_{ds(on)}$ = 200 mΩ per leg
2.   VNH5180A in PowerSSO-36 Triple Pad with $R_{ds(on)}$ = 168 mΩ per leg
3.   VNH5050A in PowerSSO-36 Triple Pad with $R_{ds(on)}$ = 46 mΩ per leg
4.   VNH5019A In MultiPowerSO-30 with $R_{ds(on)}$ = 18 mΩ per leg

The input signals IN_A and IN_B can directly interface with the microcontroller to select the motor direction and the brake condition. $DIAG_A/EN_A$ or $DIAG_B/EN_B$ enable one leg of the bridge and provide diagnostic feedback. The CS pin allows monitoring the motor current by delivering a current proportional to its value when CS_DIS pin (not present in the VNH5200AS) is driven low or left open. The PWM signal (not present in the VNH5200AS), up to 20 KHz, allows controlling the speed of the motor in all possible conditions.

Short to Vcc latch: in case of output shorted to Vcc, as soon as the shutdown current of the low side driver is triggered, the device is turned off and latched.

Overvoltage shutdown: the internal circuitry shuts down the device when the supply voltage is higher than 27 V. The overvoltage occurrence does not trigger a diagnostic flag.

Cross conduction protection: the logic inside the dual HSD does not allow switching on both switches of the same leg (see *Section 5: "PWM operation and cross current protection (for VNH5XXX H-bridges)"*)

Shoot-through problem free: this protection is related to a typical dynamic issue of the bridge configuration. Referring to *Figure 10: "VNH5XXX block diagram"*, let's imagine the diagonal (HSA, LSB) is on, as soon as the LSB goes in PWM, a dv/dt is generated when the LSB is turned on. The slope dv/dt on the source of the HSB couples through the Cgs capacitance of the high side HSB. In this case, a current proportional to dv/dt flows through the gate/source capacitor of the high side HSB, charging it and turning it on. The result is a current flowing from battery to ground which is not limited by the motor; it creates extra power dissipation (especially at high frequencies) and can be hazardous for the devices.

The VNH5XXX devices with PWM capability are immune to this phenomena thanks to an optimized gate charge and a suitable internal dead time.

2.3 VNH5XXX general application schematic

The following figure illustrates the general application scheme for device connection to the microcontroller and to enable the basic functions.

Figure 11: Typical application circuit forVNH5XXX for DC to 20 kHz PWM operation

MCU I/Os protection: When negative transients are present on the Vcc line, the control pins are pulled negative to approximately -1.5 V (2 x V_{BE}) due to the internal path from the pin to ground (the parasitic bipolar transistor goes in saturation, see the figure below).
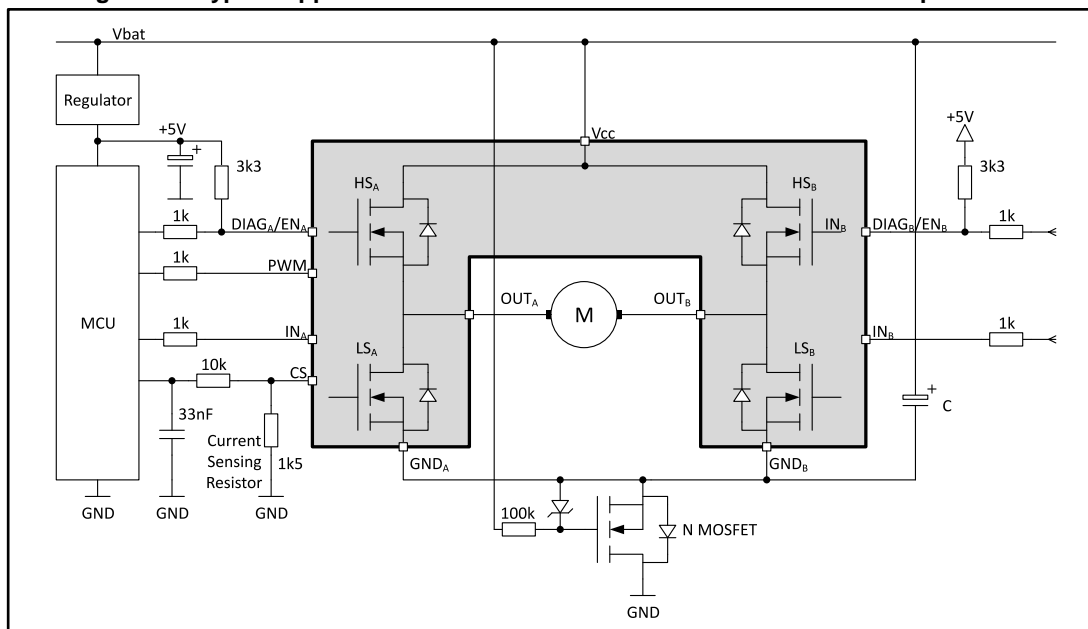
Figure 12: Simplified schematic in case of negative transients
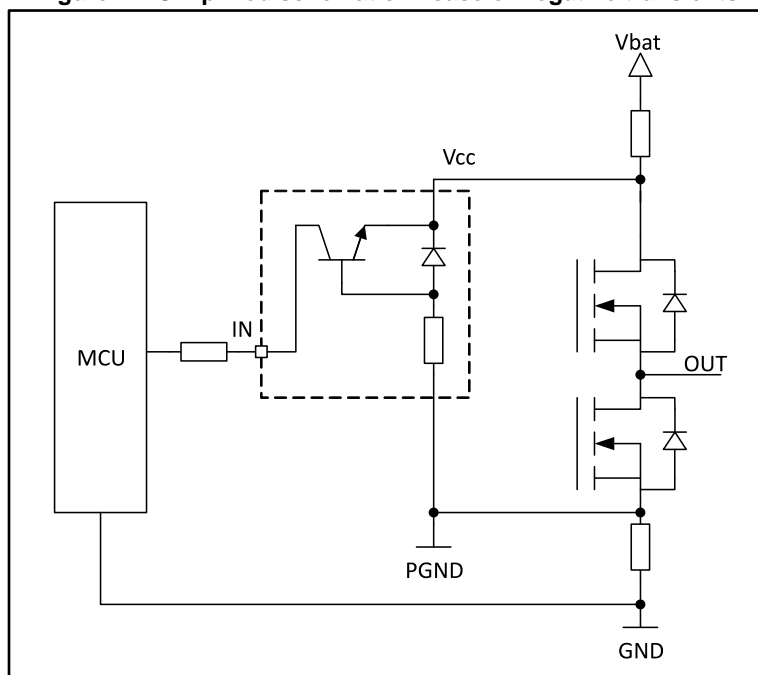
ST suggests connecting a resistor (Rprot) between the microcontroller and the device input in order to prevent the microcontroller I/Os pins from latching-up. The value of these resistors is a compromise between the leakage current of microcontroller and the current required by the HSD I/Os (input level compatibility) with the latch-up limit of microcontroller I/Os:

$$\frac{1.5}{I_{latchup}} \leq Rprot \leq \frac{(VOH\mu C - VIH)}{I_{IHmax}}$$

Example:

- Ilatchup > 20 mA
- VOHµC > 4.5 V
- VIH= 2.1 V
- IIHmax = 10µA
- 75 Ω ≤ Rprot ≤ 240 KΩ: recommended Rprot = 1 KΩ

IN$_A$ and IN$_B$: The input signals are used to select the motor direction and the brake condition. State INx =1 means the related HSx of the leg is turned on and the LSx is turned off (when INx=0, HSx is off and LSx is on). In all cases, a low level state on the signal PWM turns both the low side switches off.

PWM pin (not present in VNH5200AS) usage: The PWM pin can be driven with a frequency of up to 20 KHz. It allows controlling the speed of the motor by driving the low side drivers MOS. In all cases, a "0" on the PWM pin turns both LSA and LSB switches off. When PWM rises back to "1", LSA or LSB turn on again depending on the states of the input signals IN$_A$ and IN$_B$.

Blocking capacitor: The value of the capacitor (C) depends on the application conditions and defines voltage and current ripple on supply line at PWM operation. The stored energy of the motor inductance may fly back into the blocking capacitor if the bridge driver goes into the 3-state. This causes a hazardous overvoltage if the capacitor is not big enough. Generally, 500 µF per 10 A load current is recommended.

DIAG$_X$/EN$_X$: in normal operating conditions, this pin is considered as an input by the device; it must be externally pulled high. As DIAGX/ENX are set from low to high, after a power on reset delay time of 2 µs, the logic with its relevant protection is enabled.

When a fault occurs, the faulty leg of the bridge is latched off and the corresponding DIAG$_X$/EN$_x$ pin is pulled low to indicate the fault. To turn on the respective output (OUT$_x$) again, the input signal must rise from low to high level (see *Section 4.5.2: "Unlatching of VNH5XX bridges"*).

CS_DIS (not present in VNH5200AS): a logic level high on CS_DIS pin sets the current sense pins of the device to a high-impedance state, thus disabling current monitoring. This feature allows the multiplexing of the microcontroller analog inputs by sharing the sense resistance and the ADC line among different devices.

2.4 VN577X features

VN5770AKP and VN5772AK, featuring an R$_{on}$ of 280 mΩ and 100 mΩ per leg respectively, are two devices made up of three independent monolithic chips housed in a standard SO-28 package. The devices are suitable to drive a DC motor in a bridge configuration or used as a quad switch for any low-voltage application.

The double high-side integrates advanced protective functions such as load current limitation, inrush and overload active management by power limitation, overtemperature shut-off with auto-restart. An analog current sense (CS) pin delivers a current proportional to the load current (according to a known ratio) and indicates overtemperature shutdown of

the relevant high-side switch by pulling to V_{senseH} (value given in datasheets) the current sense pin.

The low-side switches integrate the thermal block that protects the chip from overtemperature and short circuit conditions. Output current limitation protects the low-side switch in case of overload or short circuit conditions.

In H-bridge configuration, demagnetization of inductive loads is achieved at turn-off through the Power MOS body diodes.

For the VN5772AK (STATUS 3 and STATUS 4 pins), fault feedback for overtemperature shutdown of the low side switch is indicated by the status pin (open drain digital diagnostic pin). For the VN5770AK (in which no status pins are present), when the overtemperature event on one low side occurs, the internal impedance of the corresponding low side driver is reduced and the pin draws the Igf fault sink current value indicated in the datasheet.

Figure 13: VN5772AK block diagram
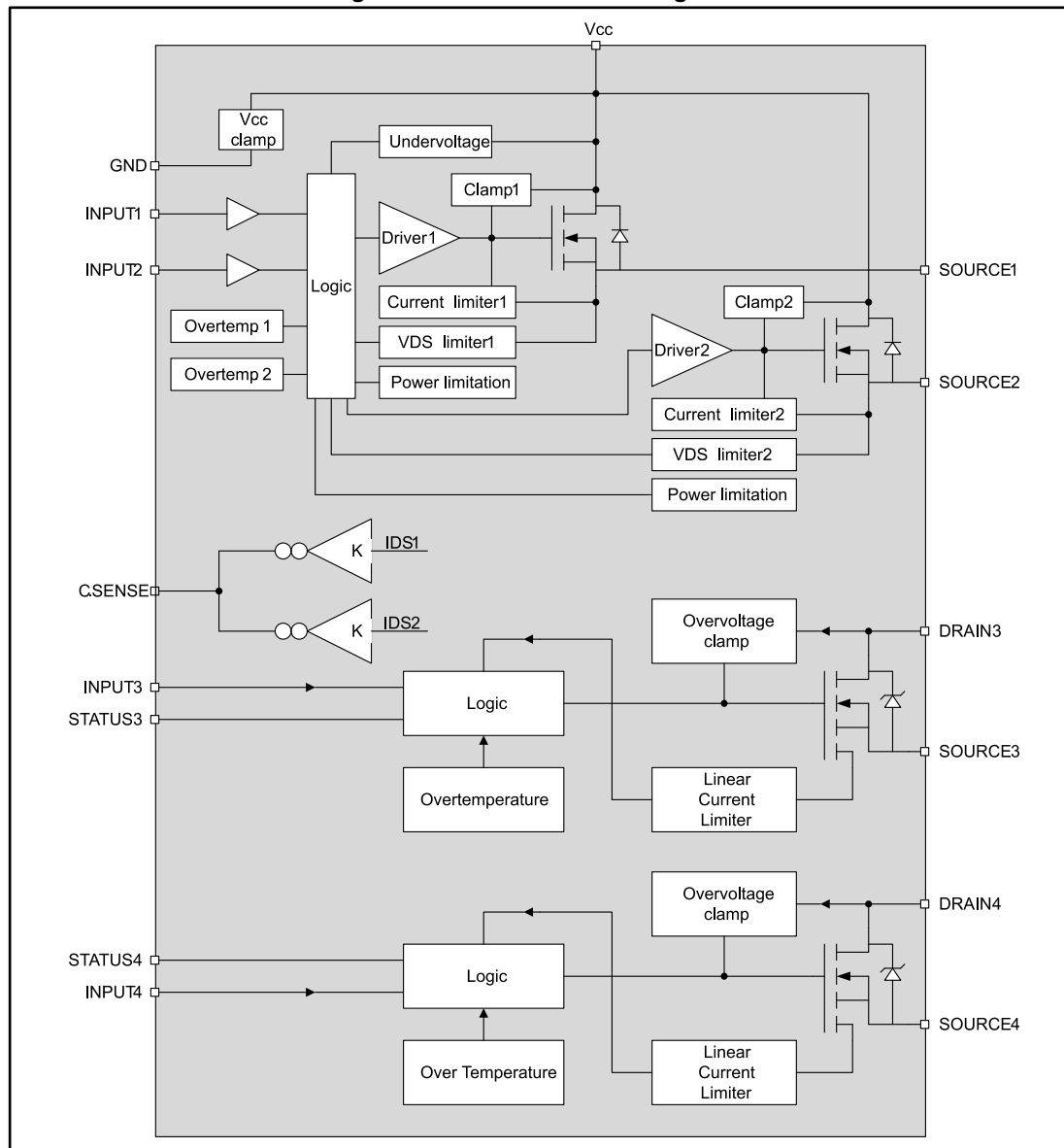
2.5 VN577X general application schematic

The figure below shows the general application scheme to connect the device to the microcontroller and enable the basic functions.

