High Voltage General Purpose Drive (GPD) with Hall-Effect Current Sensor

Current Sensor TLI4971

About this document

Scope and purpose

This document provides a reference solution for interfacing the TLI4971 Hall Effect current sensor in the GPD to measure the motor current for better performance and accuracy. The following key aspects are addressed:

- Hall Sensor measurement principle
- Isolation coordination scheme
- Circuit 2 Go
- Layout 2 Go
- Supply requirements / Scheme
- EMI/EMC recommendations
- PCB stack-up influence on sensitivity
- Cooling strategy
- Applicable standards
- Stray field suppression
- Signal conditioning/guarding

Also, this document describes how the high-side in phase current sensing is best choice when compared with the other measurement techniques.

As the application is cost sensitive, the document gives a guidance on how to implement the minimum needed protection circuit to design the PCB (printed circuit board).

Intended audience

Inverter and Current Sensor Module Designers responsible for measurement and detection of current in general purpose inverters.

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1 Sensor Description

1.1 Measurement Principle

The TLI4971 coreless current sensor IC uses the Hall-effect to measure the magnetic field produced by an integrated current carrying conductor. The conductor that carries a current I_{PN} generates a magnetic field B as shown in the Figure 1. This field can be measured by using a Hall element as it has the property of converting the magnetic flux into a voltage, when the Hall element is supplied with a constant current.

This technology has many advantages, including galvanic isolation, low power loss, and high accuracy over temperature. Also has near zero magnetic hysteresis, as there is no core used for concentrating the field.

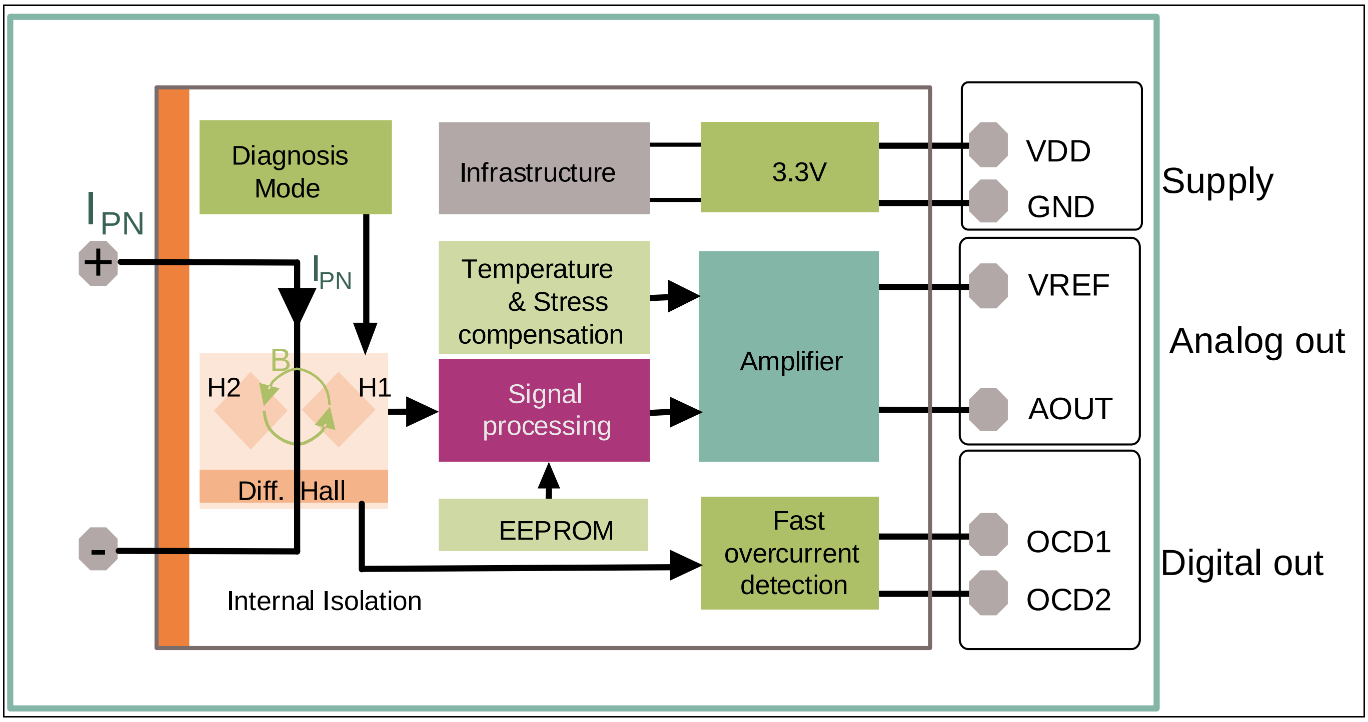


Figure 1 Operating Principle of Coreless Hall Transducer

The TLI4971 coreless current sensor uses the differential measurement principle to reduce the effect of common mode stray fields on the sensor output. In case of core based solutions, the stray magnetic fields are shunted around the sensor IC through the core which provides a low reluctance path for the stray fields. But the core based solutions are expensive than the coreless solutions.

The basic principle behind differential current sensing is that the fields produced on either side of a current carrying conductor are opposite in polarity. This means that when a current I_{PN} flows through the primary conductor, as shown in Figure 1, Hall plate 1 (H1) will see a field out of the page, and Hall plate 2 (H2) will see a field into the page for the current flow shown. When there is a common mode field on the current sensor IC, both Hall plates will see the same field. By subtracting the outputs of the two Hall plates, one is able to reject these interfered fields. For more information, refer to the stray fied application note [4].

1.2 Current Sensor Placement in the GPD

Current measurement is an inherent part of any power electronics converter or GPD application. One important reason for measuring the motor current is to execute a control algorithm for better performance.

Therefore, fast and precise current sensing is required to have the best dynamic motor control, minimum torque ripple and thus minimum audible noise.

Any Vector control and direct torque control algorithms require current sensing of the three phases for optimal inverter control. The motor-phase winding current can be sensed by using different methods, for which the commonly-used methods are:

- DC bus current sensing using a single device (Location 1 in Figure 2)
- Inverter leg current sensing (Location 2 in Figure 2)
- Inline/Inphase current measurement (Location 3 in Figure 2)

The current measurement is also used for overload and fault detection by placing a current sensor on DC+ node as shown in the below figure. The current measurement assists in de-rating the inverter current to keep the power devices within the permissible range of operating temperatures. In case of short circuit in the system, the over current detection function triggers the system to shut down for safety reasons.

