Power dissipation and thermal calculations for H-Bridge motor drivers

1 Introduction

NXP offers a wide assortment of integrated H-Bridge devices to drive brushed DC motors. In this application note, the MC34932 and MC33932 monolithic dual H-Bridge power integrated circuits are selected to discuss thermal calculations. The same principles can be applied to all NXP integrated H-Bridge motor drivers.

In the MC34932/MC33932, each H-Bridge is able to control inductive loads with currents up to a peak of 5.0 A. The RMS current capability is subject to the degree of heat-sinking provided to the device package. It has an internal peak-current limiting (regulation), which gets activated at load currents above 6.5 A ±1.5 A. Output loads can be pulse-width modulated (PWMed) at frequencies up to 11 kHz (MC33932EK and MC34932EK) or up to 20 kHz (MC34932SEK). A load current feedback feature provides a proportional (0.24% of the load current) current output suitable for monitoring by a microcontroller's A/D input. A Status Flag output reports undervoltage, overcurrent, and overtemperature fault conditions. Two independent inputs provide polarity control of two half-bridge totem pole outputs. Two independent disable inputs are provided to force the H-Bridge outputs to tri-state (high-impedance off state). A simplified application diagram is shown in Figure 1.

Contents

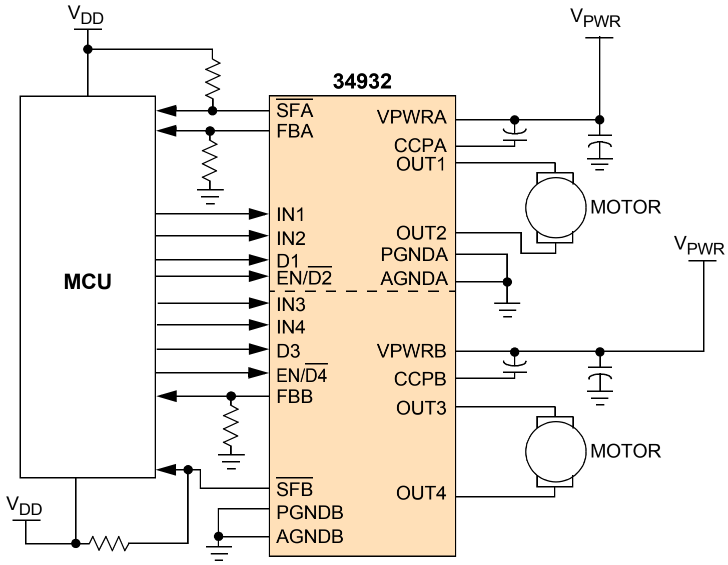


Figure 1. Simplified application diagram

Figure 2 shows the internal architecture of the dual H-Bridge. It consists of two identical full H-Bridges on same monolithic structure, with distinct gate drivers and current feedback outputs for external circuits enabling it to be used as a stepper motor.

