Ultra-low impedance current sensor with less than 1 nH inductance enabling wide-bandgap design with smallest form factor

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1. Abstract

Energy efficiency enables exploration of new fields in industrial applications. Reduced self-heating and smaller size allows integration of the inverter directly at the motor.

However, continuously increasing the switching frequency of the latest generation of industrial drives creates demanding challenges for today's inverter designs.

The new technologies, silicon carbide (SiC) and gallium nitride (GaN), as well as the latest generation of IGBTs, allow switching frequencies far above 100 kHz. To overcome the switching losses of the power devices, the slew rate is increasing every year.

As well as the power semiconductors, the traces on the PCB and the overall layout are becoming the focus of more attention. A long trace acts as an inductor over increased frequencies, so the layout engineer needs special training in RF design of the PCB to avoid creating unnecessary inductance in the trace.

But what else is in the power line aside from special inductances and RF-proven capacitors?

In an advanced design there is a current sensor monitoring the zero crossing of the charge current of an inductor, to optimize the efficiency and also to feedback dynamic loads. A special current rail design offers a parasitic inductance of less than 1 nH, optimizing the RF-design of your high efficiency GaN inverter.

2. Introduction

One of the possibilities for increasing energy density and energy efficiency is increasing the switching frequency of the inverter design.

First, the physical size of capacitors and coils can be dramatically decreased, by using smaller capacitors and smaller inductors at the same power transfer. Imagine the old Nokia® power supplies in the 1990s providing 3.7 V at something like 500 mA. These supplies got hot whenever they were plugged into the grid. Today, the latest chargers give 5 V at a rate of 2 A. They use a smaller design on the PCB, take up less space, and they do not get warm when they are connected to the grid in idle mode.

Exactly this principle is applied on modern inverters, enabling new possibilities to apply power to a motor. While 20 years ago a rack could house a 100 kW inverter, today it can carry a 300 kW inverter, or just use one-third of the space of the rack. The high switching frequency with reduced thermal losses is enabled by fast slew rates in the different switching topologies. Thanks to new material and enhanced design, the semiconductors enable these fast slew rates, and this will continue to improve in the future.

The resulting challenge for the system is using components with the lowest possible inductance in order to get the fastest slopes when switching between the voltage levels. As the fast switching could harm other components, the devices selected for the high-efficiency inverter design must be tested for:

- extreme current slew rates up to several hundreds of A/µs
- extreme voltage slew rates up to 50 kV/µs
- extreme temperature conditions as in industrial drives –
  made possible and supported by the high-temperature GaN technology.

As the PCB and the components are optimized in terms of parasitic inductance, the current sensor in the power loop must support these features as well.

When optimized shunts in the class of 200 µΩ show a typical inductance of minimum 3 nH the TLI4971 differential magnetic current sensor offers an inductance of less than 1 nH through its internal current rail. In both ranges a multilayer PCB with the return-path of the energy is in the layer below the current-measuring device.

Finally, the reduced power loss and the minimized area enable integration of the power semiconductor and the control circuit into the foot of a robot arm. The power range starts at something like 1 kW in a 48 V design and goes up to almost 100 kW in a three-phase 480 V design. We call this a very smart drive design.

3. The ingredients for a low-impedance and highly efficient design

Semiconductor technology once allowed gallium nitride LEDs to glow blue. Today the switching times of switched-mode power supplies and inverters can be significantly accelerated with this special semiconductor. GaN technology is the key to achieving smaller designs, because long lines and thus line parasites must be avoided.

3.1 GaN technology

In 2012, the first prototypes of field-effect transistors based on gallium nitride were used in switched-mode power supplies and were able to achieve significantly higher levels of efficiency than comparable field-effect transistors based on silicon. These components are popular in high-performance high-frequency amplifiers such as those used for base stations and the infrastructure of cellular networks.

Compared to silicon, the temperature stability of these power semiconductors is particularly noteworthy. The switch-on resistance remains constant up to well over 100°C, and this simplifies the design because no additional power reserves have to be taken into account for operation across the complete temperature range. The comparatively low temperature development allows the built-in volume to be reduced in the application.

