How to Design an eBike Motor Drive Inverter Using EPC9173 Evaluation Board

Motivation

Due to the ever-increasing demand for highly efficient and compact motor drive applications, EPC has designed the **EPC9173** board eGaN IC-based to provide a reference design to achieve maximum performance for the eBike inverters. The EPC9173 is based on six **EPC23101** eGaN ICs. Such a board is a three-phase inverter capable of up to 1.5 kW operation; when powered with a 48 V_{DC} supply voltage, it can deliver 20 A_{RMS} per phase without a heatsink and with a heatsink it can provide continuously 25 A_{RMS} per phase with peak operation up to 35 A_{RMS} (for time intervals smaller than 30 seconds). The EPC9173 supports PWM switching frequencies up to 250 kHz.

System overview

The inverter board includes all the function circuits required to support a complete inverter for eBike motor drive as described in the following:

- Three-phase inverter based on six **EPC23101** eGaN ICs;
- DC link capacitors;
- Regulated auxiliary power supplies;
- Voltage, current, and temperature sensors with conditioning circuits;
- Protection functions

The pictures of the inverter board and are displayed in Figure 1.

A controller connector (J60) interfaces the EPC9173 signals with an external digital microcontroller unit.

The switching cells are arranged with a symmetrical layout. The phase output current is measured through shunt resistors. There are sensing resistors in phase and in the source path of the lower devices for each phase. Furthermore, a compatible motor shaft encoder or hall effect sensor can be connected to the EPC9173 motor control drive inverter through the connector J80 and the output filtered signals are available to the microcontroller on the connector J60. [1]

A built-in overcurrent detection circuit is triggered if an overcurrent (OC) occurs; the OC signal is sent through the J60 connector to the microcontroller.

The DC-link capacitors balance the fluctuating instantaneous power exchange between the battery and the inverter and stabilize the ripple caused by the inverter high-frequency power switching circuits. High switching frequency allows reducing the required capacitance value. For this reason, the DC-link is realized by ceramic and electrolytic capacitors and the user can customize the EPC9173 to find the optimum filtering in both high and low switching frequency operative conditions.