Figure 14: Typical application circuit
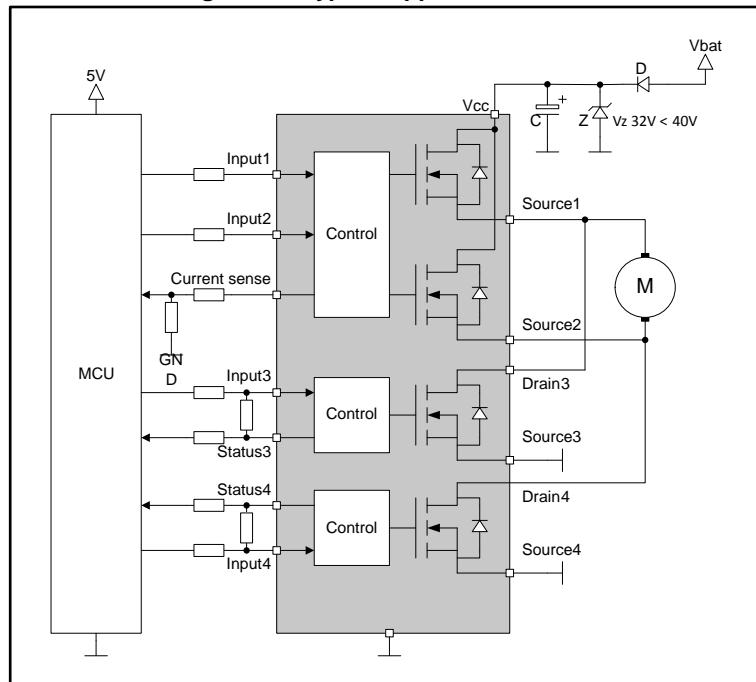
MCU I/Os protection: when negative transients are present on the VCC line, the control pins are pulled negative. ST suggests inserting a resistor (Rprot) in line to prevent the microcontroller I/O pins from latching up. The value of these resistors is a compromise between the leakage current of the microcontroller and the current required by the HSD/LSD I/Os (input level compatibility) with the latch-up limit of the microcontroller I/Os:

$$HSDI/O \rightarrow \frac{1.5}{I_{latchup}} \leq Rprot \leq \frac{(VOH\mu C - VIH)}{I_{IHmax}}$$

Example:

- Ilatchup > 20 mA
- VOHµC > 4.5 V
- VIH > 2.1 V
- IIHmax = 10 µA
- 75 Ω ≤ Rprot ≤ 240 KΩ: recommended Rprot = 10 KΩ

$$LSDI/O \rightarrow \frac{0.75}{I_{latchup}} \leq Rprot \leq \frac{(VOH\mu C - VINTH)}{I_{ISSmax}}$$

Example:

- Ilatchup > 20 mA
- VOHµC > 4.5 V
- VINTH> 3.5 V
- IISSmax =110µA
- 37.5 Ω ≤ Rprot ≤ 9 KΩ: recommended Rprot = 1 KΩ

INx: these input signals are used to turn on/off the selected switch.

Status: this pin is considered an open drain output, which must be externally pulled high through a resistor that limits the current below the ISTAT (see absolute max. rating). In a thermal shutdown event, the pin is tied low.

Blocking capacitor: to prevent hazardous overvoltage at the circuit supply terminal (Vcc), a capacitor (C) limits the voltage overshoot. Generally, 500 µF per 10 A load current is recommended. Alternatively, Zener protection (Z) can be deployed.

3 Protection of H-bridges

The VIPower M0-5 bridges are equipped with smart circuitry that protects them from a series of events that could compromise or even damage the application or the device itself. The following tables summarize these protections available for each series.

Table 2: Protections of VNH5XXX devices

Event	VNH5200A	VNH5050A	VNH5180A	VNH5019A
Undervoltage shutdown	Yes	YES	Yes	Yes
Overvoltage shutdown	No	Yes	No	Yes
ISO pulses	Yes	Yes	Yes	Yes
Load disconnection	Yes	Yes	Yes	Yes
Vcc disconnection	Yes	Yes	Yes	Yes
Ground disconnection	Yes	Yes	Yes	Yes
Overload	Yes	Yes	Yes	Yes
Short circuit	Yes	Yes	Yes	Yes

Table 3: Protections of VN577X devices

Event	VN5770AKP	VN5772AK
Undervoltage shutdown	Yes	Yes
Overvoltage shutdown	No	No
ISO pulses	Yes	Yes
Load disconnection	Yes	Yes
Vcc disconnection	Yes	Yes
Ground disconnection	Yes	Yes
Overload	Yes	Yes
Short circuit	Yes	Yes

3.1 Undervoltage protection

This function shuts down the device when the battery voltage is lower than V_{USD}: the Vbat < V_{USD} condition (V_{USD} given in the datasheet) generates an active high signal that acts directly on both LS and HS gates, turning them off.

Figure 15: VNH5050 supply voltage ramp down Ch1=Vin, Ch2=Ven, Ch3=Vbatt, Ch4=Iout
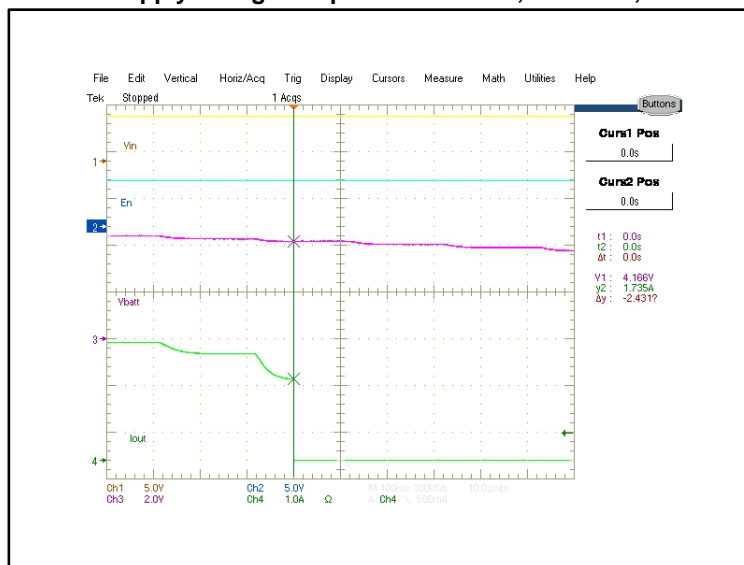
The goal of this protection is to validate the internal supply as soon as it is appropriate for supplying all the blocks. The device recovers normal behavior as soon as Vbat returns to V_{USD} + $V_{USDhyst}$ ($V_{USDhyst}$ given in the datasheets). The undervoltage condition is not considered a fault condition and is not detected by the diagnostic.

3.2 Overvoltage shutdown protection

This function shuts down the device when the battery voltage is higher than Vov.

Figure 16: VNH5050 supply voltage ramp up Ch1=Vin, Ch2=Ven, Ch3=Vbatt, Ch4=Iout
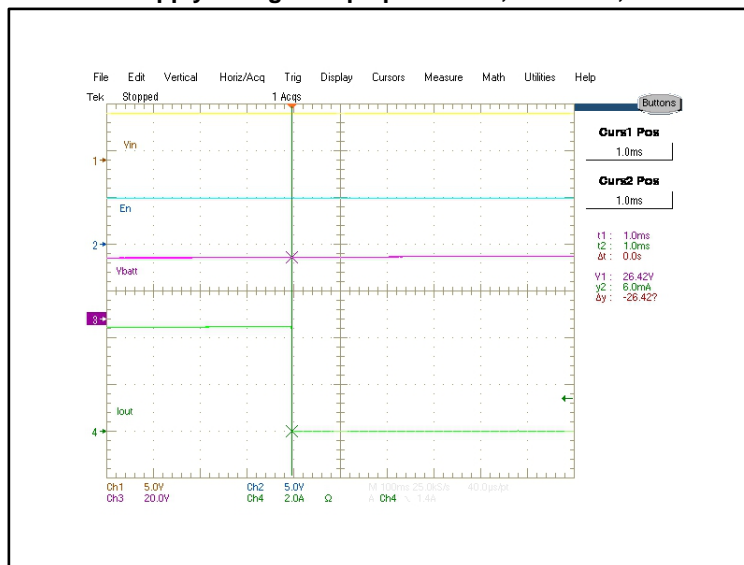
The goal of this protection is to avoid motor operation under anomalous supply voltage conditions so it protects the motor as well as the device.

At the voltage threshold of Vcc pin of V_{OV} = 27 V typical, the driver shuts down the device. Normal behavior is recovered as soon as the supply pin voltage drops again. The overvoltage condition is not considered a fault condition and is not detected by the

diagnostic.Only the VNH5050A-E and VNH5019A-E have the overvoltage shutdown protection. The other devices have internal clamping at a given clamp voltage value.

3.3 Protections against transients on battery

ISO tests measure the transient emission on supply lines and device immunity against such transients. Components or systems are tested under expected device operating conditions.

The suggested test levels and results are shown in the following tables.

Table 4: Standard ISO 7637-2:2004(E) 12V system test levels for VNH5XX

ISO 7637-2: 2004(E) Test pulse	Test levels[1]		Number of pulses or test times	Burst cycle/pulse Repetition time		Delays and impendance
	III	IV				
1	-75 V	-100 V	5000 pulses	0.5 s	5 s	2 ms, 10 Ω
2a	+37 V	+50 V	5000 pulses	0.2 s	5 s	50 μs, 2 Ω
3a	-100 V	-150 V	1 h	90 ms	100 ms	0.1 μs, 50 Ω
3b	+75 V	+100 V	1 h	90 ms	100 ms	0.1 μs, 50 Ω
4	-6 V	-7 V	1 pulse			100 ms, 0.01 Ω
5b[2]	+65 V	+87 V	1 pulse			400 ms, 2 Ω

Notes:

[1]The test levels must be considered in reference to V_{CC}=13.5 V, except for pulse 5b

[2]Valid in case of external load dump clamp: 40V max. referred to ground

Table 5: Standard ISO 7637-2:2004(E) results for VNH5XX

ISO 7637-2: 2004 (E) Test pulse	Test level results[1]	
	III[2][3]	IV[2][3]
1	C	C
2a	C	C
3a	C	C
3b	C	C
4	C	C
5b[4]	C	C

Notes:

[1]The test levels must be considered in reference to Vcc=13.5 V for pulse 5b

[2]C=all the device functions performed as designed after exposure to disturbance

[3]E= One or more device functions did not perform as designed after exposure to disturbance and cannot return to proper operation without replacing the device

[4]Valid in case of external load dump clamp: 40V max. referred to ground

The V_{CC} to GND structure typical of VNH5XXX is commonly protected against high voltage transients with a special circuit shown below.