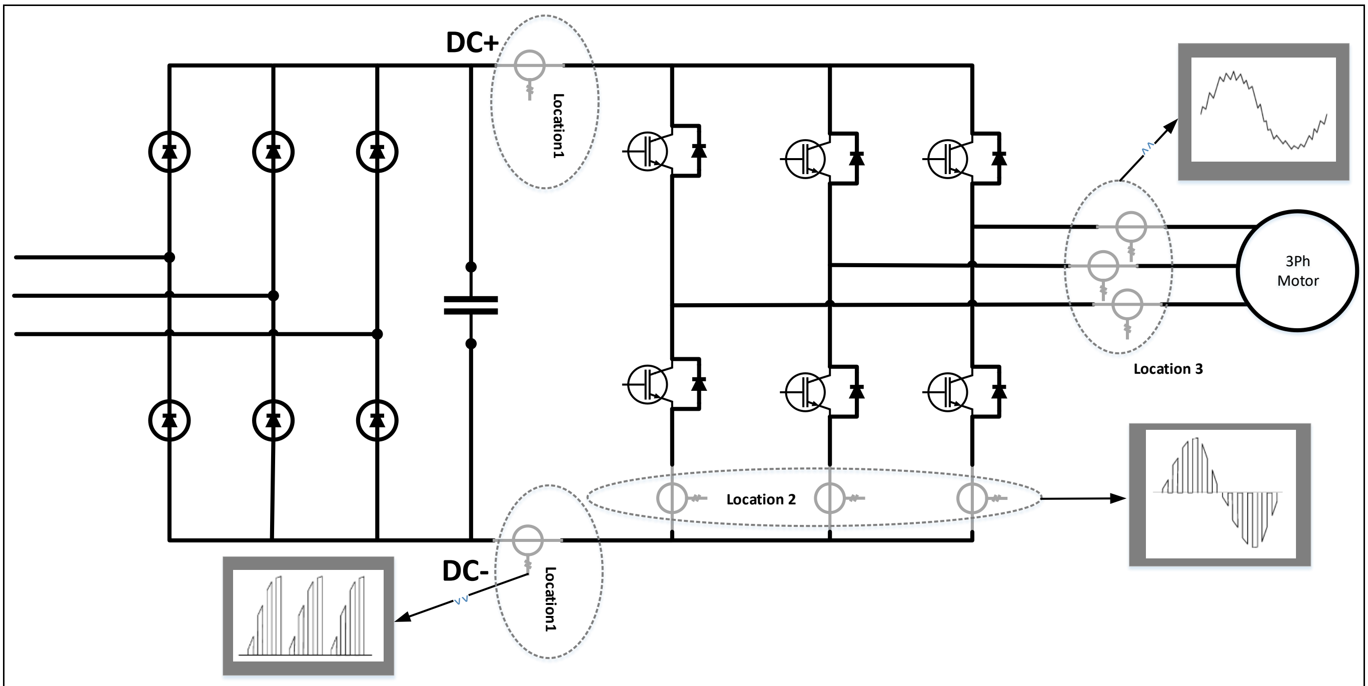


Figure 2 Different Possible Current Sensing Locations in Inverter

The current measurement either in the DC+ or DC- bus, as shown in the Figure 2 (Location 1), is the most cost effective solution often used for lower power applications as the required total number of current sensors are one. This is indirect current measurement method, typically, the current measurement is done on the DC- minus bus as this location may be used as the reference potential of the MCU to avoid the isolation between the current sensor and MCU. The main disadvantage of this method is that the individual phase current control is not possible resulting in an unbalanced inverter operation.

On the DC+ measurement node, the constant HV, short current spikes and high frequency current signal are expected due to the converter operation. Use this method to deal with low-side measurement issues. The system regains the ability to detect ground faults, and the load path to ground is no longer impeded.

Whereas, on the DC- measurement node, the constant LV, short current spikes and high frequency current signal are expected due to the converter operation (see bottom of Location 1 in Figure 2). However, this solution comes at the cost of ground voltage variation, and places an additional impedance between the load and ground. The disadvantage of this method is that it cannot measure the circulating currents in the inverter, more complex control algorithm and requires high bandwidth.

Another location of current measurement is at the emitter terminal of the low side IGBT on each leg of a three-phase inverter, see location 2 of Figure 2. This is primarily used in low-to-medium power applications. The current sampling has to be done when the low-side switch is ON and must be synchronized with the pulse-width modulation (PWM). The ideal method is to use three-leg inverter current sensing.

The advantage of current sensor placement in location 2 is similar to that of location 1, as the negative section of the DC-bus can be taken as the common reference potential. However, the disadvantages of current sensor placement in location 2 are increased stray inductance on the emitter terminal, sensor shall therefore have high bandwidth and high sampling rate which makes control loop very complex.

The simplest method of obtaining motor winding current is by placing a current sensor in series with each phase connection (see Location 3 in Figure 2) of the inverter with the motor. The common-mode voltage existing in the in-line sensing is equal to the DC bus voltage, which makes non-isolated shunt-based sensing difficult or more expensive.

In high dynamic drives and high-power applications, current is usually measured in the output phases of the inverter as shown in the location 3 of Figure 2 in the dotted lines. The following reference design recommends to use 3 sensors in each motor phase because the sensor does not require high bandwidth as the motor current is continuous when compared to other locations and one sensor in the location 1 of DC+ terminal to detect the over load or short circuit current.

The requirements of the inphase current sensing and advantages of the TLI4971 are discussed in 0. Also,the benefits of using TLI4971 device in this location compared to shunt measurement technique is Low temperature rise, low power loss due to low primary resistance and the inherent functional isolation which supports high voltage applications. Please refer to the device datasheet for the isolation voltage specifications.

Table 1 The Advantages of the TLI4971 for the inphase Current Measurement

In-Phase Current Sensing Requirement	Features of TLI4971
Level shifting	Intrinsic due to magnetic sensing principle
Amplification /Signal Conditioning	Internal amplifier with trimmable gain
High dV/dt robustness (Tested up to 10kV/µs)	Best settling time (5µS) after each switching or transients occurred in the current measurement path
Overload capability	250A for 10uS (Tested for 10 times)
Insertion Resistance, power loss	Best in industry, Max of 220µΩ (including solder material)
Sensing path inductance	51pH (includes solder)
Thermal Capability	Low Thermal Resistance of 0.6 K/W (Current rail to soldering point, on Infineon reference PCB, see related application note)
Stray Field Suppression	Yes
Bandwidth	120k Hz @ -3dB cut-off frequency
Corsstalk compensation	Yes

1.3 Applicable Standards & Requirements

The requirements from IEC are focused on the influence of the variable speed drive (VSD) on the motor efficiency at speeds close to the motor rated speed. The IEC 60034-25 defines the method of summation of losses in order to evaluate the impact of a VSD control on the efficiency of a motor with sinusoidal supply.

IEC 61800-5-1 specifies creepage & clearance of equipements for adjustable speed power drive system at different pollution degrees, except traction and electric vehicle drives. Based on IEC 60664-1, insulation coordination for equipment within low-voltage systems are defined.

Overvoltage categories are defined as category III based on IEC 60664-1 as for industrial drives category II or III are most appropriate. For parts or circuits that are not significantly affected by external transients, functional insulation shall be designed according to the working voltage across the insulation.

Table 2 Different Standards

Parameter	Specification
ESD standards	IEC 61000-4-2
EMC Standards	IEC 61000-4-4
Isolation Standards	IEC 61800-5-1

2 Reference Design

The following section provides an overview of the GPD and details about the TLI4971 current sensor module design and implementation in the GPD. The TLI4971 current sensor is available for different applications with different current ratings, refer to the datasheet [6] to choose the correct device for your current sensor module design.

One very common method to measure the current is to use single-ended ADCs integrated into the controller. Single-ended measurements are more prone to noise in a larger drive system, which can lead to inaccuracies in the measurement. DC offset and/or noise in the signal path will decrease the dynamic range of the input signal. Single-ended inputs are ideal if the signal source and ADC are close to each other (i.e., on the same board so that signal traces can be kept as short as possible). Single-ended inputs are more susceptible to coupled-noise and DC offsets as shown in the below Figure 3. However, signal conditioning circuitry can used to reduce these effects.

Differential measurement helps to overcome the noise issues. Another key advantage of differential signals is the increased dynamic range as the power supplies of the sensors dropping to 3.3V and lower. In theory, given the same voltage range for single-ended and fully-differential inputs, the fully-differential inputs will have double the dynamic range as the output is {AN+} - {AN-} (see Figure 3). This is because the two differential inputs will be 180° out of phase, as shown in Figure 3. The advantage of TLI4971 is that the user can configure the sensor to operate in either differential or single ended mode.