Unfortunately, GaN technology is still comparatively expensive and is therefore only used where a particularly small installation space is necessary and temperature development plays a decisive role. With the increasing production volume, this technology is becoming cheaper and more competitive in more and more applications.

3.2 Low-inductance design

In order to be able to fully exploit the advantages of the new GaN technology, components must not be connected with simple cables as usual, and the conductor width must be taken into account according to the current-carrying capacity. In this system it is increasingly important to control the impedance and to conduct the returning current, and also to keep the parasitic inductances as small as possible so that the GaN bridges can switch between two voltage levels in a few nanoseconds.

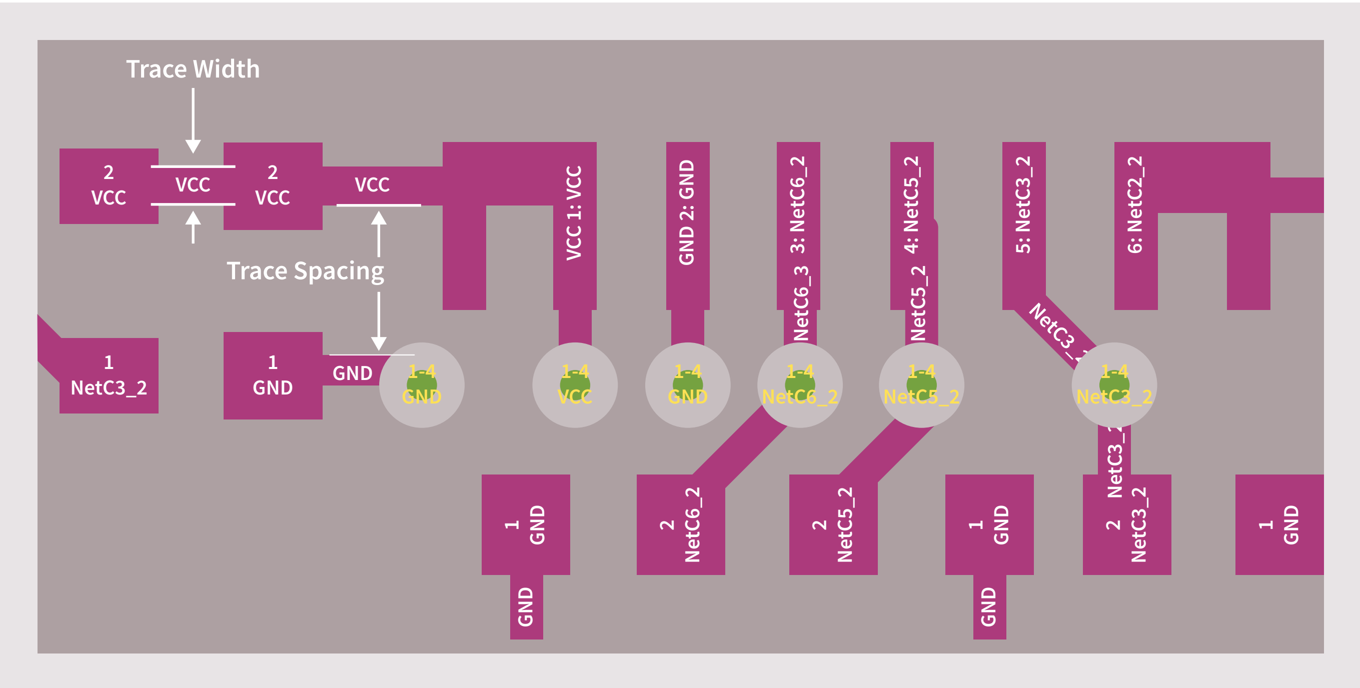

Figure 1: Typical wiring on a PCB

The distance between the components should be as short as possible in order not to unnecessarily increase the parasitic capacitances. Overall, the position of the components should be well chosen and the cable routing should be carefully considered. For the design of inductivities that are as small as possible, a ground plane is essential – which, if possible, is only a few hundred micrometers below the phase to be switched. In this way, the energy is transported like in a waveguide, because the return current can move exactly below the outward current. It is clear that an SMT housing for components is preferable to a wired housing.