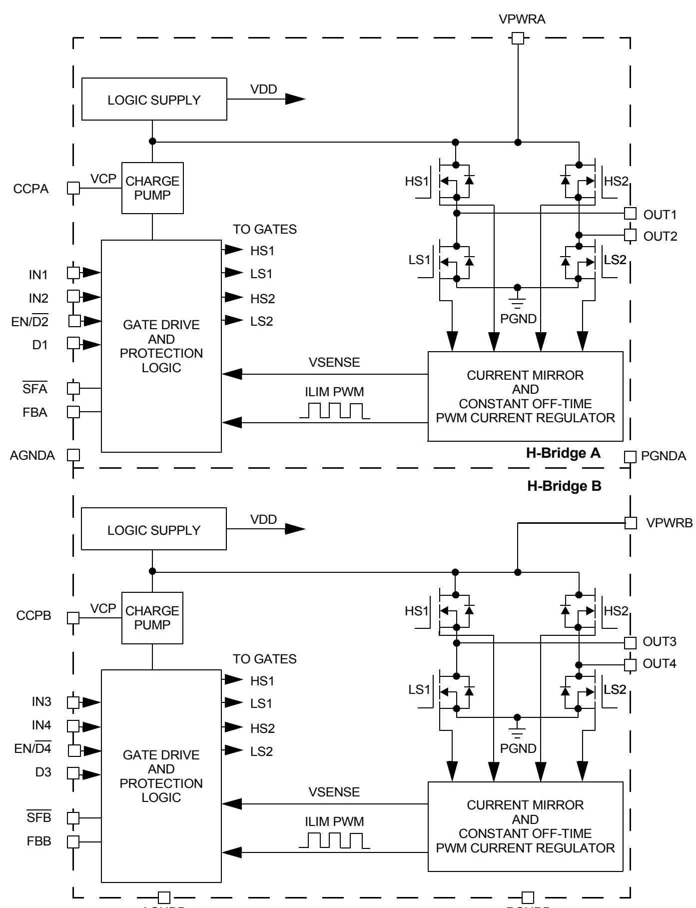


Figure 2. Architecture of MC34932/MC33932

2 Features

H-bridge configuration for bi-directional motors.

- 5.0 V to 28 V continuous for the MC33932 and 5.0V to 36 V continuous for the MC34932; to 40 V transient operation
- Output current up to 5.0 A
- Protected against common failure conditions

3 Differentiating Points

- Overtemperature protection – current fold back at 165 °C
- Current mirror 0.24% of the current flowing through MOSFET
- Ultra-low junction to case thermal resistance < 1.0 °C/Watt for superior heat dissipation
- Sleep mode current < 20 µA for MC34932
- 235 mΩ maximum at T_J = 150 °C, 120 mΩ typical $R_{DS(on)}$ at T_J = 25 °C (for each H-Bridge MOSFET)
- Overcurrent limiting (regulation) via internal constant-off-time PWM
- Output short-circuit protection (short to VPWR or ground)
- Temperature dependent current limit threshold reduction
- 3.0 V and 5.0 V TTL/CMOS logic compatible inputs

4 Power dissipation calculation

4.1 Steady state power dissipation

In a motor driver IC, there are many sources of power dissipation. However, at steady state operation without any switching activity, most power dissipation takes place at the on resistance ($R_{DS(on)}$) of the MOSFET device. Other sources may include stand-by power dissipation at the internal supplies, and regulators and leakage power. Nonetheless, these sources of power dissipation are typically negligible.

4.1.1 Power dissipation due to on-resistance ($R_{DS(on)}$)

This is the biggest source of power dissipation in a motor driver IC when the drive is used at steady state without any form of switching. The power dissipated in an H-Bridge due to the MOSFETs on high-side (HS) and low-side (LS) is calculated as follows:

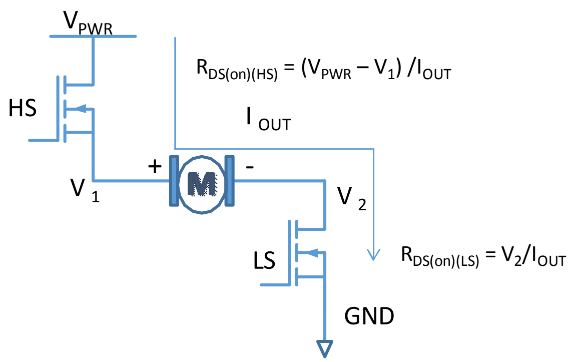


Figure 3. Internal Structure for a Single H-Bridge

$$P\_R_{DS(on)} = I_{OUT}\ 2*(HS\_\ R_{DS(on)}) + I_{OUT}\ 2*(LS\_\ R_{DS(on)}) \qquad \textit{Eqn. 1}$$

Here, HS_$R_{DS(on)}$ and LS_$R_{DS(on)}$ are the on resistances of high-side (HS) and low-side (LS) switches. I_{OUT} is the RMS value of output current. One important thing to note is, $R_{DS(on)}$ increases with junction temperature. Hence, power calculations based on specified nominal values $R_{DS(on)}$ in the data sheet lead to calculation errors. To determine the correct value, use the set-up shown in Figure 4.