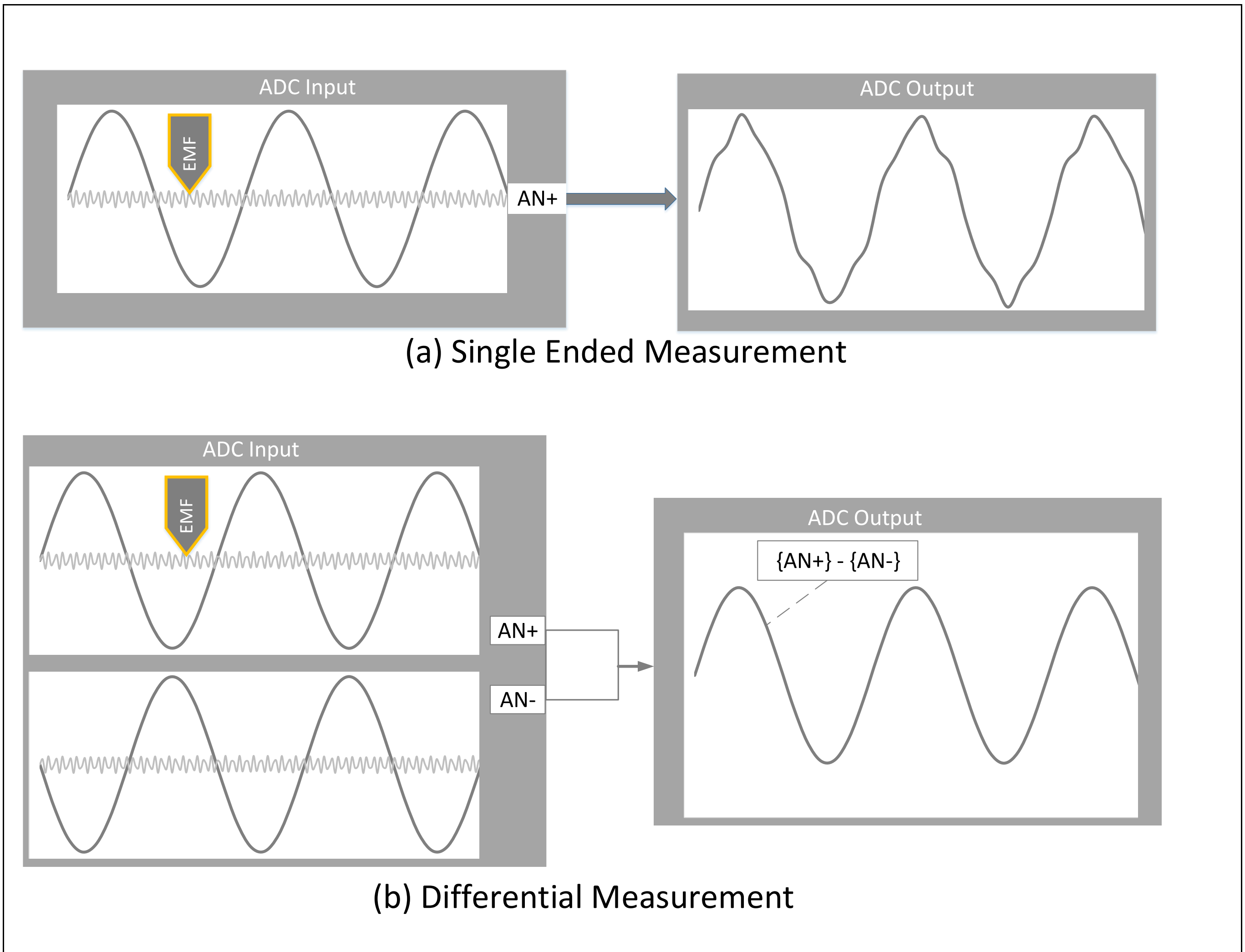


Figure 3 Comparison of Sinle-ended & Differential mode ADC Measurements

The signal conditioning circuit, interfacing the Hall effect sensors with the controller, is required for the following reasons:

- In case the TLI4971 interfacing with the 5V devices in an application, then it requires an amplifier for level shifting to interface the current sensor output to an ADC with a 5V reference. For further information on how to interface the 3.3V sensor with 5V devices, refer the TLI4971 programmer guide application note [3].
- Proper filtering circuit must be chosen for the analog output of the sensor, otherwise the control loop bandwidth will be effected which results in unbalanced operation of the GPD.
- Proper layout implementation is necessary to prevent errors in motor current measurements due to cross-tals and stray fields, which also affects control loop performance. Therefore, the proper implementation of a signal conditioning and guarding for better accuracy is discussed in the below sections.

2.1 Isolation Co-ordination Scheme

In GPD, isolators and isolated power supplies are typically used in both functional and safety isolation circuits to separate the low voltage control circuit from the high voltage power path, and keep interface circuits separated from circuits that are dangerous to touch. GPDs requires an isolation between different voltage levels of power, interface and control circuits to reduce the noise interference and safety purpose.

In the system structure of a VFD, circuits are separated into three parts, which are power, control, and the interface as the voltage levels and safety requirements are different in each part and galvanic isolation is needed in between them.

From system point of view, minimizing the number of signal channels that require isolation and reducing the use of reinforced level insulation components are important design concerns.

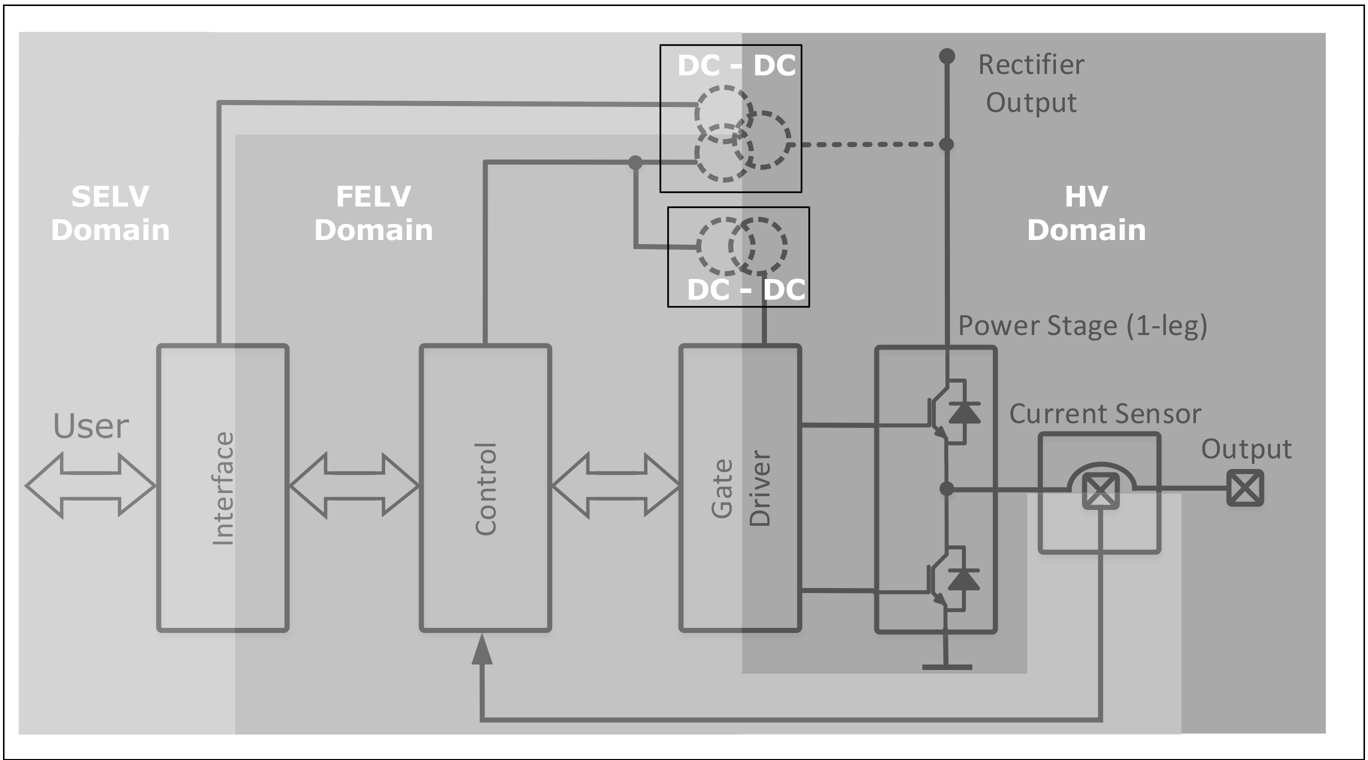


Figure 4 Proposed two barrier isolation architecture for the GPD

The proposed system architecture block diagram shown in Figure 6 depicts the two isolation barrier design scheme for the GPD application. One isolation barrier is between power & control circuits, and another one is in between control & interface domain. The Isolation between power and control circuits can be achieved by using an isolated IGBT gate driver and current/voltage sensing components. TIL4971 provides functional isolation, therefore the suggested architecture is necessary to achieve reinforced isolation. Additionally, the separation of power and control domains can also reduce power switching noise impact on other domains. The isolation between Interface and control circuits can be unnecessary if the isolation between the power and control circuits already meets the system safety requirements. Furthermore, double insulation can be achieved by a combination of components in the two barriers.

2.2 Bandwidth requirements

The current loop controls the torque in motor by manipulating the pulse-width modulator (PWM) outputs that drives an inverter. The current-loop feedback path measures the analog output of the current sensor with a high-precision analog to digital converter (ADC), and then feeds the result in to the current-loop controller. The current control loop bandwidth becomes the linchpin upon which the rest of the inverter drive system depends.

This section describes an interface filter circuit design between the sensor and ADC of the micro-controller, which is important to scale and filter the high frequency noise of the current signal. Here, the designer must choose the proper C_{AIN} and R_{AIN} (see Figure 8) values to reach best measurement accuracy and meet bandwidth requirement.