Figure 17: ISO pulses protection circuits (relevant to one leg only)
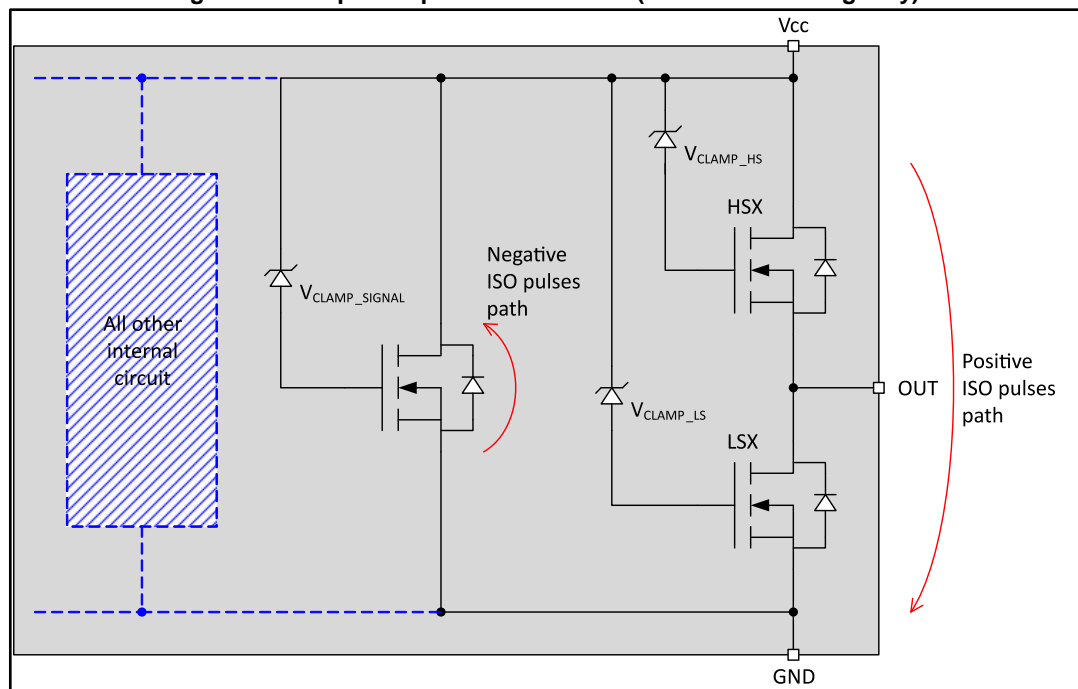
- The positive ISO pulses pass through the HSx + LSx series, switched on when the voltage on Vcc exceeds VCLAMP_HS = VCLAMP_LS voltage. The LSD is forced to work in the ohmic region, while the HSD is forced to work in the linear region. HSx is therefore subject to the highest dissipation.
- The negative ISO pulses pass through the intrinsic body diode of the MOSFET MGND that is properly sized.

The VCLAMP_SIGNAL is designed to be higher than VCLAMP_HS+LS (by about 2 V).

The waveforms relevant to ISO 7637-2:2004 (E) pulses type 1 (negative peak) and 2a (positive peak) are shown below. *Figure 19: "Test setup for ISO pulse 5b (load dump) applied to a VNH5XXX device"* gives the test setup and plots for the load dump pulse. The H-bridges withstand all of these disturbances.

Figure 18: ISO pulses waveforms 1 and 2a applied to a VNH5XXX device
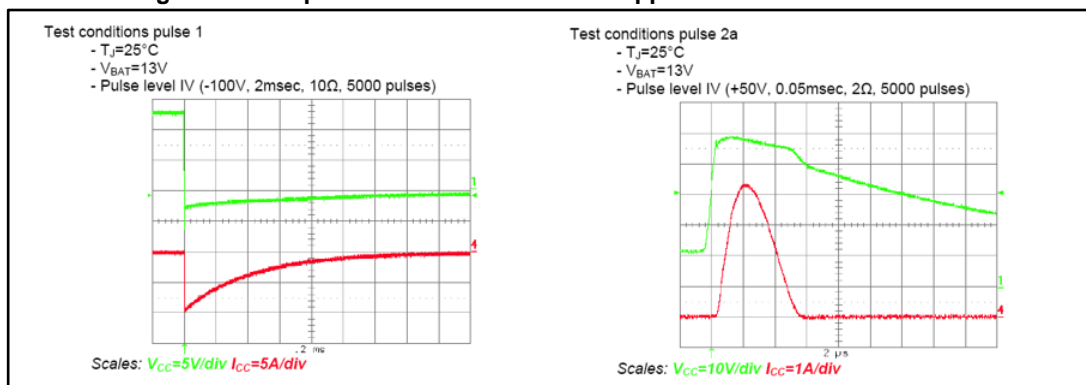
Test setup pulse 5b:

- V_{CC} connected to the power supply and pulse generator
- Source high side A and B shorted to drain low side A and B respectively
- V_{MOV} = 41 V

- R$_{LOAD}$ = 2 Ω
- Test condition of load dump test is with INx, PWM, ENx/DIAGx, CS and CS_DIS pins all set floating

Figure 19: Test setup for ISO pulse 5b (load dump) applied to a VNH5XXX device
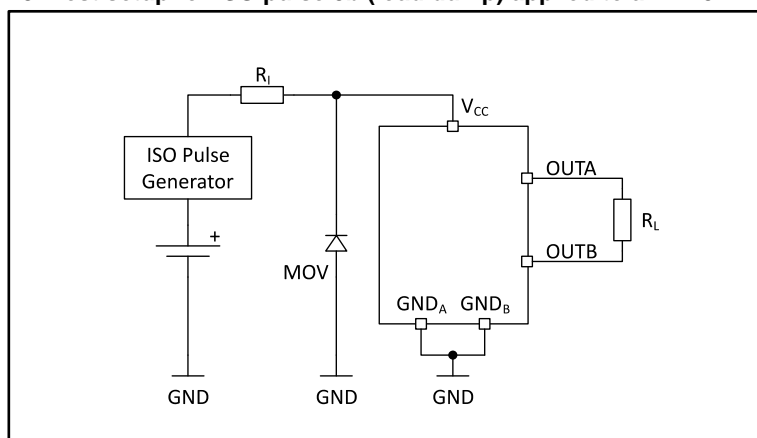
Figure 20: Example waveforms for ISO pulse 5b (load dump) applied to a VNH5XXX device
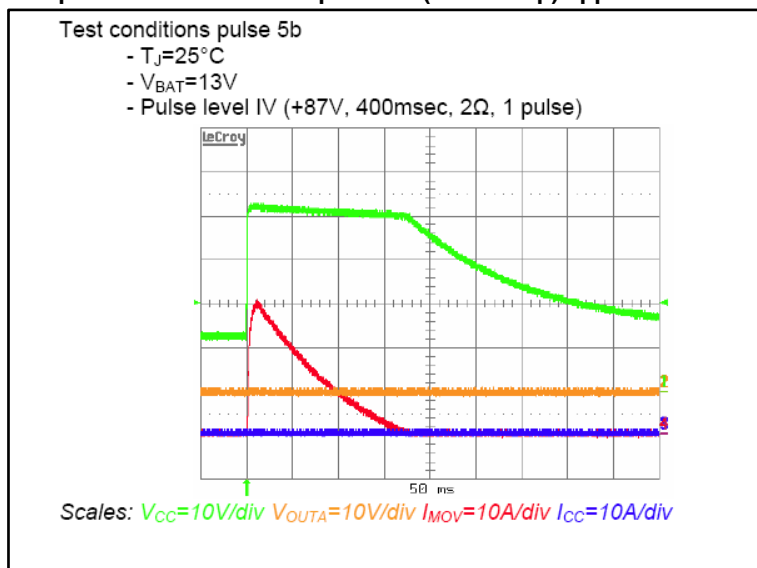
3.4 Battery disconnection and GND disconnection

In case of device GND pin loss or supply line loss, the device switches off immediately (see *Figure 21: "GND loss and battery loss"*). As the H-bridge power elements may enter the tri-state, the eventual residual motor energy can recirculate and charge the capacitor on the V$_{CC}$ pin, which must be dimensioned appropriately (see recommendations for V$_{CC}$ blocking capacitor in *Section 2.3: "VNH5XXX general application schematic"* and *Section 2.5: "VN577X general application schematic"*).

Figure 21: GND loss and battery loss

Scales: V_{INA}=10V/div, V_{GND} = 10V/div, V_{SENSE} = 10V/div, I_{OUT} = 10A/div
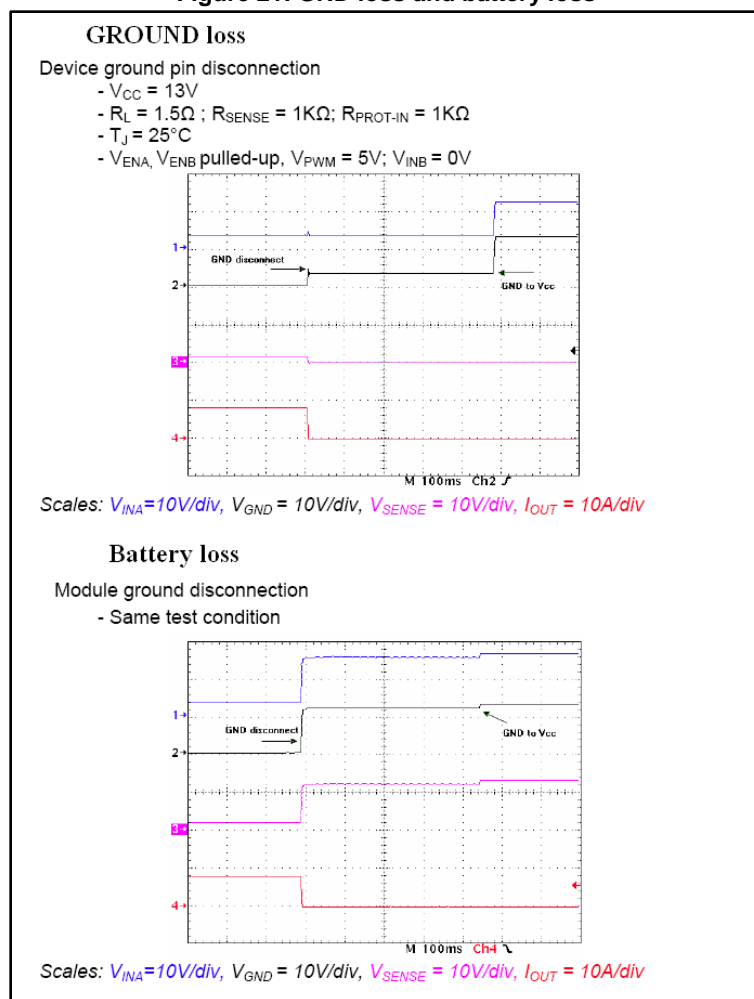
3.5 Short OUTPUT to GND protection

3.5.1 VNH5XXX family

In case of short OUTPUT to GND, the high side of the VNH5XXX device initially enters current limitation condition, followed by the power limitation condition if the short persists.

Initially, it limits the motor current to the I_{LIM_H} value (in the datasheet). In this condition, the high side Power MOS works in the saturation region and dissipates a lot of power (high voltage and high current are simultaneously present). The power limitation block in the high side chip then monitors the difference between case temperature and the junction temperature. In case of hard short circuit, the CS pin enters high impedance.

If the high-side driver junction temperature exceeds the case temperature by approximately 60 °C, the high side driver is switched off. As soon as the high-side driver junction temperature drops below a certain value (a hysteresis is implemented), the high side driver is switched on again.

The power limitation is designed to limit the fast thermal transients in the device, which benefits device lifetime.

The power limitation condition is not detected by the diagnostic. If the short circuit persists, the temperature of the device increases up to the thermal shutdown threshold and the device is switched off, the diagnostic enters the low level and the device latches.