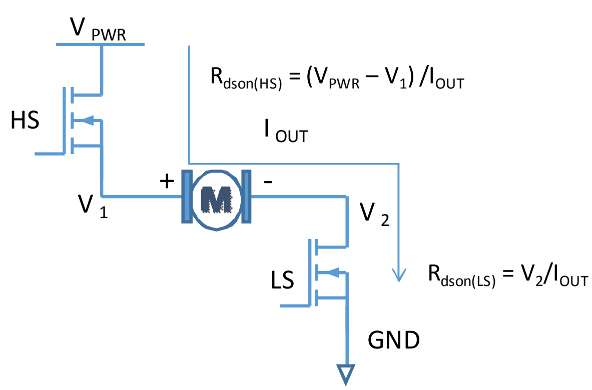


Figure 4. Setup to calculate power dissipation H-Bridges

Since the current flowing through the device is constant throughout the circuit, the voltage drop across the HS_$R_{DS(on)}$ and LS_ $R_{DS(on)}$ gives the correct values for power dissipation. To calculate power dissipation, use the following formula:

$$\textbf{Power dissipation at HS: } (V_{PWR} - V_1)*I_{OUT} \qquad \textit{Eqn. 2}$$

$$\textbf{Power dissipation at LS: } V_2*I_{OUT} \qquad \textit{Eqn. 3}$$

$$\textbf{Total power dissipation due to } R_{DS(on)} = P\_R_{DS(on)} = (V_{PWR} - V_1)*I_{OUT} + V_2*I_{OUT} \qquad \textit{Eqn. 4}$$

4.1.2 Power dissipation due to internal supply

The internal supplies and regulators consume some power due to the operating supply current I_S. The power dissipated due to the operating supply current and the presence of supply voltage V_{PWR} in the IC is given by the following equation:

$$P_{IS} = V_{PWR} * I_S \quad \textit{Eqn. 5}$$

4.2 Dynamic power dissipation

Switching causes significant power dissipation which accounts for the switching losses. These losses can be attributed to the following factors:

1. Switching frequency (f_{SW})
2. Rise time (t_R) while switching from low to high and fall time (t_F) during high to low transition
3. Supply voltage (V_{PWR})
4. Output current (I_{OUT})
5. Body diode forward voltage drop (V_D)
6. Change in $R_{DS(on)}$

4.2.1 Cycle by cycle power calculation

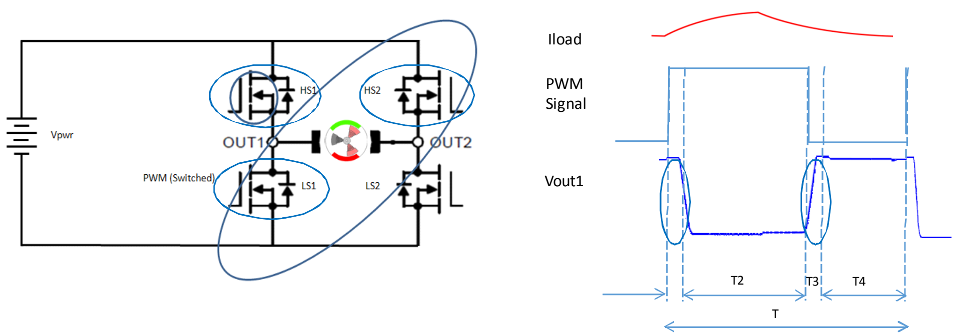


Figure 5. Cycle by cycle power calculation

Table 1. shows the power calculations on each MOSFET on the H-Bridge with active recirculation.

Table 1. Cycle by cycle power calculation

PD_HS2 over T [W]	$I_{OUT}^2 * R_{DS(on)} * T * f_{SW}$
PD_LS1 over T1 [W]	$0.5 * (V_{PWR} + V_D - I_{OUT} * R_{DS(on)}) * I_{OUT} * T1 * f_{SW}$
PD_LS1 over T2 [W]	$I_{OUT}^2 * R_{DS(on)} * T2 * f_{SW}$
PD_LS1 over T3 [W]	$0.5 * (V_{PWR} + V_D - I_{OUT} * R_{DS(on)}) * I_{OUT} * T3 * f_{SW}$
PD_HS1 over T4 [W]	$I_{OUT}^2 * R_{DS(on)} * T4 * f_{SW}$

Note that $R_{DS(on)}$ increases with junction temperature T_J, as shown in Figure 6. An increased $R_{DS(on)}$ also increases power dissipation, which in turn increases the junction temperature. Hence, this is an iterative process and should be considered while doing the calculations.