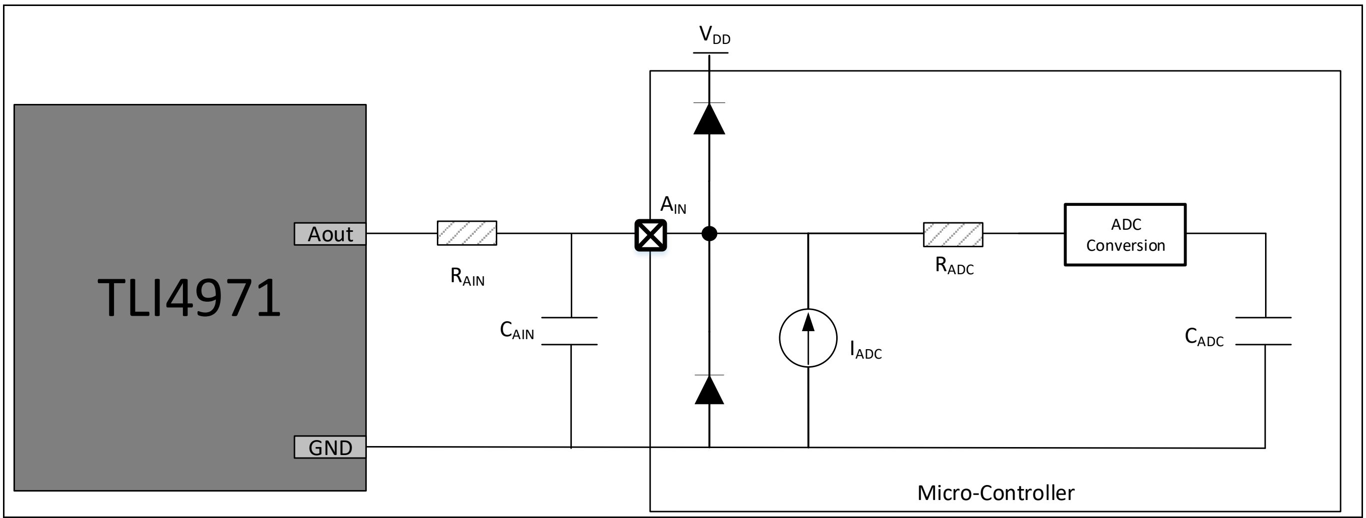


Figure 5 ADC interface circuit with TLI4971 Analoge output

For example, if the maximum error allowed is equal to 1/2 LSB then the maximum source resistance is calculated from the below equation.

$R_{\max} = \frac{t_s}{C_{ADC} \cdot \ln(2^{N+1})}$ Or $R_{AIN(\max)} = \frac{1}{2.\pi.C_{AIN}.F_C}$ if the C_{AIN} is already calculated.

Then calculate the capacity of C_{AIN} as shown in below:

$C_{AIN} \geq C_{ADC} \cdot \frac{V_{max}}{V_{LSB}}$ Or $C_{AIN} = \frac{1}{2.\pi.R_{AIN(\max)}.F_C}$ if the C_{AIN} is already calculated.

The chosen value of the C_{AIN} must meet the cut-off frequency (F_C) requirement of filter bandwidth.

Here, t_s is the sampling time

N is the ADC resolution

$R_{max}=R_{AIN(max)}+R_{ADC(max)}$

What is obvious from the above calculation is that as R_{AIN} is increased, the cutoff frequency will be reduced. So, the designer has to select the proper components to achieve the required cut-off frequency.

2.3 Over Current Detection scheme

The TLI4971 IC comes with two over current detection (OCD1 & OCD2) pins with fast pulse response time. Here, the user can select 6 different OCD threshold levels with different glitch timings, for further information refer to the device datasheet. Also, the user has the ability to select the hysteresis whether to ON or OFF.

Among the two OCDs, the OCD1, which is fastest, can be connected directly to the gate driver to enable or disable the PWM outputs of the converter. The below Figure 6 shows the over current detection scheme proposed for the GPD. All OCD1 pins from four different current sensors are tied together and connected to gate driver as well as micro-controller to report the over current immidiately. Also, all OCD2, which is slower compared to OCD1, pins from four different current sensors are tied together and connected to micro-controller. When there is short circuit or over current in the system, based on the threshold settings, initially the OCD1 will disable the gate driver to switch off the PWM signals which are connected to power stage.

The TLI4971 current based shutdown is a better option when compared to the Desat function as it has fixed threshold level to trigger the fault. Whereas, the Desat current sensing technique has huge variations of current threshold values due to the active and passive elements used in the external circuit connected to the Desat pin.

2.4 Hardware Description

The system block diagram of the GPD application, see Figure 6, which shows the power stage, microcontroller unit (MCU), a gate-driver, and a current sensor. The current sensors placed in this system are in phase to the motor each phase. The isolated gate-driver is the interface between the MCU and the power inverter.

2.4.1 Power Stage Module

The used power stage is a single module called the FP100R12W3T7_B11 that consists of three phase inverter, brake chopper and three phase bridge rectifier, for further information refer to the device datasheet. To sense the current through the DC+, a TLI4971 is connected in series to the DC+ bus, which is used to detect the over current through any of the three phase inverter leg, after the DC link capacitor bank. A relay circuit is used to control the inrush current through the capacitor bank. Once the capacitor is fully charged, a relay is used to bypass the capacitor. Brake chopper IGBT is used to limit the voltage across during regeneration.

Three current sensors are used inphase to the motor to measure and detect the current through each motor phase. These sensors outputs are used to control the motor performance such as torque and speed.

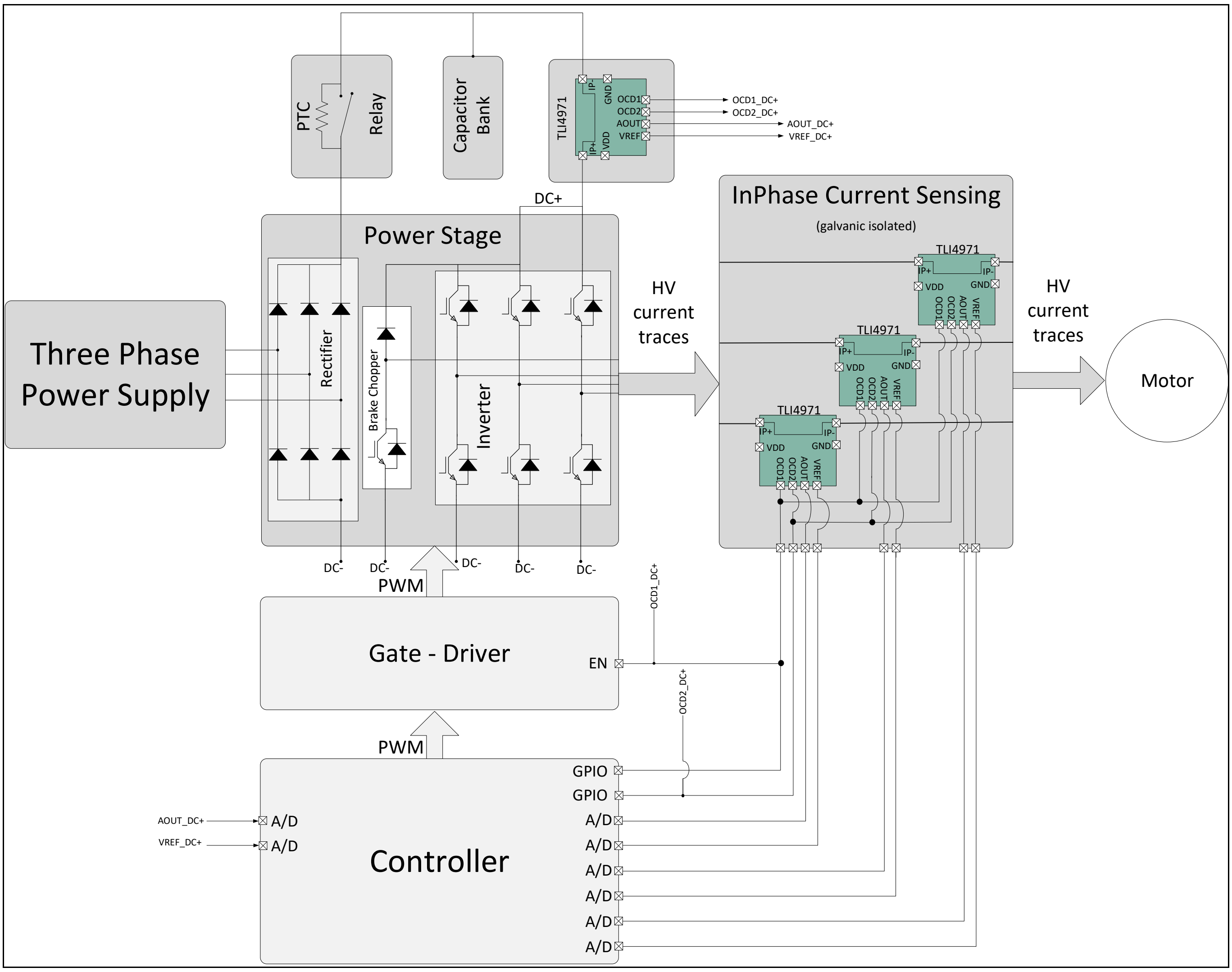


Figure 6 Block Diagram for GPD

An IGBT based three phase inverter output of power stage is connected to the motor input by placing three TLI4971 current sensors in series with the each phase of the motor. The 3-phase inverter bridge is switched such that the sinusoidal current is injected into the motor windings (see wavefrom in location 3 of Figure 2). For example, the current sensor chosen based on the motor winding peak current which is calculated as follows:

- Motor rating, P_{out}= 22 kW
- Line-to-line voltage, V_{LL}= 415-V AC
- Power factor, $\cos\emptyset = 0.8$
- Motor efficiency, $\eta_{motor} = 85\%$

$$I_{LL} = \frac{P_{out}}{\eta_{motor} \times V_{LL} \times \sqrt{3} \times \cos\emptyset} = 47A$$

Therefore, the peak value of the motor winding current is 66 A. Considering an overloading of 150%, the peak winding current would be 99 A. The TLI4971 supports the peak current range upto 120A with different sensitivity settings, refer the datasheet [7].