Figure 22: Power limitation event in VNH5XXX
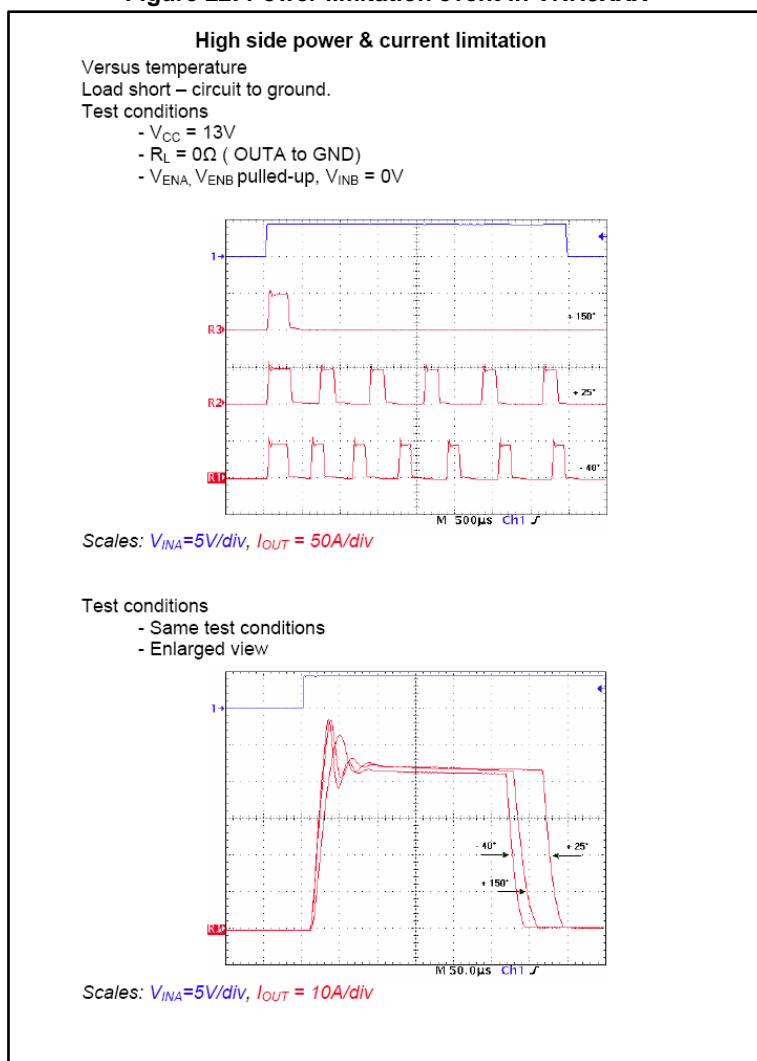
The figure above shows the power limitation condition at several temperatures; if the device enters power limitation when it is already hot (150 °C), it reaches the thermal shutdown threshold more rapidly (as per the first plot where only one current pulse occurs at 150 °C and the device is latched off).

3.5.2   VN577X family

In a short OUTPUT to GND event, the device enters the current limitation condition followed by the power limitation condition, if the short persists.

Initially, it limits the motor current to the I_{LIM_H} value (in the datasheet) and then limits the power dissipation of the high side driver inside a safe range. In a hard short circuit event, the CS pin enters high impedance, otherwise the CS signal mirrors the output current signal.

If the short circuit is not removed, the temperature of the device rises up to the high side thermal shutdown threshold (TTSD in the datasheet) and the device is switched off, the CS

voltage is fixed at the V_{SENSEH} value and the temperature drops down to the T_R value (reset temperature given in the datasheet). At this point, the device is able to switch on again, but the current level is fixed at the I_{LIM_L} value (in the datasheet). This avoids overstressing the Power MOS in a permanent short circuit event. This behavior is illustrated below.

Figure 23: VN577X waveforms relevant to a hard short to GND event
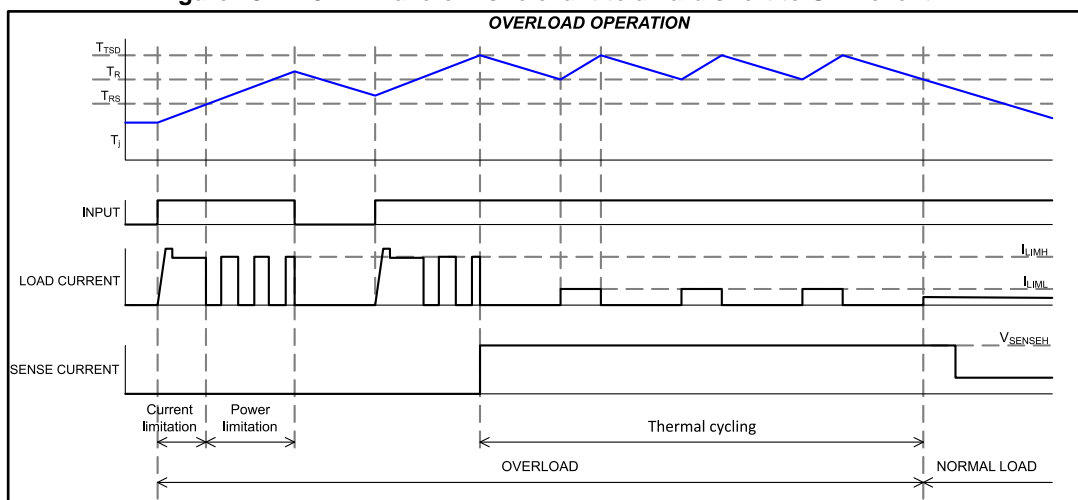
3.6   Short to V$_{CC}$ protection

3.6.1   VNH5XXX family

In a short to Vcc event, the device has a double protection depending on whether the short circuit is hard or resistive.

In a hard short circuit (resistance in the order of a few milliOhms), the current flowing through the low side MOSFET exceeds the shutdown current I_{SD_LS}, the device is switched off (with a T_{SD_LS} filtering time given in the datasheet) and the fault condition is detected by the diagnostic. The DIAGx/ENx pin of the faulty leg is pulled low. The device latches (see *Figure 24: "VNH5XX short to Vcc event"*)

In a resistive short circuit, if the current of the low side MOSFET doesn't reach the I_{SD_LS} (given in the datasheets), the temperature rises and reaches the low side thermal shutdown. Also in this case, the device is switched off and the fault condition is detected by the diagnostic. The DIAGx/ENx pin of the faulty leg is pulled low; the device latches.

Figure 24: VNH5XX short to Vcc event

Scales: V_{PWM}=5Vdiv; V_{ENB} = 5V/div, V_{OUTB}=10Vdiv, I_{CC} =20A/div,
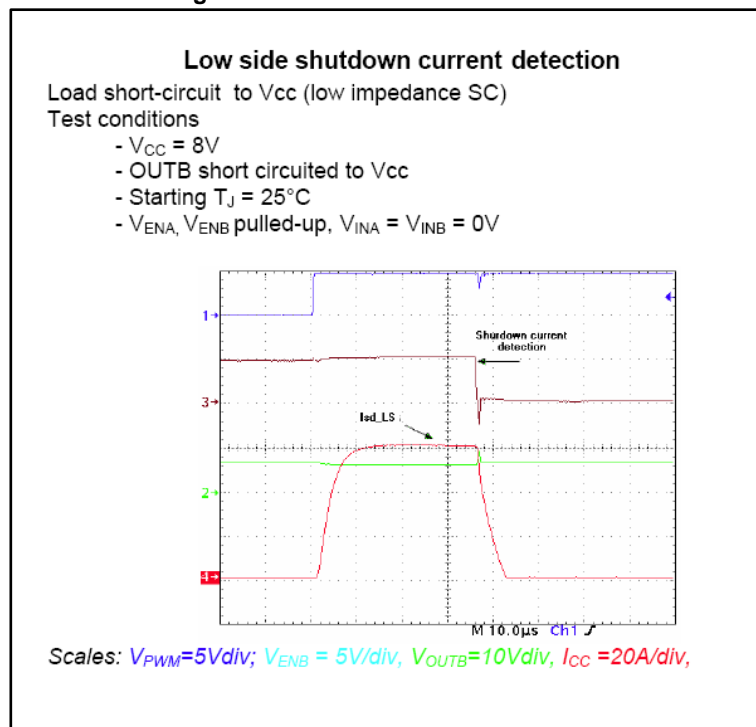
3.6.2 VN577X family

In a short to Vcc event, the device has the same protection as in short to GND. The low side MOSFET is initially protected by the current limitation phase and then by the power limitation phase (in the VN5772AK only) and finally by the thermal cycling phase. The behavior is similar to that shown in *Figure 23: "VN577X waveforms relevant to a hard short to GND event"*. For the VN5772AK device, the status pin is pulled low, indicating a thermal shutdown event.

3.7 Short circuit across the load

For VNH5XX bridges, in a hard short circuit across the load, the protection is from the overload current shutdown on the low side (which is shut down with filtering time t_{SD_LS} for VNH5XXX, in the datasheet); if the short across the load is not absolute enough to reach the I_{SD_LS} value, the protection is performed via high side current limitation and power limitation.

For VN577X bridges, a short circuit across the load can trigger protections in the low side and/or high side switches.

Figure 25: VH5XXX waveforms relevant to a sort circuit across the load

Load short circuit event. Various protection mode

I_{SD_LS} detection ("pure" short circuit)
Test conditions
- V_{CC} = 13V
- R_L = 1.5Ω then 0Ω
- Starting T_J = 25°C
- $V_{ENA,}$ V_{ENB} pulled-up, V_{INA} = V_{PWM} = 5V; V_{INB} = 0V

Scales: V_{ENB} = 5V/div V_{CC}=5Vdiv, I_{CC} =50A/div,

Thermal shutdown detection (resistive load short-circuit)
Test conditions
- Same test conditions
- R_L = 5Ω then 0Ω

Scales: V_{ENA} = 5V/div V_{CC}=5Vdiv, I_{CC} =20A/div,
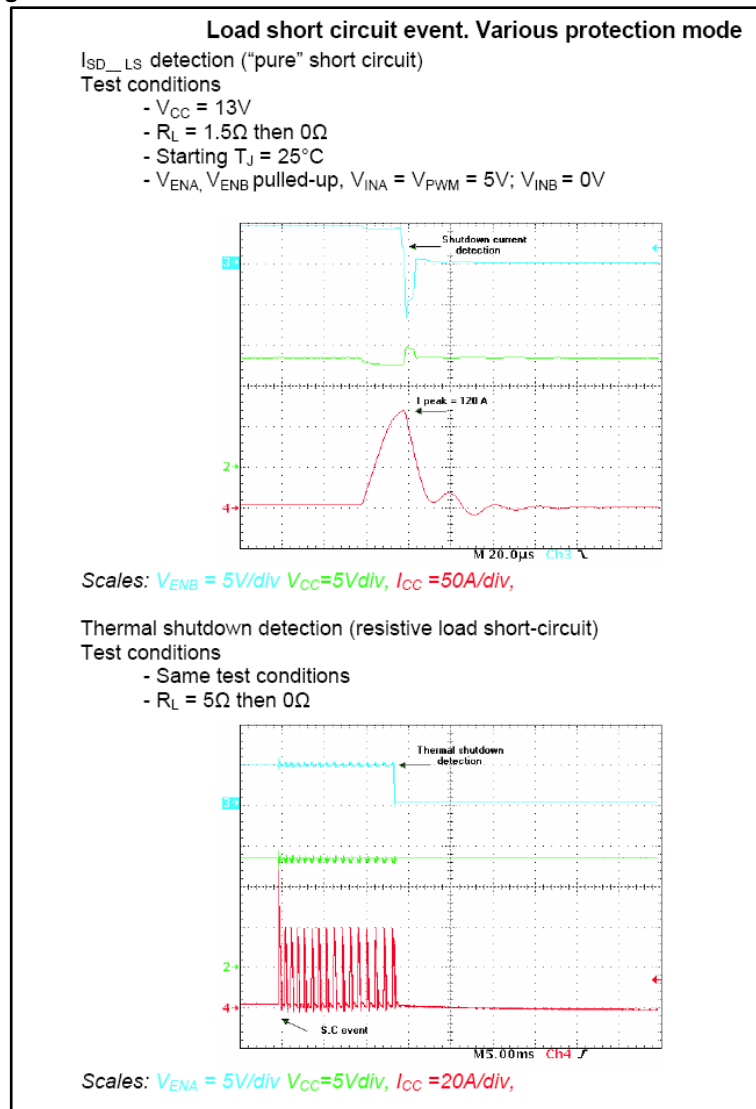
3.8 Protection against reverse battery

A universal problem in automotive applications is the threat of damage when an end user inserts the battery backwards.

Users of battery powered equipment expect safeguards to prevent damage to the internal electronics in the event of reverse battery installation. These safeguards can be either mechanical (use of special connectors) or electronic. Battery powered equipment designers and manufacturers must ensure that any reverse current flow and reverse bias voltage is low enough to prevent damage to the equipment's internal electronics. To provide these electronic safeguards, manufacturers typically choose either a diode or transistor for reverse battery protection.

In a power bridge configuration, the device sinks a reverse current through the body diodes of the power MOSFETs that can destroy the device. Specific protection is required to avoid exceeding the device's reverse capability.

To overcome this problem, the following silicon-based solutions are possible:

1. a) Schottky diode D connected to Vcc pin
2. c) N-channel MOSFET on GND pin
3. d) P-channel MOSFET on Vcc pin
4. e) Dedicated Reverse FET on Vcc line.

The VNH5019A-E device features a charge pump output pin which can drive an N-channel MOSFET for reverse battery protection on the Vcc line, thus avoiding the use of a P-channel MOSFET (a P-channel MOSFET is generally larger than an N-channel MOSFET for the same $R_{ds(ON)}$).

3.8.1 Schottky diode solution

When the battery is installed backwards, the diode reverse–biases and no current flows. The advantage of the Schottky diode is the very low voltage drop, but it is more expensive than a standard diode.