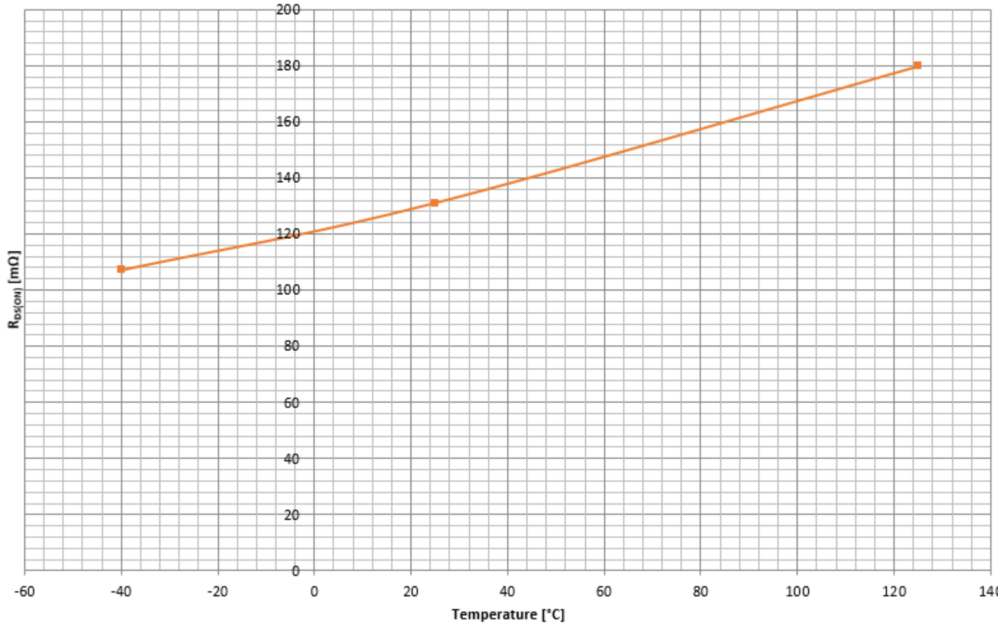


Figure 6. $R_{DS(on)}$ Variation with junction temperature

5 Junction temperature estimation

The junction temperature may be estimated by several methods which include:

1. Mathematical calculation
2. Experimentation
3. Simulations

Based on available resources and the degree of accuracy required, select one or more methods cited previously. However, before making this selection, know the factors affecting junction temperature.

Junction temperature depends on following factors:

1. Ambient temperature (T_A)
2. Thermal resistance from junction to ambient ($R_{\theta JA}$) which depends on:
   • Number of layers in PCB
   • Amount of copper used on each layer
   • Thermal via size and number of vias
   • Type of solder used
   • Heat sink efficiency
   • Interface material
   • IC packaging
3. Power dissipated on the die (PD)

5.1 Mathematical Calculation

The mathematical estimation of junction temperature may be done as shown in Equation 6.