The device with ±100A full scale current capability is used for this application with a sensitivity of 12mV/A.

2.4.2 TLI4971 Power Supply Concept

This section describes the power supply design for the current sensor which is placed in between power and control circuits. Figure 7 shows the supply concept of the FELV & HV domain in the GPD application where the current sensor is placed in the FELV domain (see Figure 4), where all the control devices are placed. Here, an isolated DC/DC Converter is used to convert the three phase rectifier output into 15V_HV & 24V_SELV voltages. The 15V_HV is used for supplying IGBTs gate driver with an isolated DC-DC Converter, and IFX_91041_ADJ voltage regulator, which generates the 5V isolated output. Using TLS115DOLD, the 3.3V is generated from the 5V to supply the current sensor. Please refer the TLI4971 datasheet [7] for the supply tolerance requirements.

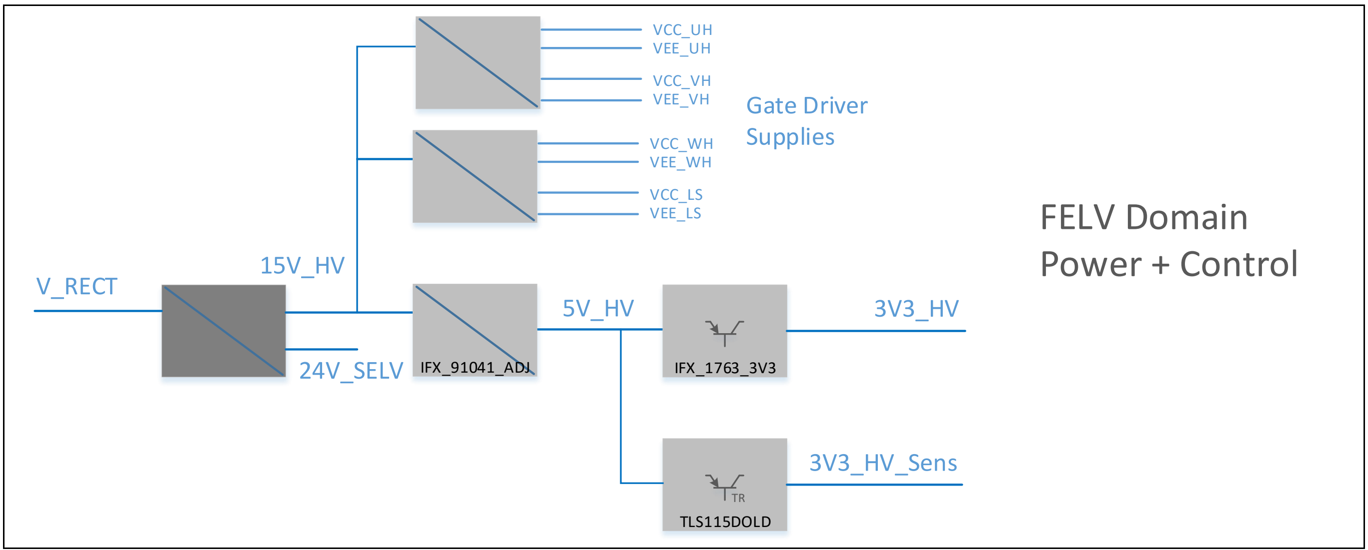


Figure 7 FELV & HV Domaon Power Supply Concept

2.4.3 TLI4971 Current Sensor Schematic

The inphase current measurement method is used to measure the motor phase current. Figure 8 shows the schematic of the TLI4971 current measurement circuit which supports a measuring range of $70A_{RMS}$ within an accuracy of at least 3.4% over life time and temperature. To reduce the error furthermore, TLI4971 can be calibrated at the user end or end of line using the programming feature of the TLI4971 (Please refer the AppNote for programmer guide [7], EVAL120 [1] & ProgGUI [2]). By using this programming feature one can achieve an error less than 2% over life time and temperature after end of line calibration.

As shown in Figure 8, the decoupling and bypass capacitors, which are connected to each pin on the sensor output/input signal, to suppress the high frequency noise and meet the EMC and ESD requirements is as follows:

- A decoupling capacitor of 220nF is recommended at the VCC pin of the sensor
- A bypass capacitor of 6.8nF is recommended for the AOUT and VREF to each output pin
- A 1nF bypass capacitor is used to each pin of the OCD1 and OCD2 pins to meet the EMC requirements.

When the sensor is used in three phase applications, all the OCD1 pins can be tied together as well as OCD2 pins as shown in the below Figure 8 since both are open drain pins and connected to a 4.7k Ohm pull-up resistor to each pin.