The following parameters can be used to guide component selection:

*   the average current used by the electronic module
*   the maximum repetitive peak reverses voltage VRRM
*   the maximum ambient temperature Tamb

The following inequality must apply in all cases:

$$T_{amb} + R_{th} \cdot P < T_{jmax}$$

$$P = V_{TO} \cdot I_F(AV) + rd \cdot I^2_F(RMS)$$

where:

I_F (AV) = maximum average forward current

I_F (RMS) = RMS forward current

Rth = thermal resistance (junction - ambient) for the device and mounting in use

rd = small signal diode resistance

V_{TO} = is a constant (in V) associated with the physical diode characteristics

If the losses at high output power levels cannot be handled by one diode, more devices must be connected in parallel. One important consideration is the peak reverse voltage limit of the diode VRRM = 100 V, which seems a good compromise if we refer to the ISO 7637-2: 2004 (E) pulse 1 Test levels IV.

The direct diode reverse battery protection can also be replaced with a simple fuse. However, this fuse will blow on battery inversion and the module will need to be replaced or repaired.

3.8.2 N-channel MOSFET solution

The N-channel MOSFET is connected so that its gate is driven directly by the battery voltage and its drain is connected to ground. It is normally ON, but a reverse battery event switches it OFF (because $V_{GS} < 0$) and protects the H-bridge.
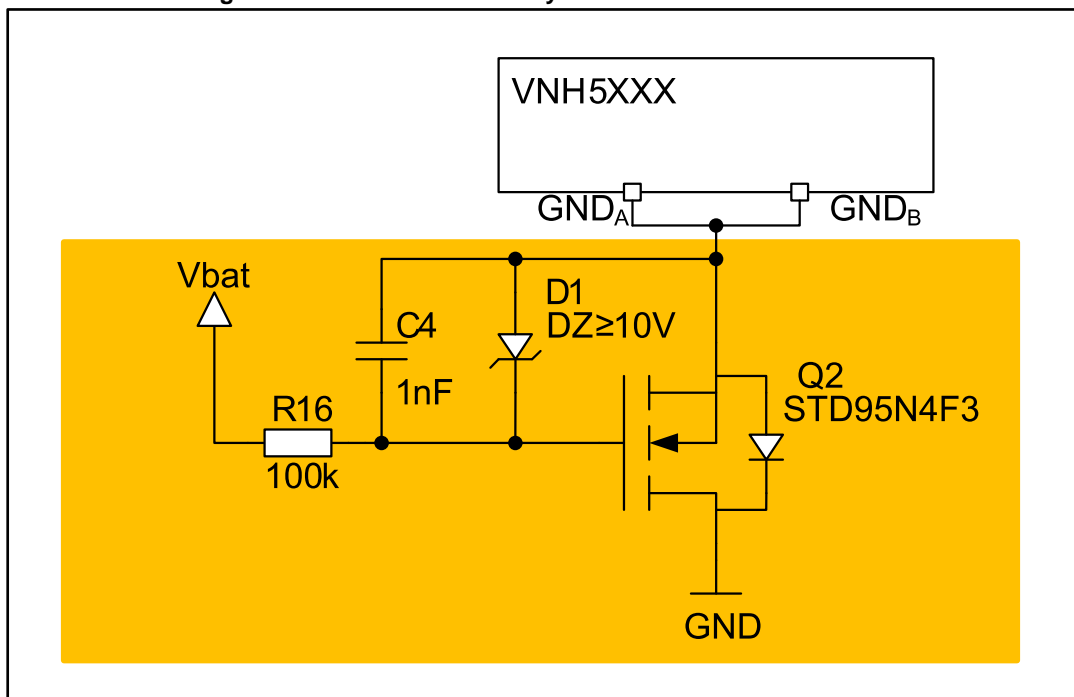
The following figure shows an example with a VNH5XXX device.

Figure 26: Reverse battery protection of a VNH5XX with an N-MOSFET on GND
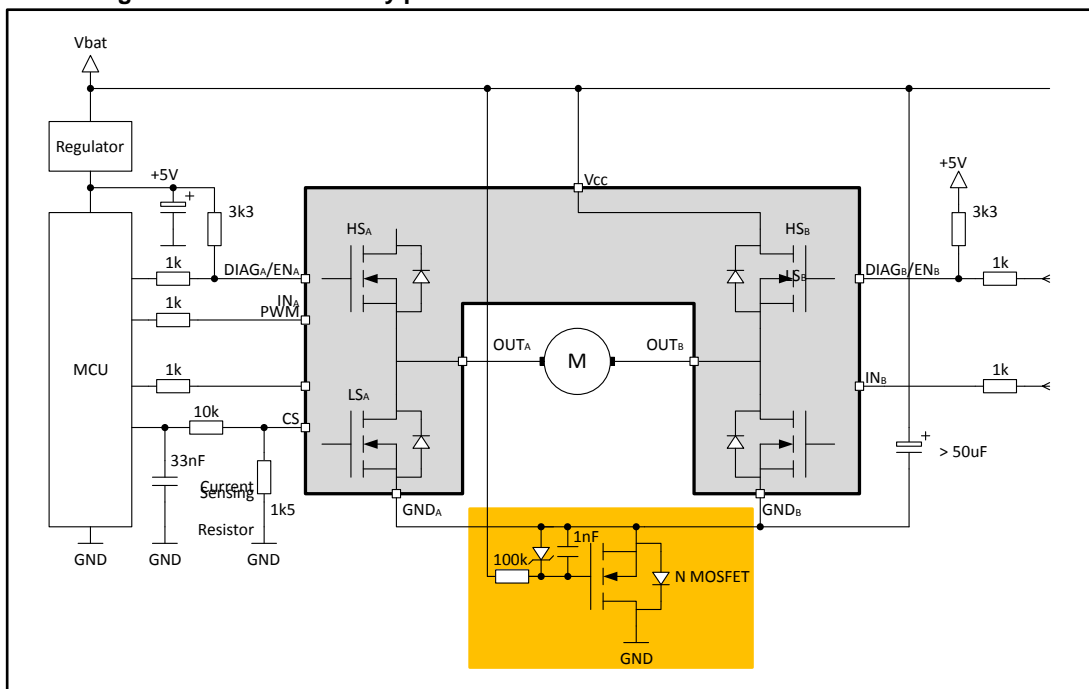
The highlighted circuit is shown in more detail below.

Figure 27: Detail of the circuitry connected to the N-MOSFET

The R16 plus C4 RC filter keeps the device operating during the fast ISO pulses, keeping the N-channel MOSFET switched ON. Instead, in a DC reverse polarity event, the RC filter will force fast OFF switching and protect the H-bridge from any damage. Resistor R16 is required to protect the gate of the N-channel MOSFET.

The Zener diode clamps the gate of the MOSFET to its Zener voltage, thus protecting it against overvoltage.

### 3.8.3 P-channel MOSFET solution

The third solution is to connect the P-channel MOSFET so that its gate is connected to GND and its drain to the battery side (see *Figure 28: "Reverse battery protection with a P-MOSFET and relevant circuitry"*).

The huge benefit of using a P-channel MOSFET is that no additional high side driver circuit is needed. As opposed to an N-channel MOSFET, the device is turned on by applying a negative gate source voltage.

It is important to insert the transistor in the right direction, because the P-channel MOSFET also has as an intrinsic anti-parallel body diode which is in the forward direction from drain to source.

By referring the gate signal to the ground line, the device is fully turned on when the battery is applied in the right polarity.

Figure 28: Reverse battery protection with a P-MOSFET and relevant circuitry
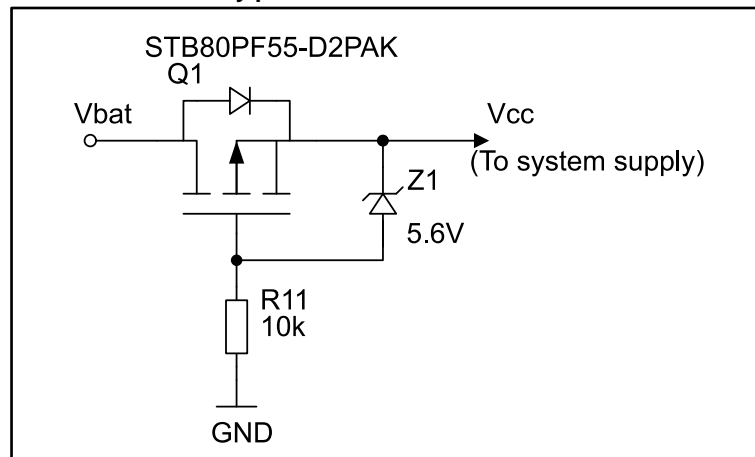
As soon as the battery voltage is applied and for the first start up, the intrinsic body diode of the MOSFET conducts until the channel is switched on in parallel. The Zener diode clamps the gate of the MOSFET to its Zener voltage and protects it against over voltage.

Reverse polarity switches the MOSFET off, because the gate source voltage for this case is positive $V_{GS} > 0$ (voltage drop over the Zener diode), and protects the H-bridge.

The same reverse battery protection can be shared among several bridges connected to the battery.

3.8.4 Dedicated ST reverse FET solution

The VN5R003H-E device uses STMicroelectronics VIPower™ technology for providing reverse battery protection to an electronic module. The figure below shows the device, which consists of an N-MOSFET and its driver circuit, two power pins (drain and source) and a control pin, IN.

Figure 29: Reverse battery protection with VN5R003H-E
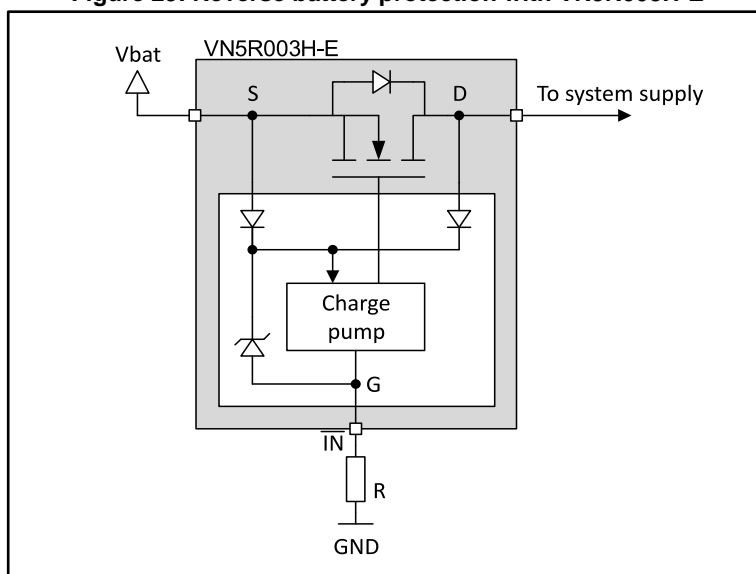
Note that a MOSFET has always an intrinsic anti-parallel body diode. The MOSFET is fully turned on when applying the battery voltage the IN pin appears negative versus drain. As the source is at high potential, the MOSFET in the normal configuration cannot switch on. A charge pump circuit is needed to boost the gate-voltage above the source-voltage to turn the MOSFET on.

During reverse battery polarity, no voltage supplies the gate of the MOSET, which automatically switches off. When IN is left open, device is in the OFF state and behaves like a power diode between the source and drain pins. The power losses of an N-channel MOSFET for a reverse battery protection are determined by the R_{ON} of the device and the load current.

The device is able to withstand abrupt high load currents typical of applications where several H-bridges are activated simultaneously; some Motors loads can temporarily have a maximum stall current above the DC maximum current rating of the device.

The diagram below gives information about the safe operating area as well as the maximum pulsed drain current the device is able to manage during normal operation.

Test conditions: VBATT = 13 V, PCB FR4 area = 58 mm x 58 mm, PCB thickness = 2 mm, Cu thickness = 35 mm, Copper areas: minimum pad lay-out and 2 cm2

Figure 30: VN5R3003H-E maximum pulsed drain current Vs time
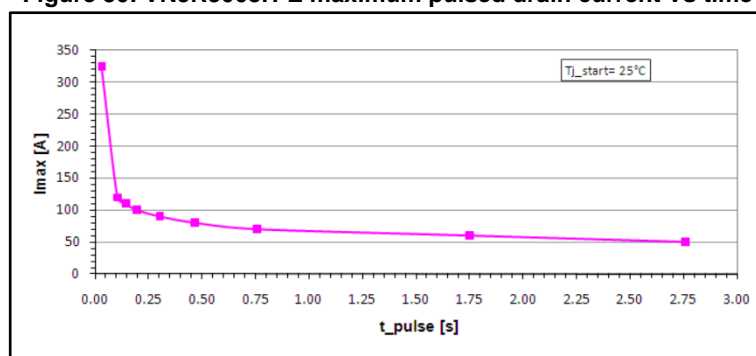
3.9 ESD protection

An ESD pulse on a powered ECU output connector is an expected event during the life of a car. Typically, contact and air discharge tests are performed during module qualification. Most automotive module makers require +/-8KV IEC61000-4-2 contact discharge on the output connector of the powered module.