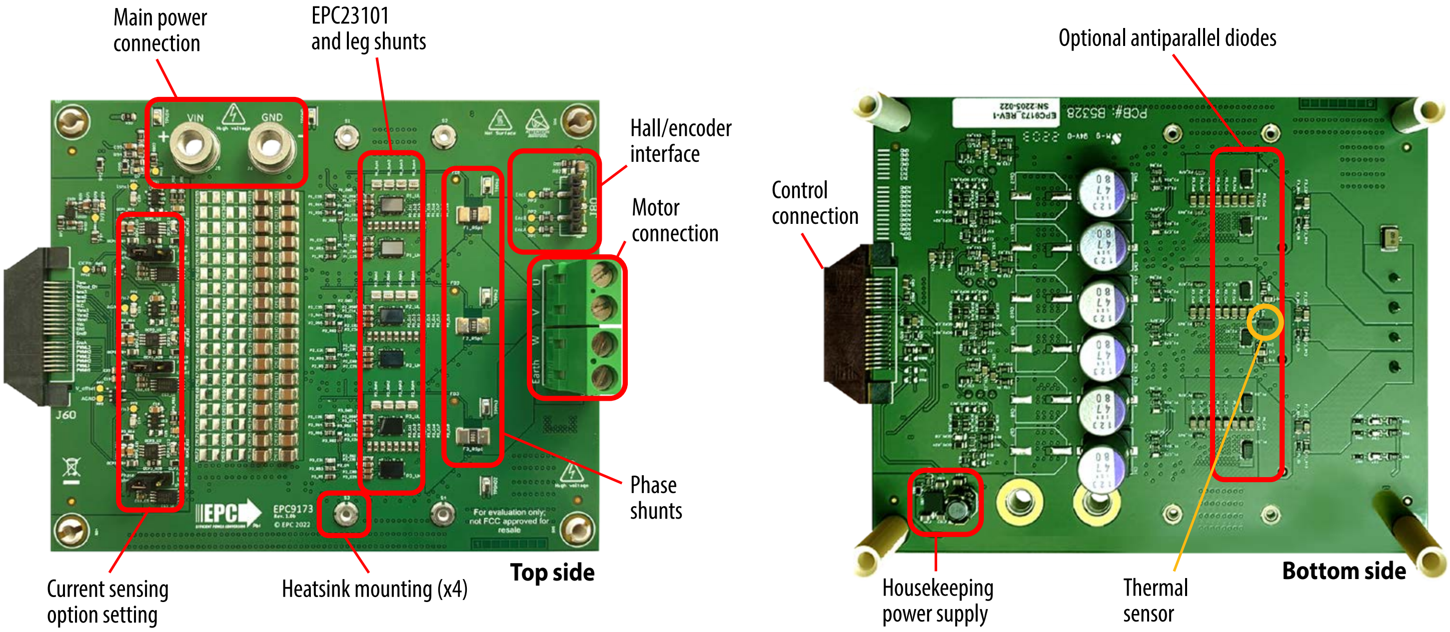

Figure 1. Photo overview of the EPC9173 board highlighting the main sections

The EPC9173 is equipped with a dedicated heat sink for natural convection cooling shown in Figure 2.

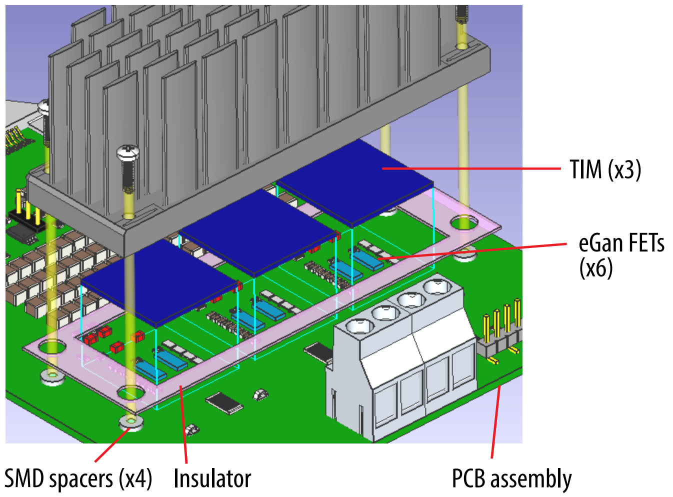

Figure 2. Details for attaching a heatsink to the board.

The heat sink is grounded and is mounted on top of a thin layer of insulation material to prevent the short-circuit with other components that have exposed pins conductors. The thermal interface material (TIM) is placed above the eGaN ICs to improve the interface thermal conductance between the die and the attached heatsink. The TIM used for this board is t-Global P/N: TG-A6200 x 0.5 mm with a conductivity of 6.2 W/m·K.

eGaN IC selection for motor drive inverter

The EPC9173 is a three-phase inverter made of six EPC23101 eGaN ICs.

Gallium nitride device technology has an exceptional high electron mobility and low-temperature coefficient. The EPC23101 eGaN IC has a typical Drain-Source ON Resistance $R_{DS(on)}$ of 2.6 mΩ (@25°C).

In addition, the lateral structure of the eGaN device and the absence of an intrinsic body diode provide an exceptional low gate charge Q_G and a zero reverse recovery charge Q_{RR} when operated in reverse conduction. When compared to MOSFETs with similar $R_{DS(on)}$, eGaN FETs have five times smaller switching losses, so the inverter can be operated at higher PWM frequency and with shorter dead time. High PWM frequency and short dead time allow to place ceramic capacitors only in the DC-Link and then to increase reliability, decrease cost and size. Usually, in conventional eBike designs, a LC filter is inserted between the battery and the inverter to comply to the electromagnetic emissions rules. When EPC9173 is used at 100 kHz, the input filter can be removed.

The chip-scale package (CSP) of the eGaN ICs allows reducing the common source and the power loop parasitic inductances by interposing drain and source connections and by soldering the chip directly onto the printed circuit board. The small footprint allows inserting six EPC23101 in the board in a relatively small area providing high power density. The footprint of the EPC23101 is shown in Figure 3.