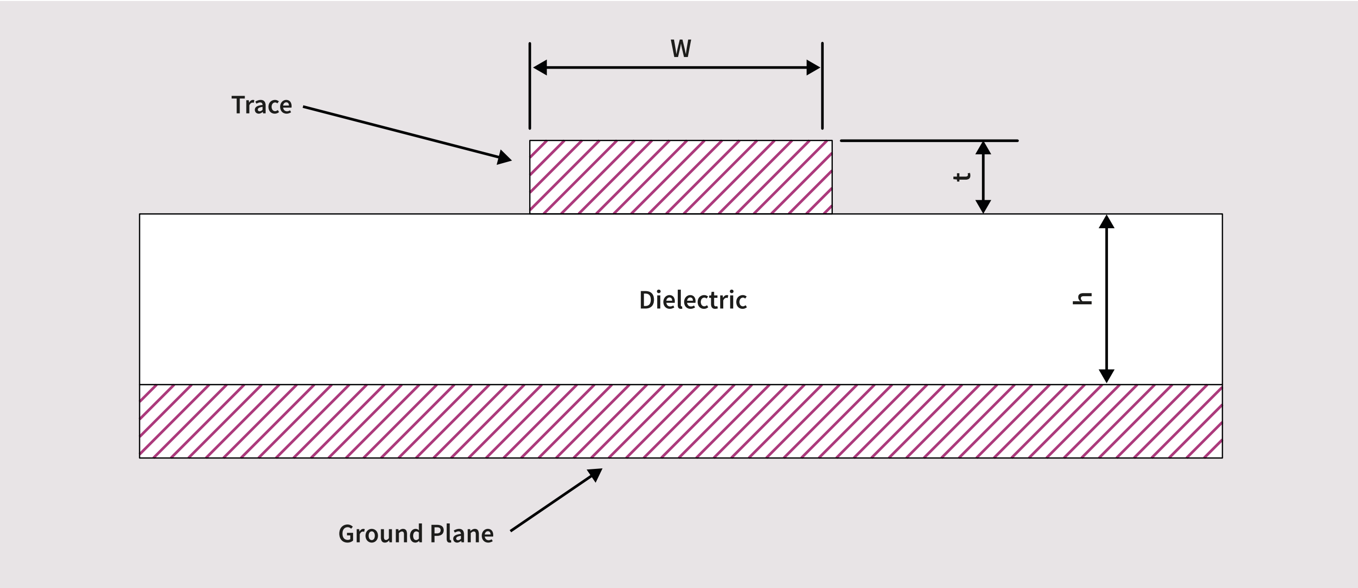

Figure 2: Dimensions of a microstrip design

3.3. Low-inductance current rail

The method of using the lead-frame as an integrated conductor rail has the advantage that the current carried in the conductor track is not PCB-conducted in the conductor track for a distance of less than 1 mm.