$$T_J = T_A + P_D \times R_{\theta JA} \qquad \textit{Eqn. 6}$$

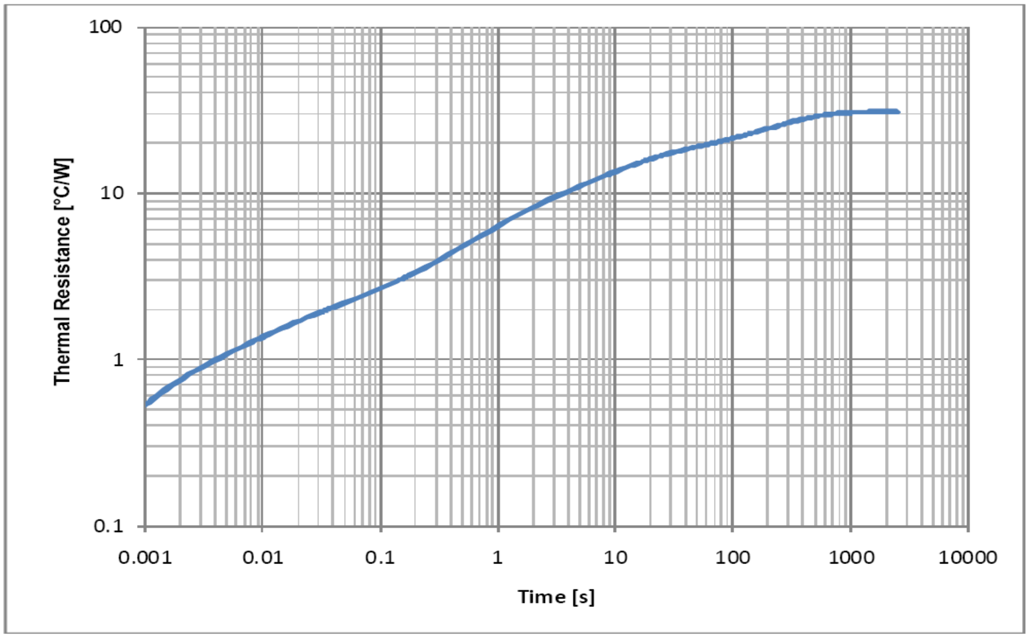


Figure 7. Transient thermal response curve

$R_{\theta JA}$ at any point of time, for the 2s2p board, the JEDEC High-k standard board can be obtained from the transient thermal response curve, shown in Figure 7. However, power dissipation on the die must be obtained experimentally as shown in Figure 8.

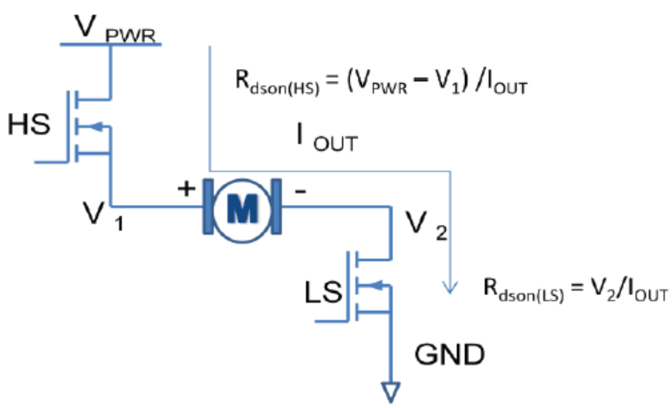


Figure 8. Power dissipation calculation.

Total Power Dissipation on the Die P_D [W] = $I_{OUT} * (V_{PWR} – V_1) + I_{OUT} * V_2 + I_S * V_{PWR}$ ***Eqn. 7***

In Figure 8, I_S is stand-by current, which is typically very small and may not contribute much to the total power. This setup should be a fairly accurate measure of power dissipation in the die. However, for measuring the $R_{DS(on)}$ of power MOSFETs, this set up would include the bond wire resistance. Hence, a Kelvin point measurement method should be used to measure $R_{DS(on)}$ more accurately. This method provides a good first order estimation of junction temperature. Spreadsheets are available to perform first order thermal calculations for various applications. Contact your local NXP Field Applications Engineer to obtain your copy.

5.2 Experimental method

Every input and output pin in the MC34932 and MC33932 have ESD protection diodes, as shown in Figure 9. Since diode voltage (V_D) decreases with increasing temperature, this characteristic of a diode is very precise and reliable, making it a good temperature sensor, once calibrated. The calibration is simple and is done by putting the diode in known temperature zones and recording the corresponding diode voltages while they are forward biased with a constant current source (C_S), with a current (I_F) low enough to not cause self-heating of the device. Figure 10 shows a typical behavior of the diode voltage with change in die temperature, while a constant current flows through the device. Constant current sources in the range of 1.0 mA to 1.5 mA may be a good choice. Figure 9 shows the setup.

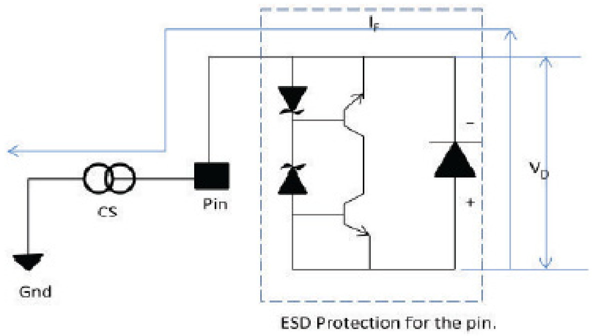


Figure 9. ESD protection structure for input pin with setup to measure die temperature