A positive ESD pulse is transferred via an internal Drain/Bulk HSD output diode to the Vcc/GND structure. This is the first structure to fail in the event of ESD pulses exceeding the device capability. Negative ESD pulses forward bias the internal Drain/Bulk LSD output diode with no risk of failure.

The ESD pulse destruction value heavily depends on the module layout.

To allow the module pass a stress level above the device capability, it is recommended to add a 100 V ceramic capacitor in the order of tens of nF between the output and GND, close to the connector, as shown below. This capacitor decreases both the applied dV/dt and the maximum output voltage.

Figure 31: PCB layout and output capacitor against ESD
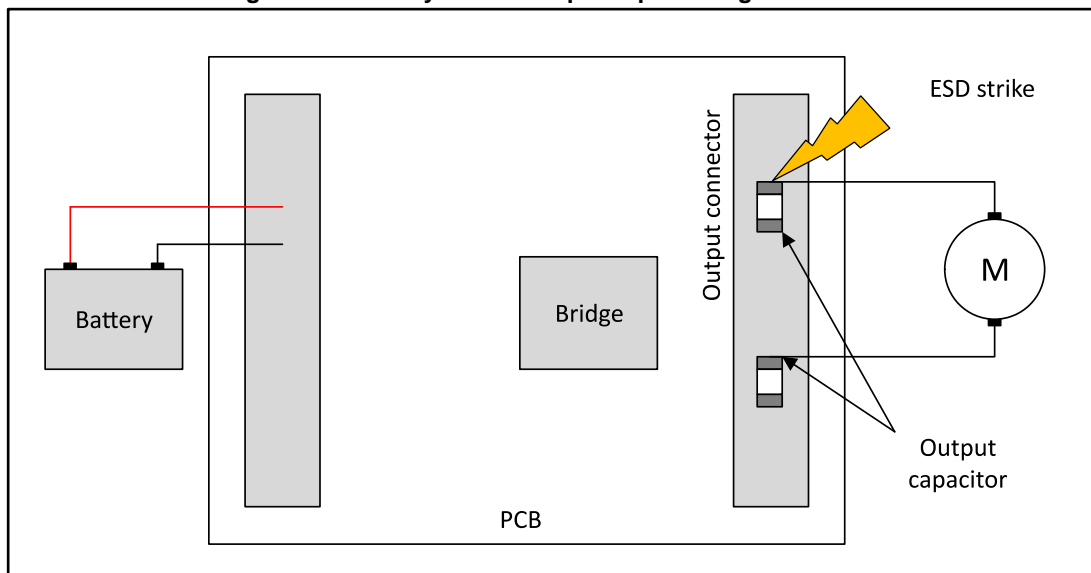
4 Description of diagnostic

4.1 Current Sensing

The VIPower M0-5 technology has brought important improvements to analog current sense operation.

The main function of the current sense block is as a current mirror of the load current in normal operation; it delivers a current proportional to the load current according to a known ratio named K.

The current delivered by the current sense circuit, located in the HSD, can be easily converted to a voltage by means of an external sense resistor, thus allowing continuous load monitoring when the CS_DIS (current sense disable) pin is driven low or left open.

Figure 32: VNH5XXX fully integrated H-bridge motor driver with analog current sense block diagram (VNH5019A is drawn as example)
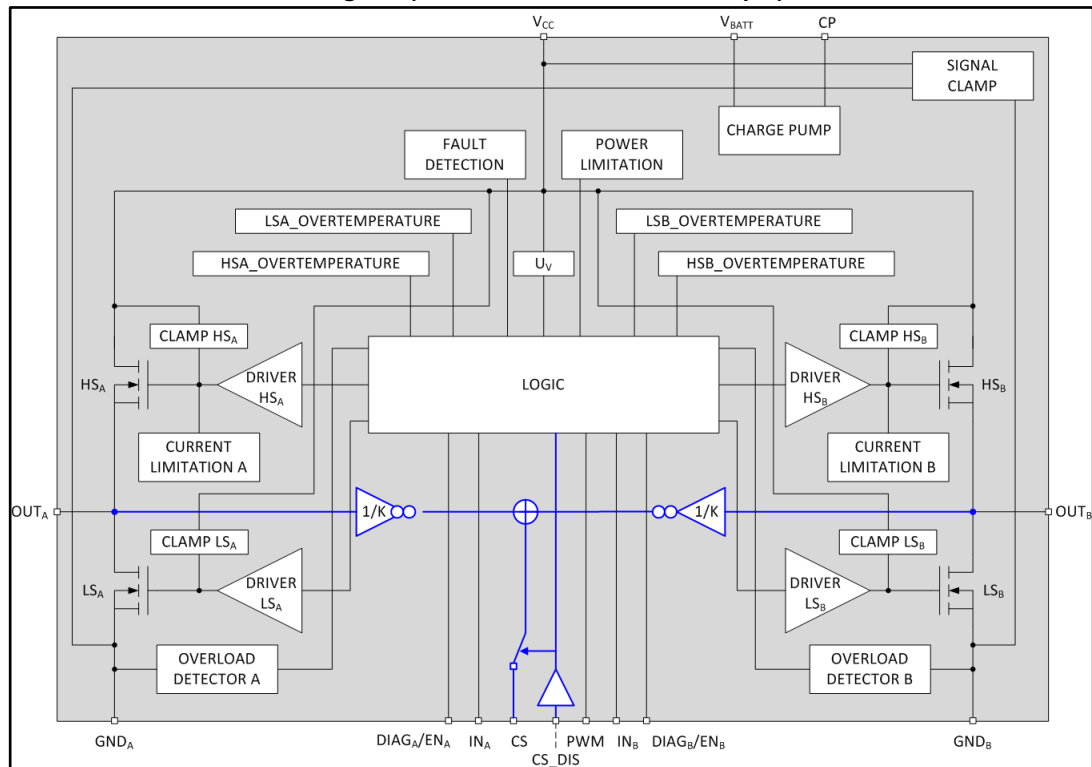
The simplified block diagram of the fully integrated H-bridge M0-5 analog current sense is given below.

Figure 33: M0-5 fully integrated H-bridge Current Sense simplified block diagram
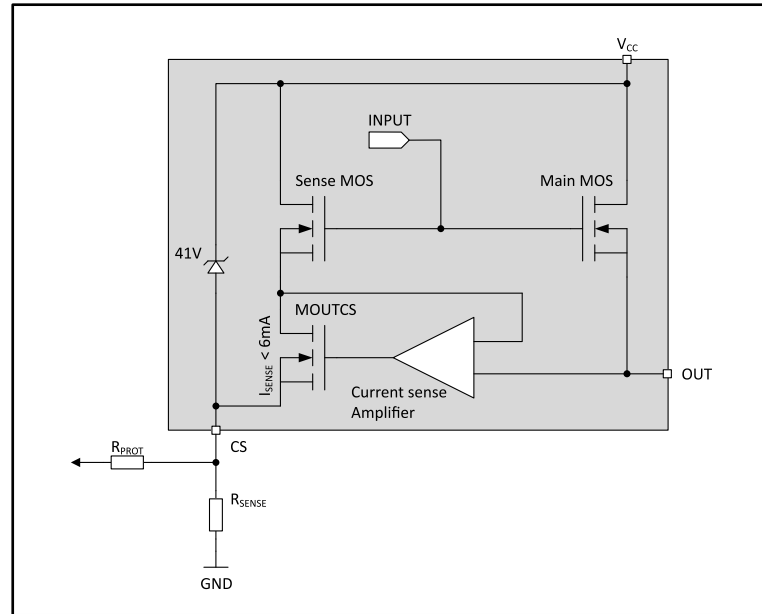
The Sense MOS is a scaled down copy of the Main MOS of the HSD according to a defined geometric ratio, driven by the same gate control circuit as the Main MOS.

4.2 Current sense in normal operation (channel ON, CS_DIS low)

The current flowing through the Main MOS of the HSD is mirrored by the Sense MOS.

The current delivered by the current sense pin is regulated by the current sense amplifier through the P channel MOSFET MOUTCS (see *Figure 33: "M0-5 fully integrated H-bridge Current Sense simplified block diagram"*) in order to have:

$$V_{DS\_Main} = V_{DS\_Sense}$$

Thus the power mos and the sense cells work at the same current density and consequently

$$\frac{I_{Sense}}{S_{Sense}} = \frac{I_{OUT}}{S_{Main}} \rightarrow I_{Sense} = \left(\frac{S_{Sense}}{S_{Main}}\right) \cdot I_{OUT}$$

…and

$$V_{Sense} = R_{Sense} \cdot I_{Sense} = R_{Sense} \cdot \frac{I_{OUT}}{K}$$

Where $K \propto S_{Main}/S_{Sense}$ encompasses the geometric ratio, the current sense amplifier offset and various process parameter spreads.

Care must be taken to ensure I_{Sense} is proportional to I_{OUT}. Indeed, the maximum drop across R_{Sense} is internally limited to 7.5 V typically as specified in the datasheet by the parameter V_{sense} maximum analog sense output voltage (5 V minimum @ 9V < Vcc < 18V; -40 °C< Tj <150 °C).

Example: VNH5050A-E with R_{Sense} selected so that V_{Sense}=1.5 V @ Iout = 5 A.

Considering (for the sake of simplicity):
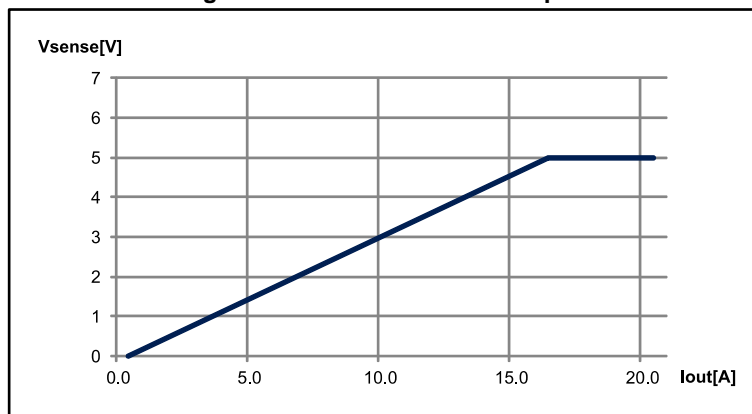
$$K_1 @ 5A = 5100(\text{typ.}) \rightarrow I_{Sense} = 980\mu A \rightarrow R_{Sense} = 1.5k\Omega$$

Assuming it is requested to read the highest load current not exceeding 5 V maximum:

$$I_{Sense} = \frac{5V}{1.5k\Omega} = 3.3mA, so to maintain linearity \rightarrow maximum I_{OUT} = 3.3mA \cdot 5100 = 16.8A$$

In other words, with the selected R_{Sense}, any load current greater than 16.8 A will produce the same V_{Sense}, as shown in the figure below.

Figure 34: VSense versus IOUT plot

On the other hand, care must be taken to prevent the P-channel MOSFET MOUTCS from achieving saturation as this will again cause I_{Sense} to no longer be proportional with I_{OUT}. This normally happens when the maximum current that MOUTCS is able to supply is reached (6 mA typical)

This value is consistent with the current sense operating range and current limitation value.

Example: VNH5050A-E with R_{Sense} selected in order to have V_{Sense} = 4V @ Iout = 25 A

Considering (for the sake of simplicity):

$$K_3 @25A = 4930(typ.) \rightarrow I_{Sense} = 5mA \rightarrow R_{Sense} = 790\Omega$$

Assuming K remains approximately 4930 for I_{OUT} > 25 A, the maximum load current which can be detected is: $I_{OUT} = I_{SENSE\_MAX} \cdot K$. This is still compatible with the minimum I_{LimH}. With the selected R_{Sense}, the maximum V_{Sense} which can be developed to maintain linearity is approximately:

$$790\Omega \times 6mA = 4.7V$$

4.3 Overload or short circuit indication (channel ON, CS_DIS low)

The current sense operation for load current approaching the current limitation is not guaranteed and predictable. Indeed, because of the intervention of the current limiter, the output voltage can drop significantly, down to approximately 0 V in the extreme case of a hard short circuit.

As the whole circuit is referenced to V_{OUT}, ambiguous and unreliable current values may be supplied by the CS under such conditions. In order to bring the CS into a well-defined state, a dedicated circuit section shuts down the current sense circuitry when V_{OUT} drops below a certain threshold (6V typically, see the figure below).