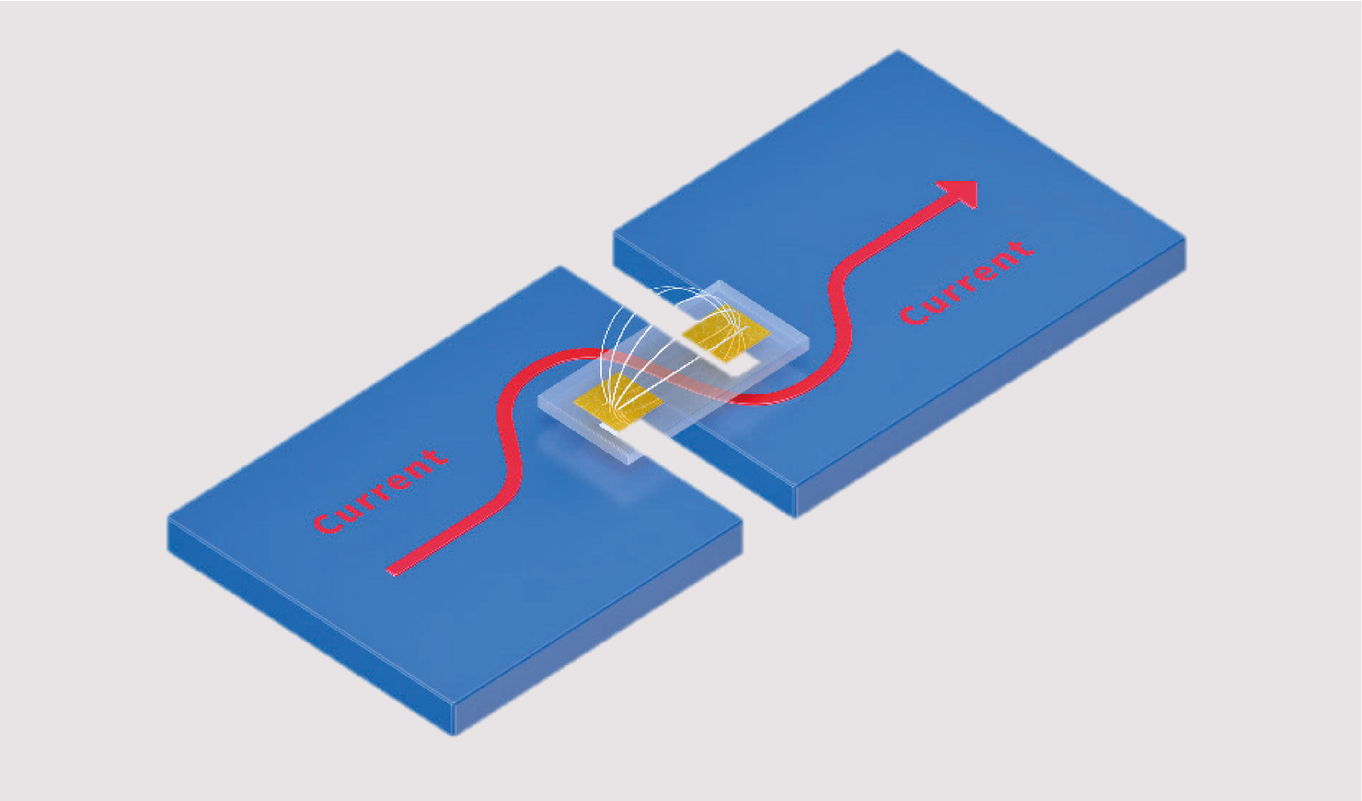

Figure 3: Scheme of a low-inductance current rail design as in TLI4971

Figure 3 describes a configuration in which, ideally, the current is continuously impedance-controlled. The S-shaped bend enables differential measurement, which intrinsically compensates for the stray fields from neighboring lines in a three-phase system.

Of course, this ideal state cannot be reproduced exactly due to mechanical position tolerances. The position of the Hall elements in relation to the edges in the cable routing would be too imprecise. The path leads over a small interruption in the power rail on the circuit board – exactly at the position between the two Hall elements.