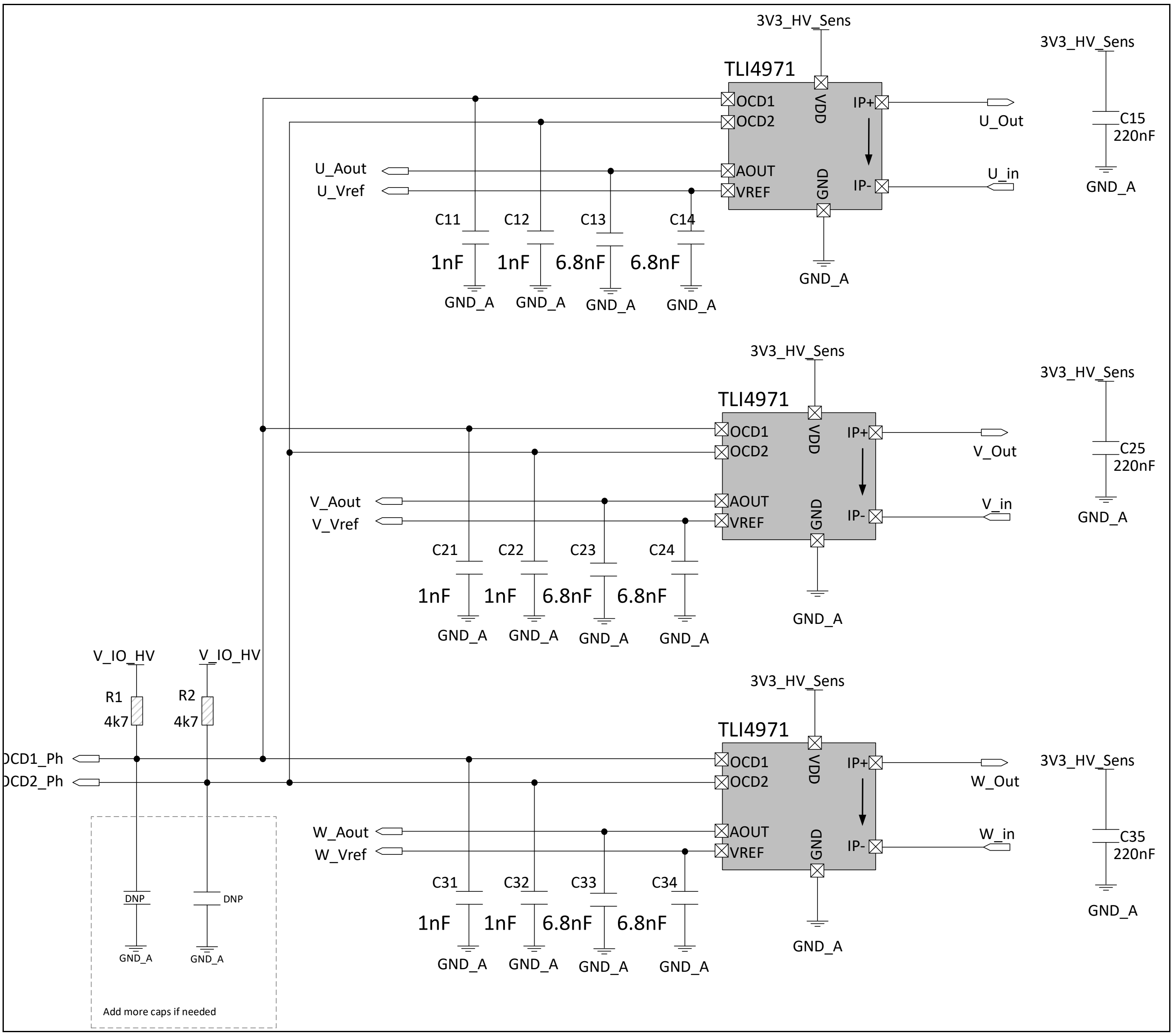


Figure 8 TLI4971 Schematic Connection Diagram

2.5 Current Sensor Layout Guide Lines

As the current sensor is used in high voltage applications, special attention has been paid to the layout of the current sensor stage. For better cooling of the current sensor, thermal vias are placed around the current sensor as shown in the below figure.

Proper clearance and creepage distances between PCB traces are critical to avoid flashover or tracking between electrical conductors. Clearances are dimensioned based on supply voltage and creepage distances are based on the R.M.S. value of working voltage across the spacing of interest. Here, in the GPD application, overvoltage category III and pollution degree 2 are considered for the PCB design. IEC 61800-5-1 specifies requirements for adjustable speed power drive system, except traction and electric vehicle drives.

For example, supply mains-powered equipment, the minimum allowed PCB spacing should be determined from IEC 61800-5-1. This standard specifies creepage and clearance distances for various grades of insulation depending on working voltage, pollution degree, PCB material group and coating.

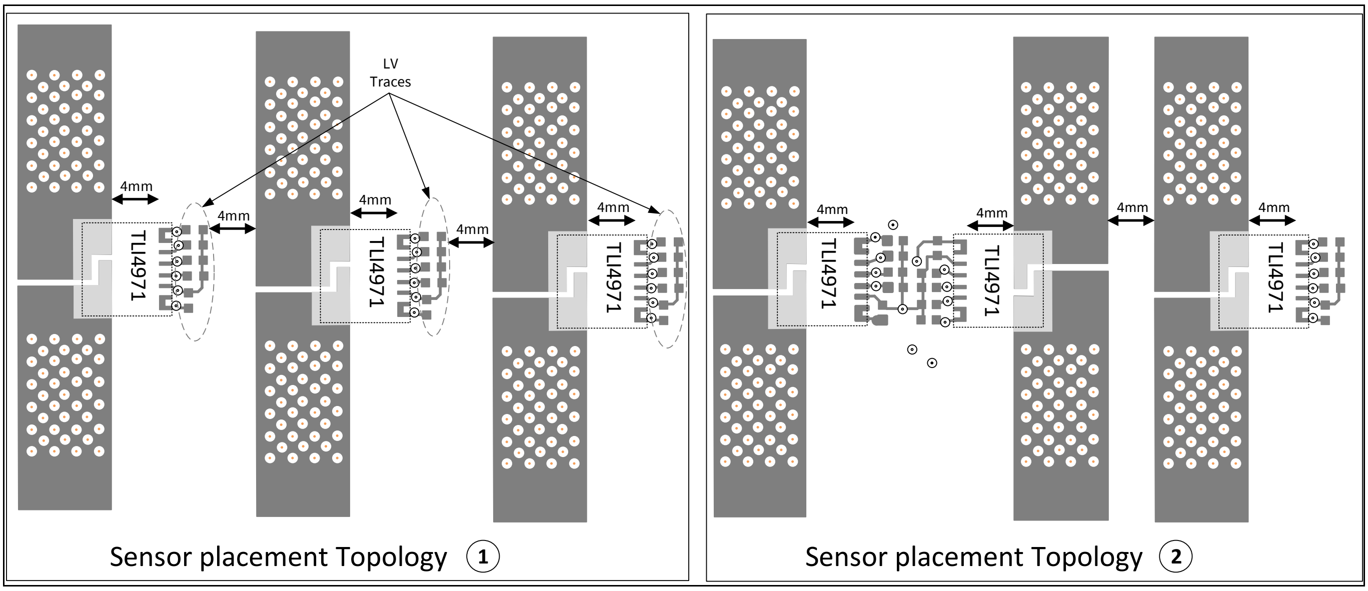


Figure 9 High level Block Diagram of the current sensor arrangement

2.5.1 Current Sensor PCB Size Optimization

The current sensor arrangement to optimize the PCB size is shown in Figure 9 and also compares two different topologies. The total space required in the x-direction on the PCB is less for Topology 2 compared Topology 1 (see Figure 9). If we assume that the HV current trace width is X (mm) for each phase, then the minimum 4mm can be reduced irrespective of the space required for the other LV traces of the current sensor.

2.5.2 Signal Conditioning or Guarding Trace

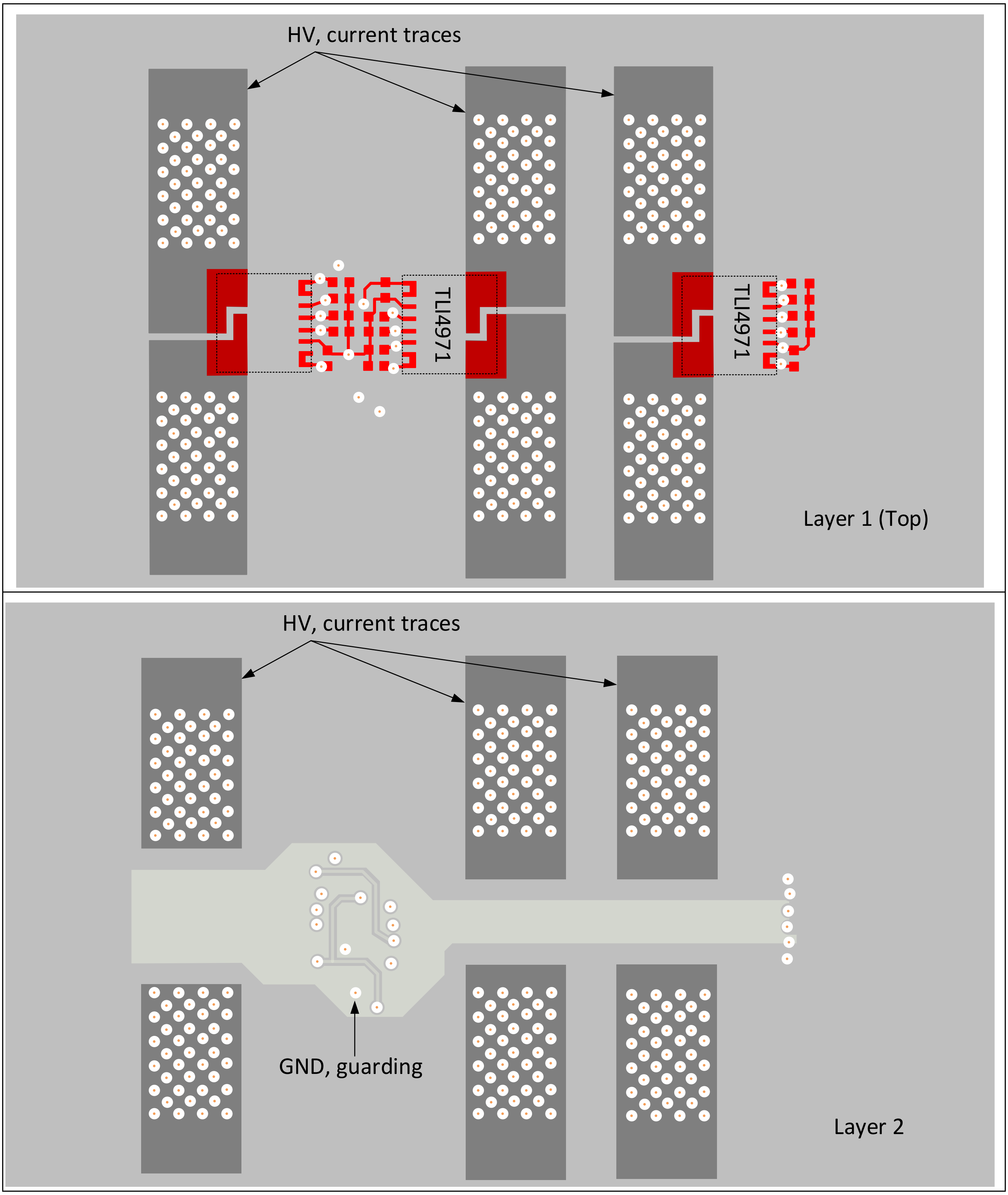
Figure 10 shows an example layout implemented for the GPD application. Here, a four layer PCB with 140um copper layer thickness is used. In the below figure, the proposed routing and placement of the HV traces, vias and sensor in each layer is discussed.