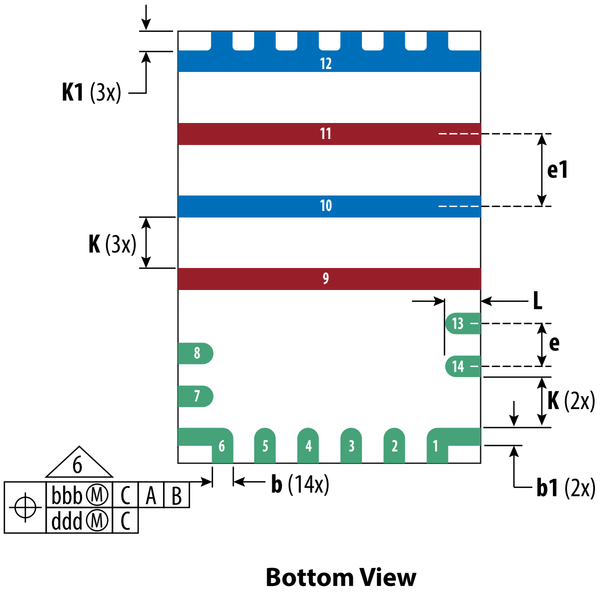

Figure 3. EPC23101 eGaN package footprint bottom view

Design Overview

The eGaN ICs of the power stage have a maximum voltage of V_{DS} =100 V. The dV/dt is optimized for motor drive applications to be less than 10 V/ns.

The current is sensed in both directions per each leg by using either phase shunt or leg shunt resistors. The choice of the current sensing method is done by using the jumpers J_{sns1}, J_{sns2}, and J_{sns3}. In both phase or leg sensing, the shunt value is 1.0 mΩ and the voltage drop across the shunt is amplified with a gain of 20 mV/A, and an offset of 1.65 V is added. The amplifiers bandwidth is 400 kHz, adequate for accurate motor control operation at high switching frequency operation. To reduce the high-frequency power loop inductance in the switching cell of every leg, the leg shunt is made of four 4.0 mΩ 0805-wide resistors in parallel. The amplified signals across the phase shunt resistors or leg shunt resistors, depending on jumpers J_{snsx} position, are used to detect the overcurrent of each leg for prompt activation of the analog circuit protections. An active-low over-current signal (OCPn) is also sent to the microcontroller connector J60 for proper fault handling. The two available sensing methods are equivalent, because in conventional field-oriented control (FOC) algorithms with center-aligned symmetrical PWM modulation, the current is measured in the middle of the ON state of the low switch, which corresponds to the PWM period center point. When the low side switch is ON, the phase voltage is low, and the phase current flows through both the phase-sensing resistor and the leg-sensing resistor. Thus, the phase and leg amplified signals overlap (yellow and pink signals in Figure 4).

Phase and leg shunt current signals are shown in Figure 4. The sampling points for the analog to digital converter are highlighted with small circles.

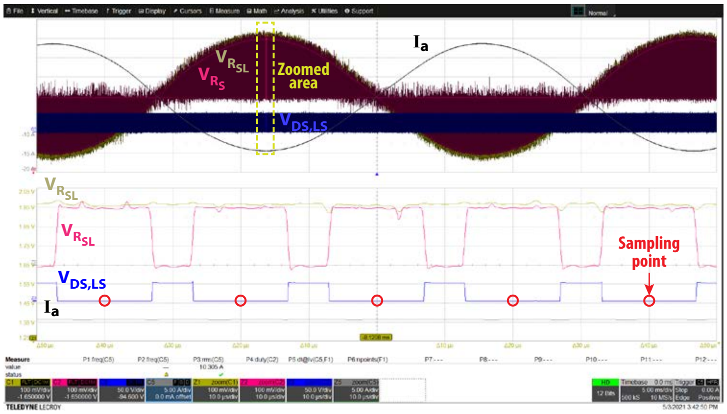

Figure 4. Phase and leg current sensing signals. Experimental waveforms during switching cycles and a zoomed view. The sampling point positions for the analog to digital signal are highlighted. I_a *= 5 A/div,* $V_{DS,LS}$ *= 50 V/div,* $V_{RS} = V_{RSL}$ *= 100 mV/div, t = 5 ms/div, zoomed view t = 10 µs/div*

The overcurrent (OC) detection circuit is triggered if a positive or negative current greater than 50 A is measured in any of the three phases. In this condition, the active-low OCPn signal will remain low for a short time determined by a 3.6 µs RC time constant. The OCPn signal is sent through the connector J60 to a dedicated interrupt pin of the microcontroller. The microcontroller reaction can be programmed accordingly, with a fast reaction time.

DC supply voltage and each phase voltage are measured using a resistor divider network that yields a total gain of 29.2mV/V.