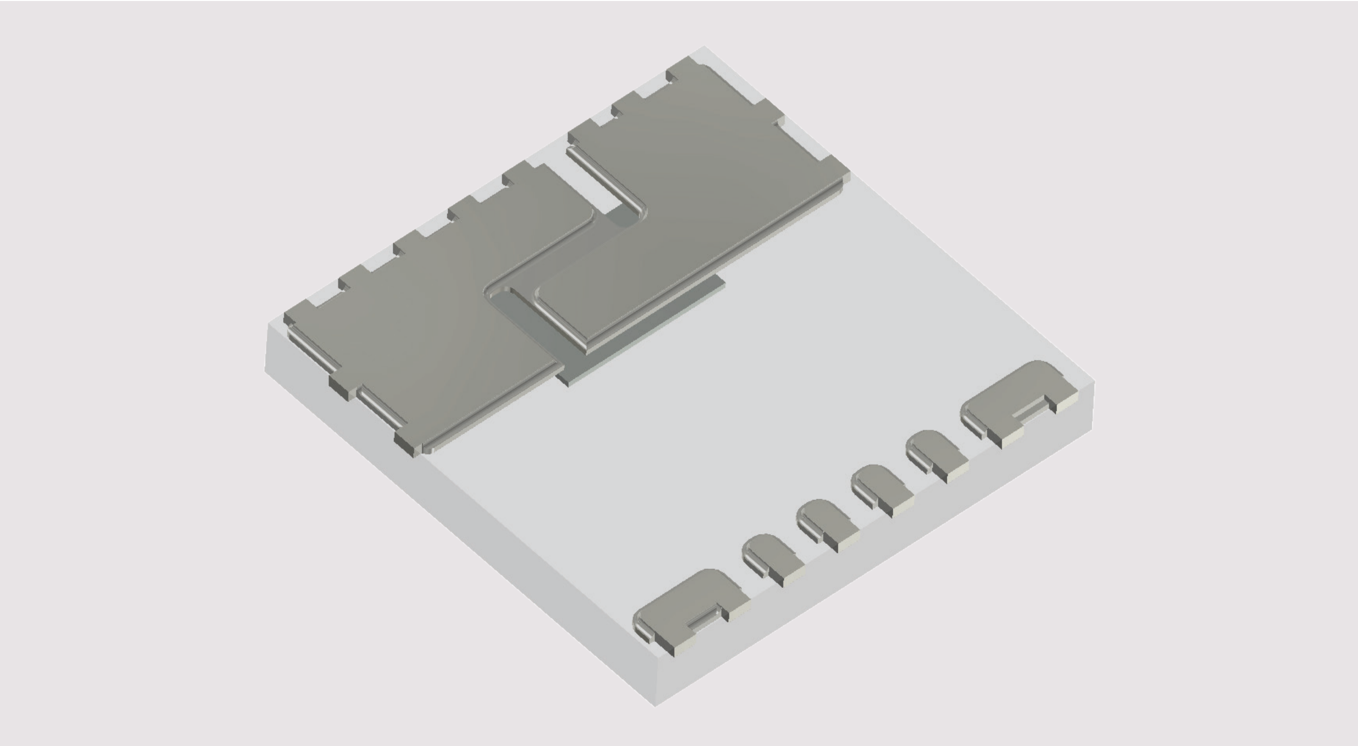

Figure 4: Bottom view (without plastic body) of the integrated current rail in the TLI4971

Figure 4 shows the inner workings of the TLI4971 as viewed from underneath. The left and right contact surfaces are suitable for soldering, and also for heat transfer up to 70 A continuous current.

Only in the narrow slot between these two surfaces is the current conducted exclusively within the lead-frame. The mechanical tolerances of the positioning of the silicon chip are compensated at the factory. The yellow-orange incisions represent the insulating layer between the conductor rail and the silicon plate. The conductor rail exactly follows the S-shaped conductor track, which is of course interrupted at the same point, so the current can flow in a defined manner through the conductor rail of the component.

The extremely small inductance, from one soldering surface to the other, can be quantified with the value 760 pH, which cannot be achieved by a shunt or any other technology where the closest value was around 3 nH as observed in a comparable shunt (in terms of resistance and power dissipation).

4. Summary

With the help of any wide-bandgap technology, it will be possible in the future to build a new type of system, such as very compact robotic arms.

The power supply, which used to be a full 19-inch slot, can now be installed in the base of the robot arm. The DC power supply is distributed to the various joints and motors. Together with a communication line, the wiring effort is very low and clear. The control of the motors is realized with an assembly attached to the motor.

Thanks to superior routing and unprecedented energy efficiency, new designs can be realized with minimal space requirements. Wide-bandgap customers will be amazed at how many benefits the high switching frequencies bring, and how much energy can be controlled within minimal volume.

5. References

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