Further information about the layout influence in terms of temperature rise or cooling strategy and sensitivity variation is discussed in a separate application document called PCB Soldering Guide Lines [5].

The guard trace is one of the most critical parts of the circuit as it reduces crosstalk within the circuit. An additional measure to reduce the crosstalk between parallel traces routed on the same layer is to separate them using a trace connected at both ends to ground, called guard trace. It is essential that the guard trace is connected at all ends to ground, otherwise it will behave like an antenna.

A guard trace will also have beneficial effects on the electromagnetic interference of the trace with the surrounding environment, so guarding very noisy and very sensitive signals is still recommended.

Figure 10 shows the current sensor placement in each layer and its current carrying HV traces in the PCB. Also, it describes the signal layer guarding concept in the PCB. Here, the sensor LV output signals are traced through the layer 3 which are protected from crosstalk & capacitive coupling by placing guard trace in the Layer 2 which is connected to the sensor ground.


HV, current traces
TLI4971
TLI4971
Layer 1 (Top)
HV, current traces
GND, guarding
Layer 2

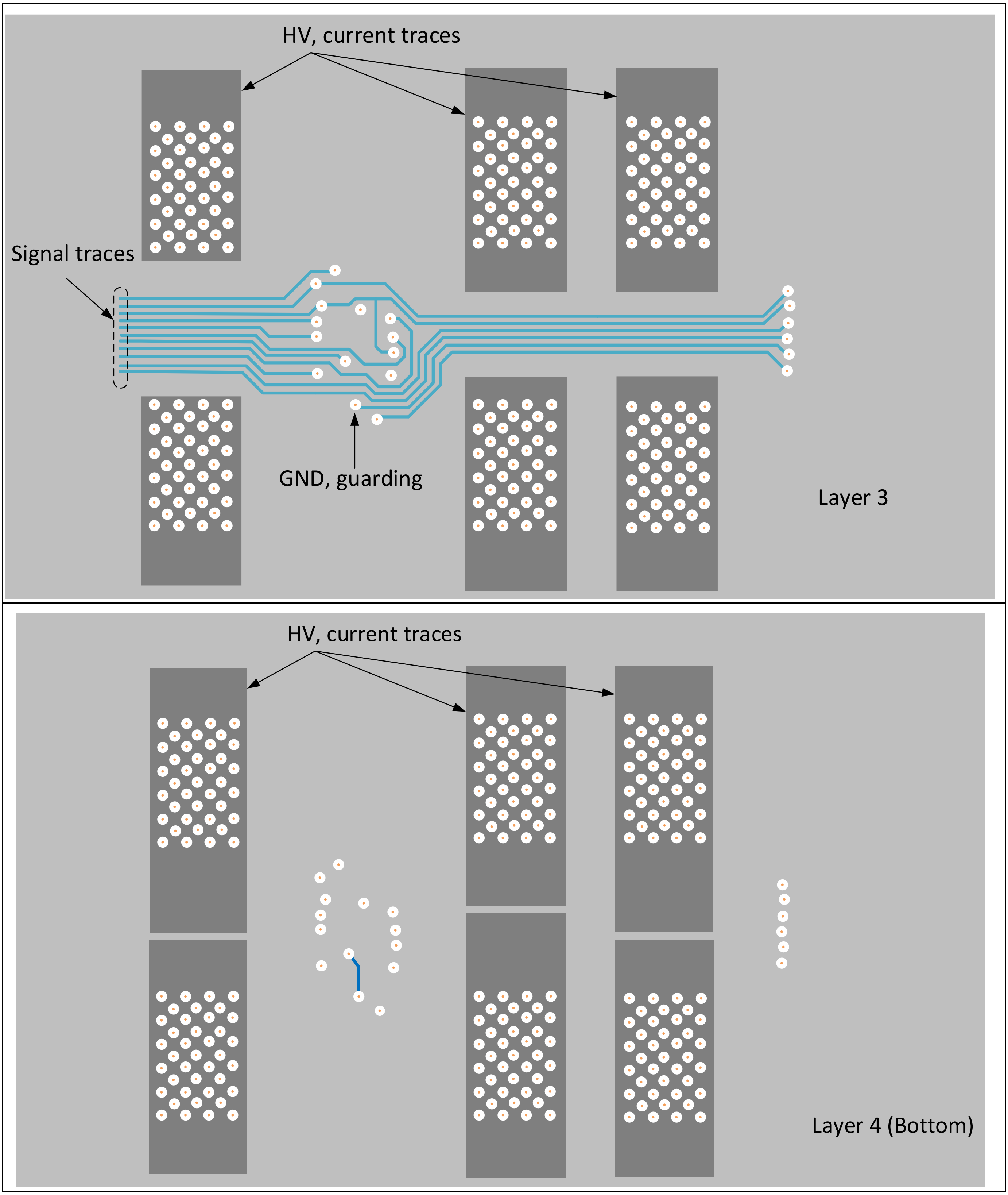


Figure 10 GPD Current Sensor Layout

2.5.3 External silicone potting on terminals and Vias

Adding external silicon potting on terminals is a common practice to provide an extension of the creepage distances and to improve the pollution degree. This solution could also work as external chemical protection, as a possible mechanical containment and protection (especially for certain types of SMD components), in case of device explosions. High temperature silicon based compounds and epoxy, urethane and polyurethane derivatives are commonly used. Here it is also recommended to avoid any formation of cavities and voids during the deposition process, in order to prevent isolation problems.