The temperature sensor (U40–AD590) on the inverter board feeds back a voltage on the J60 connector that is proportional to the temperature using the following equation

$$T = \left(\frac{V \cdot 1000}{7.87}\right) - 273.15 \ \ [°C] \tag{1}$$

The temperature sensor has been characterized with the use of an infrared camera measuring the temperature at the top of the EPC23101 case. The relationship is shown in Figure 5.

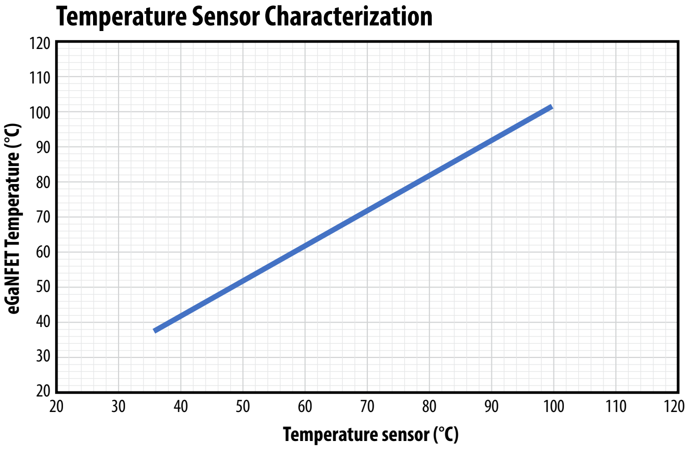

Figure 5. eGaN IC case temperature vs. temperature sensor placed on bottom of the PCB. Operation under natural convection without heatsink.

Experimental Validation

For experimental validation, the EPC9173 power board has been configured for a three-phase BLDC motor drive inverter because this is the main mode for which it has been optimized. Figure 6 shows the EPC9173 block diagram. The board can be used for either sensor-less or sensored motor control.

The EPC9173 is coupled with the **EPC9147C** (Motor Drive Controller Interface board– STMicroelectronics STM32G431RB Nucleo), which is pre-programmed to power and control a 400 W Teknic M-3411P-LN-08D NEMA 34 AC motor [2] with a sensorless FOC algorithm with space vector pulse width modulation (SVPWM). The inverter switching PWM is set at 50 kHz, with 100 ns dead-time.