Figure 35: VSense versus VOUT @ IOUT = ILIMH
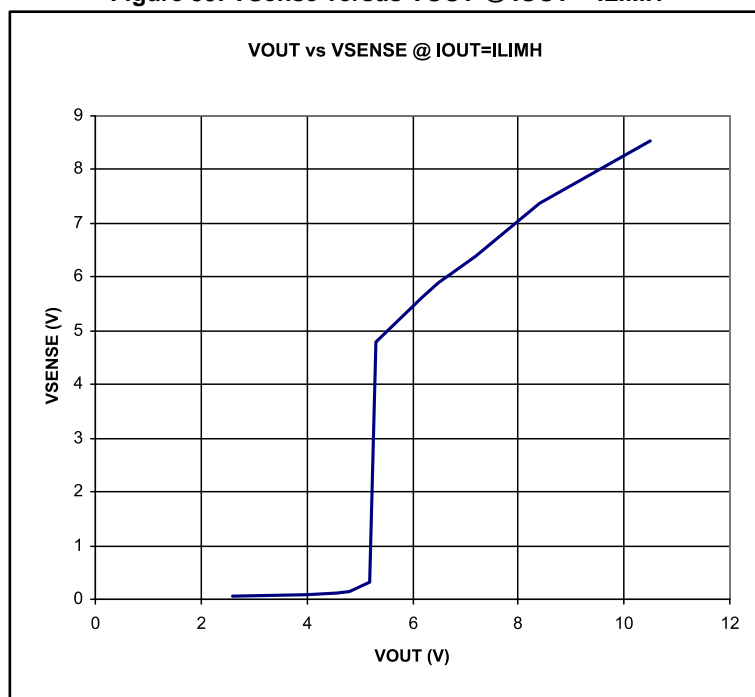
Once again, this value is consistent with the current sense operating range and current limitation value.

Example: VNH5050A-E

When the load current approaches the HSD current limitation (e.g., I_{OUT} = 25 A), the maximum drop on the output MOSFET is:

$$V_{DS} = R_{DS\_MAX} \cdot I_{LimH} \cong 1.5V$$

Therefore, at Vcc = 8 V, V_{OUT} = 8 V – 1.5V = 6.5 V, which is still sufficient to ensure the CS functions properly up to the current limited region.

In conclusion, in normal operation the current sense works properly within the described border conditions. For a given device, the I_{Sense} is a single value monotonic function of the I_{OUT} as long as the maximum V_{SENSE} (1st example) or the current sense saturation (2nd example) are reached; in other words, there is no possibility of having the same I_{Sense} for a different I_{OUT} within the given range.

Finally, switching off of CS in a hard short circuit event causes this latter condition not to be distinguishable from an open load event until the thermal shutdown is reached.

4.4 Overtemperature indication (channel ON, CS_DIS low)

In case of over temperature intervention in VNH5XXX devices, the CS pin is in a high impedance condition, as shown in the following table. This event is detected by the DIAGX/ENX (the concerned branch DIAGX/ENX goes low).

Table 6: Truth table in fault conditions on branch A

INA	INB	Fault information		Protection action		CS(VCSD=0V)
		DIAGA/ENA	**DIAGB/ENB**	**OUTA**	**OUTB**	
1	1	0	1	OPEN	H	High impedance
	0				L	
0	1				H	IOUTB/K
	0				L	
X	X		0		OPEN	High impedance

4.5 VNH5XXX bridges: latch off, unlatching and standby mode

4.5.1 Latch off

The fault conditions which cause latch-off of the affected A or B full-bridge (where OUT_A or OUT_B or both are put into high impedance) are:

- Over-temperature of the high-side HS_A or HS_B power switch (for example due to short to ground at output OUT_A or OUT_B),
- Over-current or over-temperature detection on low-side LS_A or LS_B power switch (for example due to short to battery condition on the output when Power MOSFET is in saturation state).

Latch off state is handled by VNH5XX by internal Fault flag.

Latch-off is diagnosed through $DIAG_A/EN_A$ and $DIAG_B/EN_B$. In general, logical low state of any of these pins means that corresponding leg is disabled (corresponding OUT_A or OUT_B are in high impedance).

These pins can be controlled by the microcontroller (used as EN_A and EN_B) or by VNH5XXX (used as $DIAG_A$ and $DIAG_B$).

EN_A and EN_B are used by VNH5XX as input pins when no fault occurs. It is recommended to pull both signals high by an external resistor to allow the VNH5XX device to pull $DIAG_A$ and $DIAG_B$ low. This allows the microcontroller to perform diagnosis when its controlling pins are set to input mode for diagnostic purposes.

A procedure is requested in order to clear the fault flag on the DIAGx pin and unlatch the bridge.

4.5.2 Unlatching of VNH5XX bridges

Suppose that the VNH5XXX is driven in the clockwise operation (ENA=ENB=INA=1, INB=0) and a short circuit between OUT_A and GND occurs. The device (specifically the HS_A) enters current limitation, power limitation and finally overtemperature thermal shutdown. The VNH5XX signals that the leg A has a fault state by pulling low the $DIAG_A/EN_A$ pin. The device is latched off, which means that both PMOS switches of Leg A are switched off. If an application wants to determine whether a short circuit is still present, the bridge must be unlatched and the fault must be cleared. The procedure to clear the fault is for IN_A to be set low and high again (unlatching at the rising edge). $DIAG_A$ / EN_A becomes high and enables the channel.

OUT_A and OUT_B follow the setting of IN_A and IN_B after t_{DEL} after the last transition of any IN_X. For example, after fault clearing, IN_A is set from high to low in order to set the desired state for channel A. The t_{DEL} is started and at the end the bridge is turned on again in the

clockwise operation. In general, the fault is cleared on the rising edge of IN_A (if the fault is on the leg A, $DIAG_A/EN_A = 0$) or on the rising edge of IN_B (if fault is on the leg B, $DIAG_B/EN_B = 0$).

If the fault condition persists, the fault flag is set and half-bridge latches off again. In such cases and also for other purposes, it is possible to put VNH5XX in standby mode.

Figure 36: Fault handling during motor clockwise operation
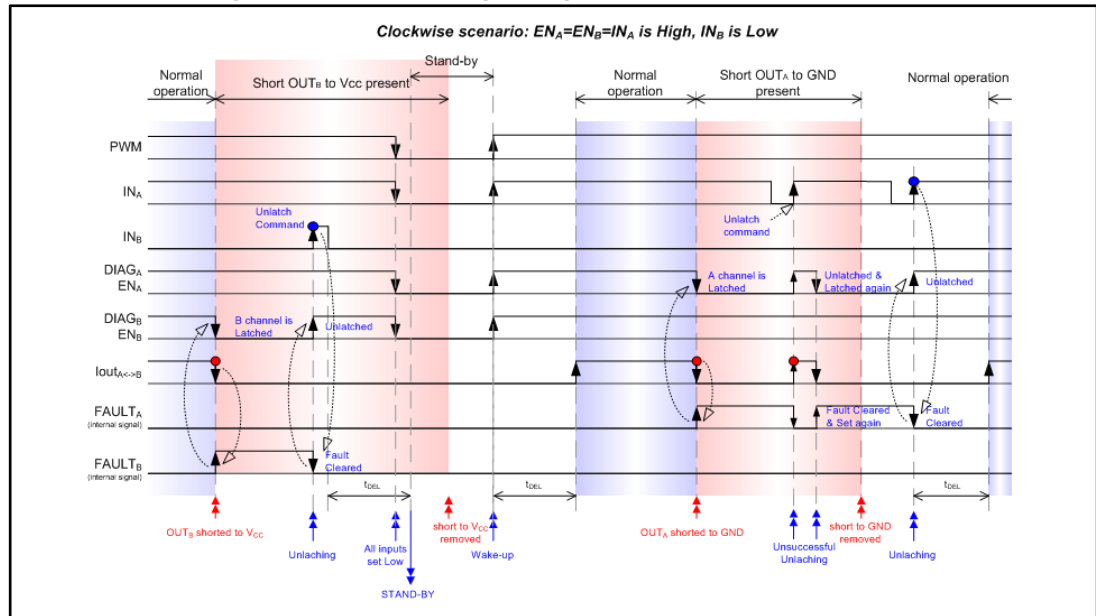
4.5.3 Standby mode

The device is put in standby mode when:

- all its inputs are set low (IN_A, IN_B, EN_A, EN_B, PWM)
- There is no Fault flag latched for any channel.

In order to put the device in standby mode after a fault, all input pins must be set low inside the t_{DEL} interval initiated by the clearing of the fault via the relevant IN signal.

5 PWM operation and cross current protection (for VNH5XXX H-bridges)

5.1 Working PWM frequency and its limits

In the VNH5XX bridges, the choice of speed control is entrusted to the low side drivers. They take in the small electrical signal on PWM which drives the appropriate LS gate and translate it into the selected motor speed.

Due to their faster switching times (1 µs typ.), a high frequency at least equal to the maximum limit of audible noise which is 20 kHz can be reached. Indeed if the frequency is too low (switch is changed slowly), then the motor will be subject to anomalous vibrations which may disturb the load.

On the other hand, if the frequency is too high, the MOSFETs may not be switched correctly and the desired current may not be achieved. As there is no dedicated shoot-through protection in the VN577X (see *Section 3: "Protection of H-bridges"*), they are not suitable to be driven at 20 kHz.

The duty cycle gives a measure of how long the LS switch remains on as a percentage of the total switching time. In essence, it is linked to how much power is being delivered to the motor. In fact, the average value of the PWM voltage applied to the motor is proportional to the duty cycle and this gives the corresponding speed of the motor.

The following figure shows an example of 25%, 50%, and 75% duty cycles. Effectively, these duty cycles correspond to a no load speed equal to 25%, 50%, and 75% of full no load speed respectively.

Figure 37: Pulse width modulation used for motor control
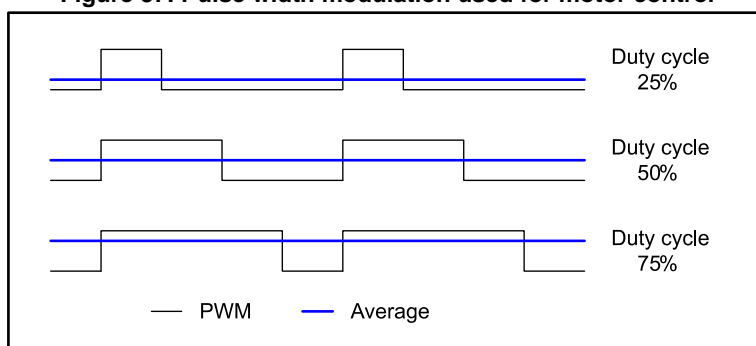
During the off phase of the period, the current of the motor freewheels through the body diode of the high side, as shown in the following figure.

Figure 38: H-Bridges with PWM with switching ON and OFF of the low side driver
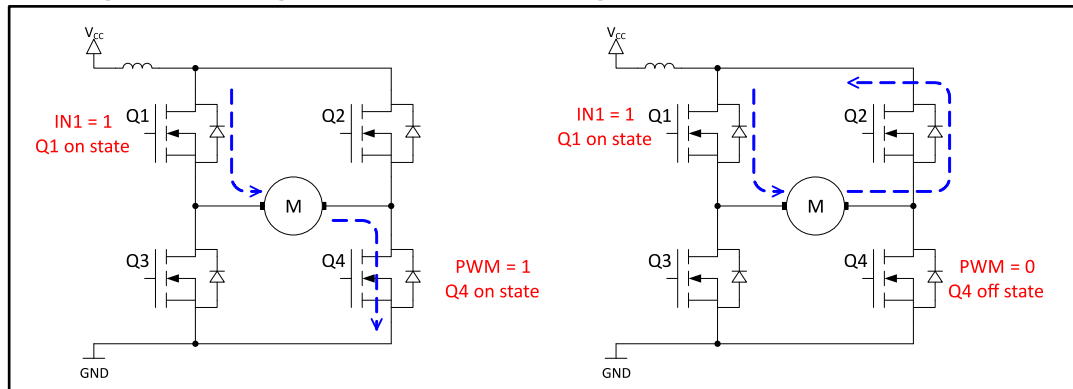

5.2 VNH5XXX cross conduction suppression

In normal operation of an H-bridge motor driver, the switches are turned on in pairs, either upper left and lower right, or lower left and upper right, but never on the same leg of the bridge. If both switches on one side of a bridge are turned on, it creates a short circuit between the battery terminals. This cross conduction phenomenon can be critical for the device.

The VNH5XX family has an internal protection to avoid this event, which takes advantage of the switching time difference between the low side MOSFET and the high side MOSFET. Due to the charge pump circuitry, the HS switch has slow turn-on/turn-off times compared to the direct drive of the LS MOSFET.