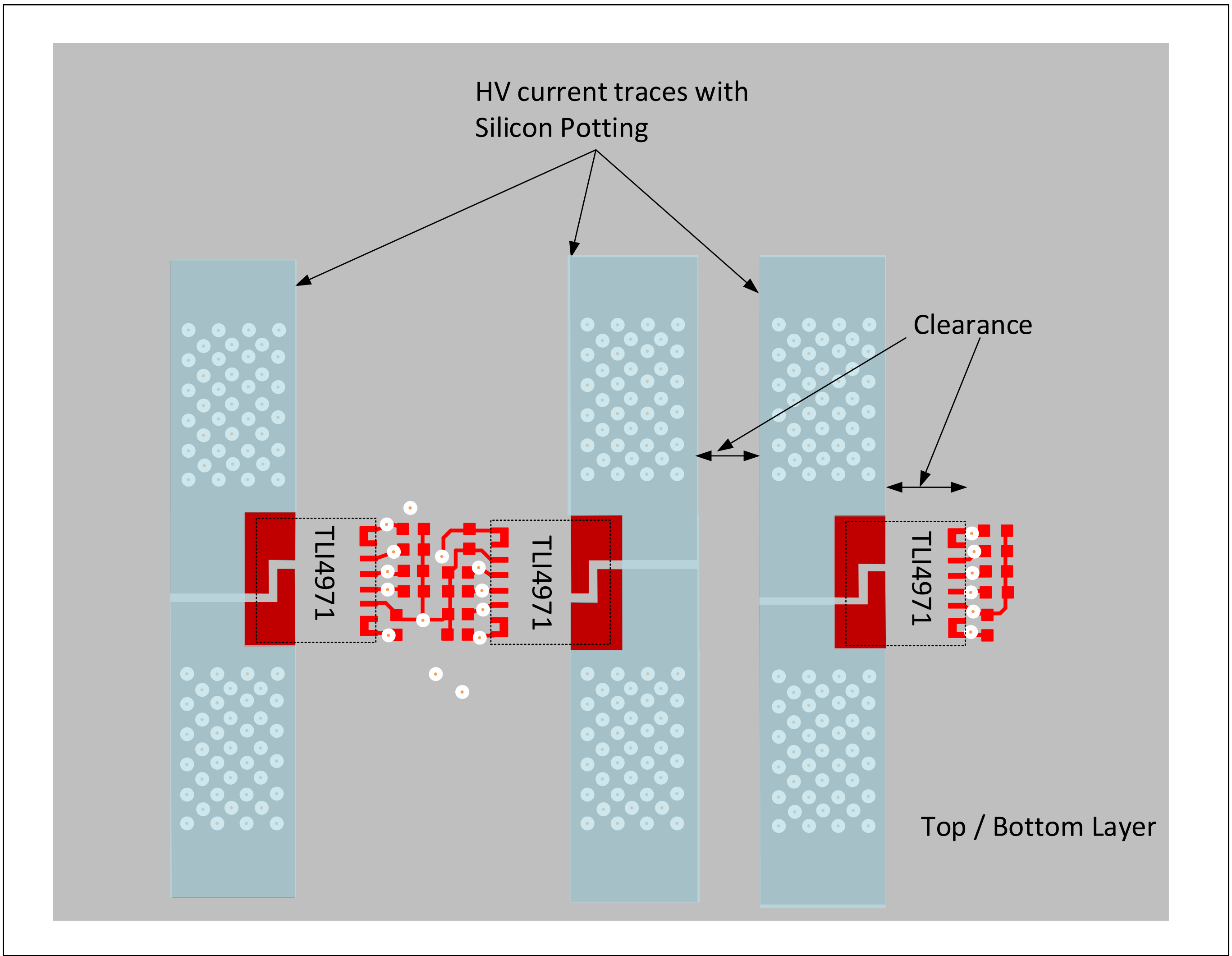


Figure 11 Silicon potting to extend spacing and to improve the pollution degree

Figure 11 shows the silicon potting on the high voltage terminals and vias. The most common example to start with is on how to increase the spacing between uninsulated live parts of opposite polarity. A TLI4971 is soldered on a Printed Circuit Board (PCB) and external components (i.e. resistors or Vias) are placed nearby the high voltage node. In case of presence of high voltage and harsh environment, such distances (black arrows in Figure 11) are not enough to fulfil most of the relevant standard for the electrical equipment. Therefore, a simple way to overcome this problem is to protect the TLI4971 providing a high temperature silicone potting directly on the device terminations in order to cover it completely. Automatically, this measure will improve the electrical safety increasing the “spacing” of the TLI4971 terminations offering a higher pollution degree level at the same time and the clearances between termination and adjacent component.

2.5.4 Slot in the PCB

This is another method to increase the creepage distances between components. The spacing distance between components that is required to withstand a given voltage is specified in terms of clearance and creepage. A visual representation of the distinction between these terms and their applicability to board-mounted components is shown in Figure 12. As discussed in the above, such as high voltage and harsh environment, another simple way to protect the TLI4971 is providing a slot in the PCB to increase the creepage (black arrows in Figure 12). Automatically, this measure will improve the electrical safety increasing the "spacing" of the TLI4971 terminations offering a higher pollution degree.

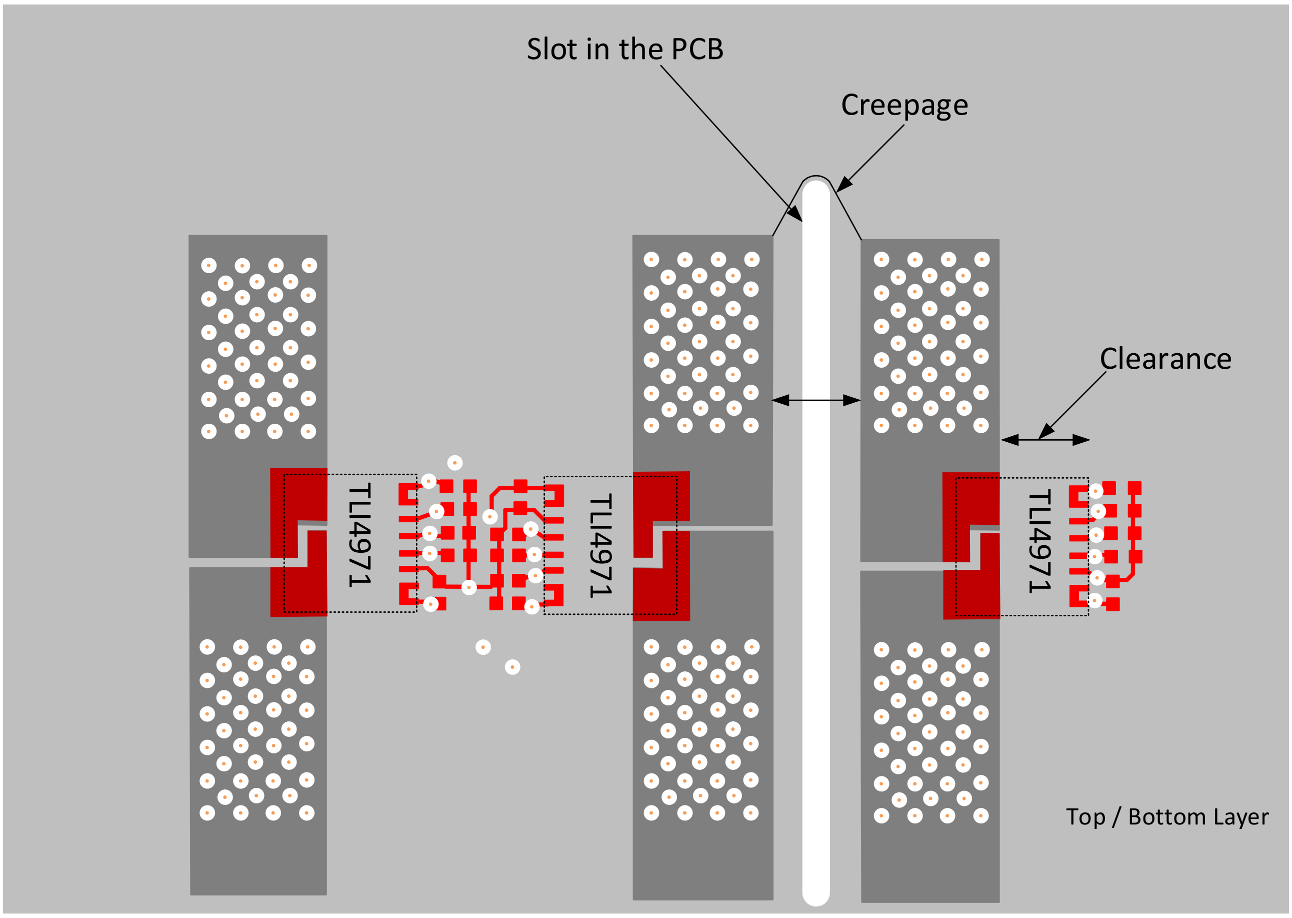


Figure 12 Slot in the PCB to improve the pollution degree

2.5.5 EMC & ESD Guidelines

Semiconductors are basically built of transistors, diodes, capacitors and resistors integrated on one piece of silicon. As very small structures are integrated on a few square millimeters an external voltage-surge or current surge may harm some of these structures. Even a small harm may lead to a nonfunctional device. Additionally even small external disturbances may affect the function of a device temporarily.

For further detailed information, please refer the TLI4971 EMC Recommendations application notes [3].

2.5.6 Stray Field Suppression

For further information about stray field suppression and compensation techniques are discussed in a separate document called Stray Field Suppression document [4].

3 Glossary

Notation	Description
FELV	Functional Extra Low Voltage
SELV	Secondary Extra Low Voltage
EMC	Electro Magnetic Compatibility
EMI	Electro Magnetic Interference
ESD	Electro Static Discharge
PCB	Printed Circuit Board
PWM	Pulse Width Modulation
MCU	Micro-Controller unit
IGBT	Insulated Gate Bi-polar Transistor
OCD	Over Current Detection
HV	High Voltage
LV	Low Voltage
AC	Alternating Current
DC	Direct Current
FOC	Field oriented control
Cap	Capacitor
AOUT	Analog Output
VREF	Reference Voltage
GPD	General Purpose Drive
I	Current
B	Magnetic Flux Density
V	Voltage
µC	Micro-Controller
LDO	Low Dropout
FET	Field Effect Transistor
LSB	Least Significant Bit
IC	Integrated Circuit
ADC	Analog to Digital Converter
VFD	Variable Frequency Drive
RMS	Root Mean Square

4 References

[1] AN_TLI4971_EVAL120A Application Notes

[2] AN_TLI4971_ProgGUI Application Notes

[3] AN_TLI4971_EMC Application Notes

[4] AN_TLI4971_Strayfield Application Notes

[5] AN_TLI4971_PCB Application Notes

[6] TLI4971 datasheet

[7] AN_TLI4971_ProgGuide Application Notes

Revision history

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