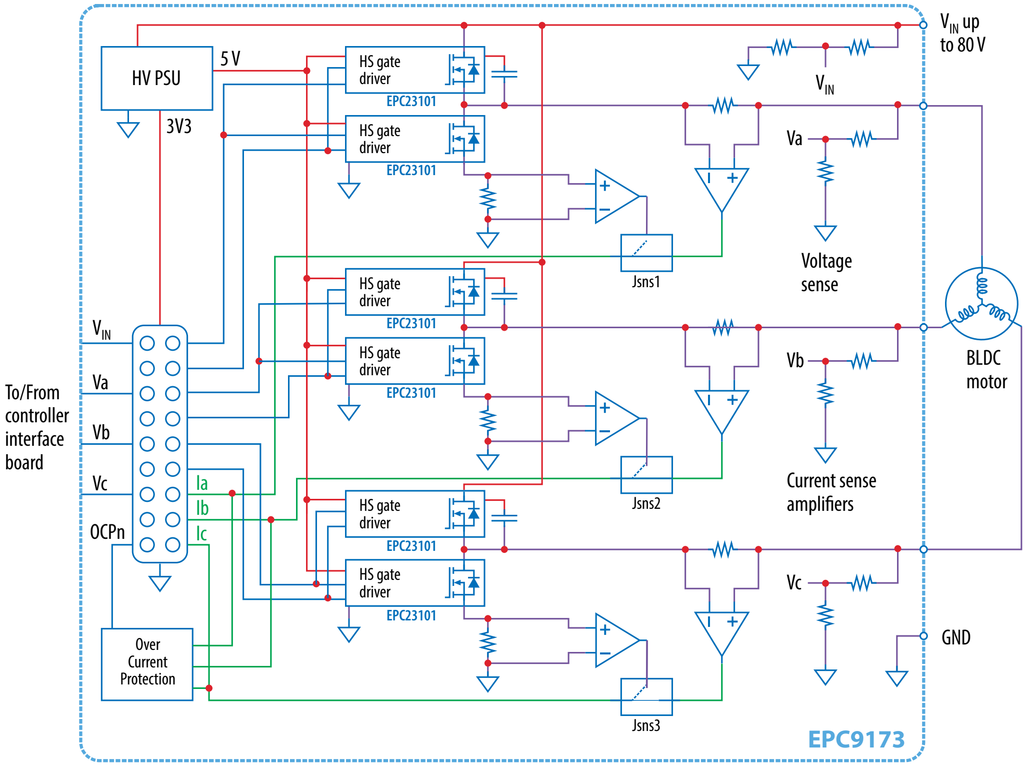

Figure 6: EPC9173 block diagram

Experimental Validation *(continued)*

In Figure 7, the graphs show eGaN IC temperature increase above the ambient vs. the current capability at various PWM frequencies. The solid lines represent the operation without heatsink and with natural convection; the dashed lines were obtained using the heatsink with natural convection. The current has been kept below 27 A_{RMS} per phase to avoid damaging the eBike motor that has been used during the experiments.

The input voltage ripple in an inverter is inversely proportional to the input capacitance and to the PWM frequency. Given a maximum input voltage requirement and the PWM frequency it is possible to determine the minimum input capacitance needed. However, at low PWM frequencies (i.e. 20 kHz) the required input capacitance value dictates the usage of electrolytic capacitor technology. The number of used electrolytic capacitors is determined by the RMS current flowing into them and not by the capacitance value required by the inverter. A practical value is to use at least one electrolytic capacitor per each 7 A_{RMS} flowing in the phase output. If the PWM frequency is increased, the required input capacitance allows the usage of ceramic capacitors that are not sized based on the rms value of the current that flows into them.

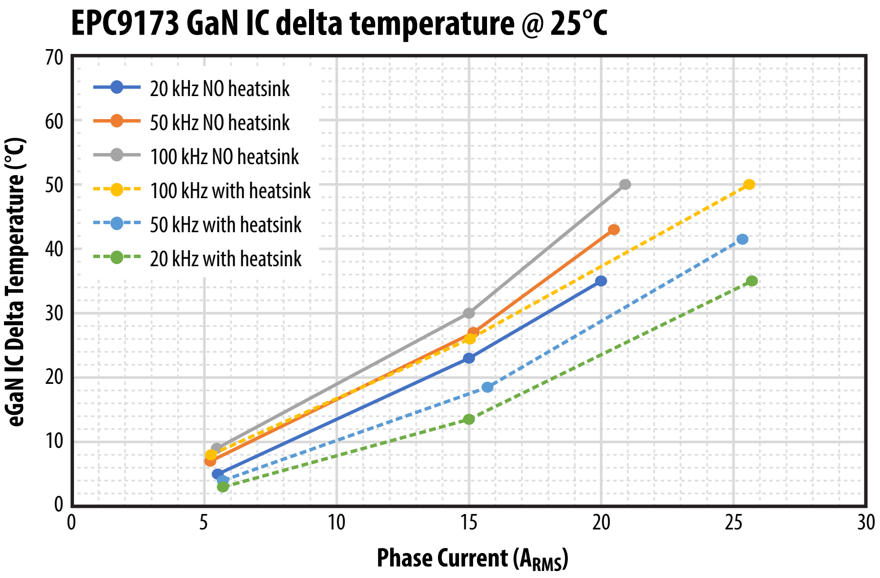

Figure 7. EPC9173 GaN IC temperature (*) increase vs. the ambient temperature [25.5°C]. Measurements taken at various PWM frequencies.

(*) With heatsink, junction temperature has not measured directly. The indicated delta temperature with heat sink is the hottest point at the base of the heat sink.

At 100 kHz PWM frequency the input voltage and current ripple decrease, allowing the designer to remove the electrolytic capacitors and use only ceramic capacitors that are smaller, lighter, and more reliable. Thereby, the volume and the weight of the inverter are reduced.

Conclusion

The EPC9173 is a 48 V input, 1.5 kW output, equipped with the EPC23101 eGaN ICs, designed for eBike applications. It integrates all the necessary circuits to operate a 3-phase BLDC motor with high performance. Thanks to the high power density and the high electrical conductivity of eGaN, the board delivers up to 25 A_{RMS} on each leg and supports PWM switching frequencies up to 250 kHz under natural convection passive heatsink and by keeping the temperature rise below 50°C. Increasing performance of the motor-drive system in terms of quality of the current output waveforms, lesser torque oscillations, and total system efficiency are achieved.

References

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