Therefore, when INA (INB) is set high, the complemented signal immediately turns off the LSA (LSB) MOSFET while the charge pump circuitry has not yet switched on the HS part. On the other hand, when INA (or INB) is set low, the HSA (HSB) switch turns off slowly and the LSA (LSB) MOSFET is not turned on again until the HSA (HSB) is in the off state.

This protection is performed by the integrated filtering block acting on the gate of both low side N-channel MOSFETs. If we consider the signals in *Figure 39: "Cross current protection filtering times"*, VG_LSA and VG_LSB as internally generated voltages driving directly the gates of LSA and LSB N-MOSFETs, at each rising/falling edge of INA (INB), two filtering times named t_{DEL} and t_{off} are generated (t_{DEL}, typically 0.4 ms, is given in the VNH5XXX datasheets).

Figure 39: Cross current protection filtering times
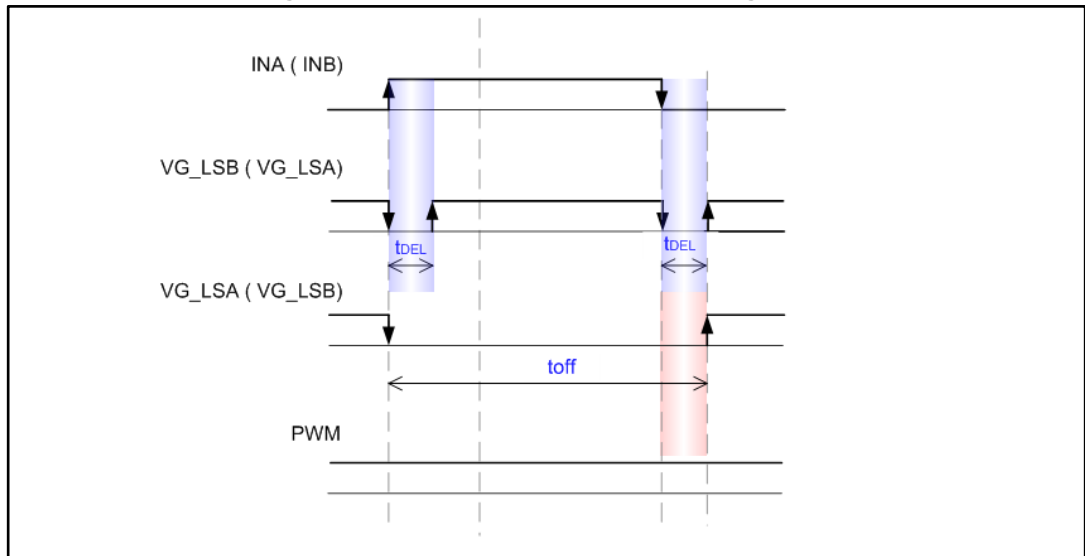
The t_{DEL} time is generated at all transitions H-L or L-H of INA (INB) to avoid the switch on of the LSB (LSA), by means of the opposite leg, before the HSA (HSB) is ON or OFF.

The t_{off} time is generated at all transitions H-L or L-H of INA (INB) to avoid the switch on of the LSA (LSB), by means of the same leg, during the on time of HSA (HSB) and during the turn-off of the HSA (HSB) when the other high side is activated to change the current direction.

The filtering times are not active until the device power on reset has occurred, which is the initialization event of the bridge when applying the Vcc voltage and/or setting the ENx signals low to high. During this time, which typically lasts 2 µs, the logic is not supplied so filtering times are not active.

6   Load and device compatibility

It is crucial to match the motor driver device with the motor; inappropriate selection of the device influences device behavior and lifetime.

All considered devices implement protection functions which may induce designers to underestimate the choice of the device. Current and power limitations are protection functions and should not be considered as part of normal operating ranges.

In general, there are three phases of motor current demand.

- Inrush phase: the motor drive device can deliver current above nominal current for a short time in order to provide peak torque in order to start the motor; the peak torque of the starting motor determines peak current inrush current of the starting motor.
- Movement phase: the moving motor draws less current; in general, it is the desired motor operation phase.
- Stall phase: the motor loses its movement speed and current becomes maximal; the current is limited by the armature winding resistance only.

Figure 40: Generic motor current profile
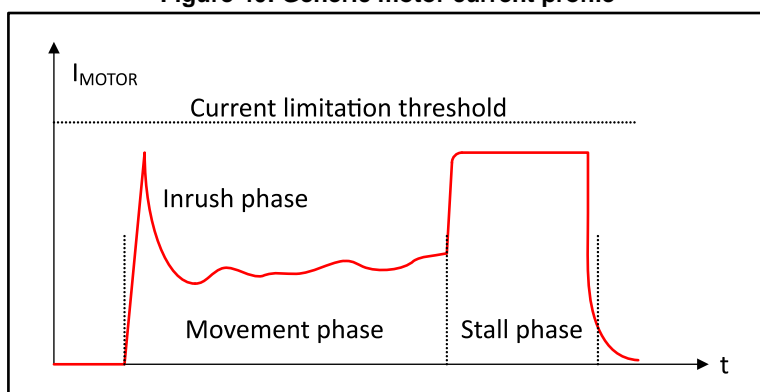
A motor drive device formed by Power MOS transistors is limited by maximum junction temperature which should not be exceeded. To ensure device reliability, the device should be rated for maximum possible current.

Now, let us consider an under-dimensioned device. With the integrated protection, it might seem possible to handle the movement phase with lower powered devices. This could lead to an underestimation of the starting and stall phases, causing:

- slower acceleration of the motor if power limitation is active
- the triggering of current limitation / power limitation and overtemperature thermal shutdown; even though the device is protected against damage, correct operation of the application is not guaranteed (for the VNH5XXX, the device is latched off).

It is therefore recommended to select the proper device with current limitation above the maximum motor inrush and stall current.

Moreover, in steady state conditions, even if the load current is well below the current limitation, it should always generate limited steady state power dissipation in the device to remain below the low side and high side thermal shutdown thresholds and avoid excessive temperatures on the bottom of the device, which could compromise the PCB.

7 Configurations with H-bridges connected together

7.1 Two VNH5XXX connected in parallel

If the current requested by one motor is quite high compared to the maximum current the VNHX can supply, it is possible to connect two identical H-bridges in parallel by simply short circuiting the two outputs of each H-bridge. The resulting R_{ON} per leg is the half of the R_{ON} of each H-bridge. Thus we have a resulting H-bridge with the double of current capability.

The High Side Drivers and Low Side Drivers of each H-bridge must be driven with the same circuit; for this reason, the input driving circuit should be driven by the same signal ($IN_A = IN_B$). Diagnostic pins can be short circuited ($EN_A/DIAG_A= EN_B/DIAG_B$) as well as PWM pins, but in this case, the current sense signal is at high impedance so no load current reading is possible.

In order to use current sensing, it is necessary to connect in parallel one leg of the first bridge with one leg of the second bridge, as shown in the figure below. The current sense pins can be short circuited and one common sense resistor adopted, whose current is the sum of the CS currents in each half bridge. Particular attention must be paid in the layout and connection tracks in order to limit any asymmetry in the distribution of the currents between the two bridges.

Figure 41: Parallel connection of two VNH5XXX H-bridges
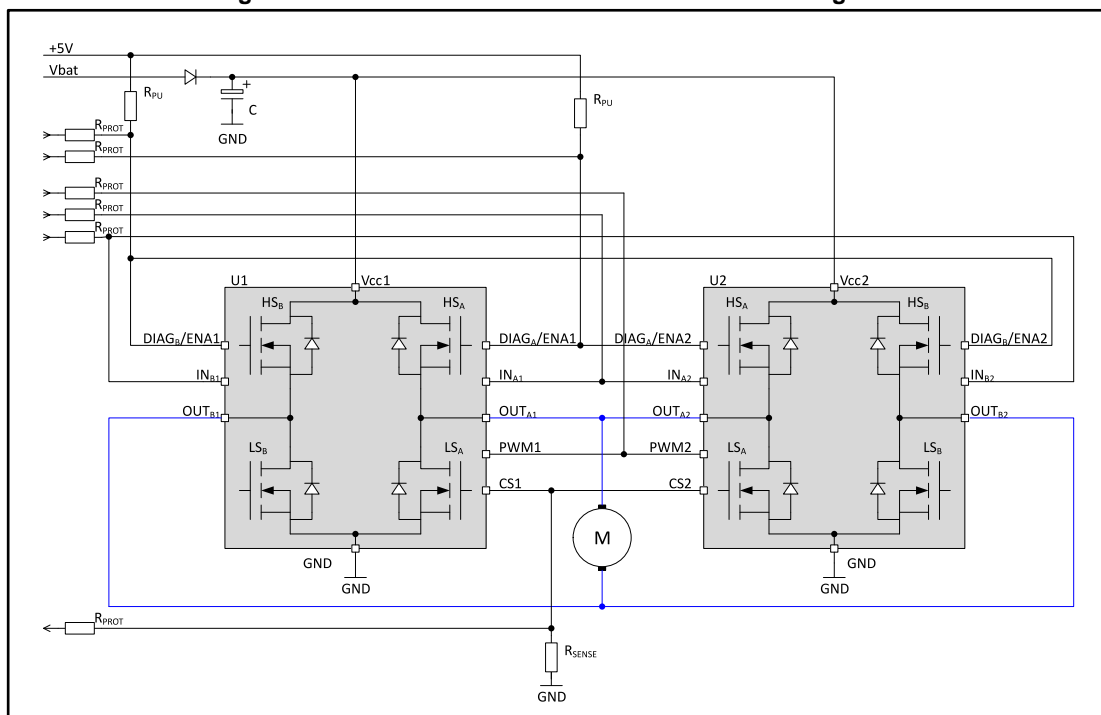
8 VIPower H-bridges FAQ

The aim of this chapter is to list the most common questions regarding VIPower H-bridges to help you find the relevant section.

Q: How can I dimension the reverse battery protection of the H-bridge?

A: *Section 3: "Protection of H-bridges"*

Q: What is the current sense circuit operation principle?

A: *Section 4: "Description of diagnostic"*

Q: What is the behavior of the H-bridge when an overtemperature event occurs?

A: *Section 3: "Protection of H-bridges"*

Q: What is the current sense circuit reaction when a short circuit of one output to GND occurs?

A: *Section 3: "Protection of H-bridges"*

Q: What happens to the H-bridge and which protections are acting when the load is short circuited?

A: *Section 3: "Protection of H-bridges"*

Q: In the VNH5XXX, how can the latch (after a thermal shutdown event) be cleared?

A: *Section 4: "Description of diagnostic"*

Q: Can I apply 20 kHz PWM frequency to a VNH5XXX? And to a VN577X? And what are the relevant PWM driven MOSFET switches?

A: *Section 5: "PWM operation and cross current protection (for VNH5XXX H-bridges)"*

Q: How can I drive correctly in PWM a motor with a certain armature inductance?

A: *Section 1: "General concepts in DC motor control"*

Q: How can I limit overvoltages on the supply pin of the H-bridges in case the device enters the tri-state?

A: *Section 2: "VIPower H-bridge features"*

Q: What is the cross current and how is the VNH5XXX protected against it?

A: *Section 5: "PWM operation and cross current protection (for VNH5XXX H-bridges)"*

Q: How can I protect the VNH5XXX against air discharge ESD?

A: *Section 3: "Protection of H-bridges"*

Q: How can I avoid overloading a VNH5XXX in normal operation?

A: *Section 6: "Load and device compatibility"*

Q: How can I dimension the sense resistor so that the micro can detect the motor current?

A: *Section 4: "Description of diagnostic"*

Q: Why are semiconductor-based H-Bridges overtaking electromechanical relays in the automotive field?

A: *Section 1: "General concepts in DC motor control"*

Q: How do you protect H-bridges against transients on the battery which exceed the absolute maximum ratings of the device?

A: *Section 2: "VIPower H-bridge features"*

Q: How can I parallel two VNH5XX in order to drive a large DC motor

A: *Section 7: "Configurations with H-bridges connected together"*

Q: What is the behavior of the device subjected to a positive high energy pulse on its supply pin?

A: *Section 3: "Protection of H-bridges"*

Q: Can I use an N-channel MOSFET connected to the battery to protect the H-bridge against the reverse battery? Does ST offer an integrated charge pump N-MOSFET?

A: *Section 3: "Protection of H-bridges"*

Q: What happens if the GND pin of the VNH5XX becomes floating?

A: *Section 3: "Protection of H-bridges"*

Q: What is the procedure to send the VNH5XX in standby after a fault has occurred?

A: *Section 4: "Description of diagnostic"*

9 Revision history

Table 7: Document revision history

Date	Version	Changes
01-Sep-2016	1	Initial release.
07-Sep-2016	2	Minor text edits.

IMPORTANT NOTICE – PLEASE READ CAREFULLY