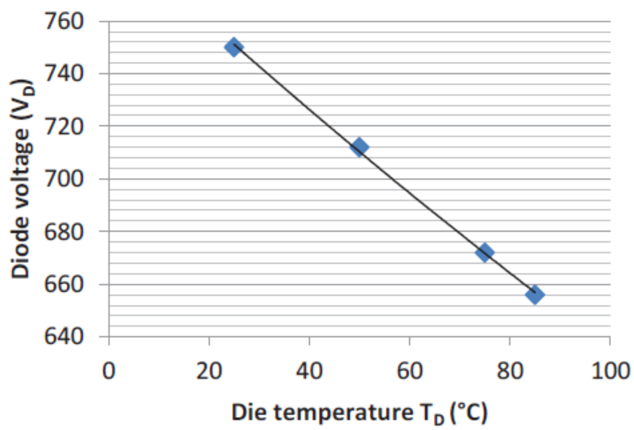


Figure 10. Typical characteristic of the diode as temperature sensor with ID = 1.0 mA

This should give a good estimation of die temperature. Note that there are transients for dynamic or switching operations, and in this case the temperature measurement point on the die becomes very important. The temperature measurement point on the die should be as close to the power dissipation area as possible. The transient thermal response is determined experimentally by giving a step change in power to the part being tested, as shown in Figure 11.

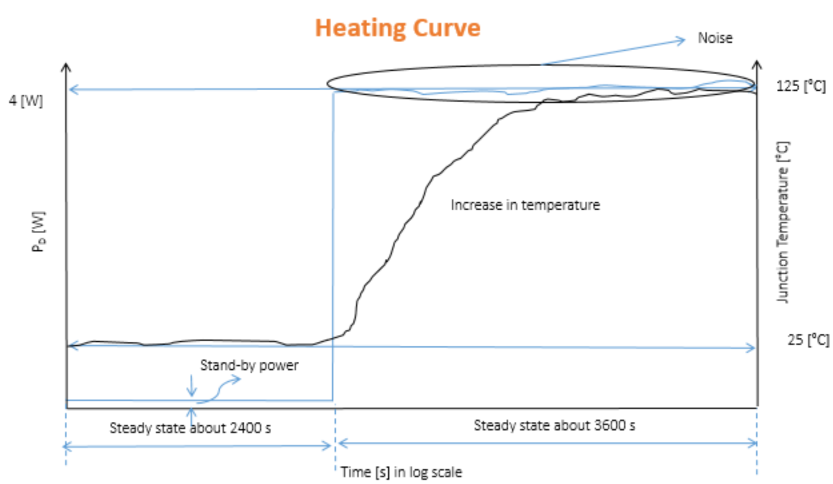


Figure 11. Heating Curve

However, as shown in Figure 11, there is a possibility of noise being captured in the data acquired. This could be due to noise from the supply or from anything in the PCB on which the part is tested. To avoid such noise, a cooling curve may be captured instead of a heating curve, as shown in Figure 12. The data is then flipped during data processing to obtain a noise free heating curve.

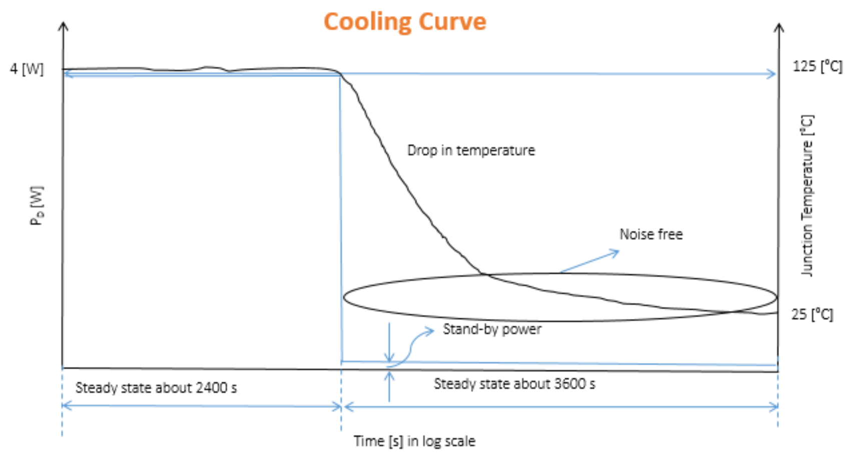


Figure 12. Cooling curve

By performing $R_{\theta JA} = (T_J - T_A)/ P_D$ on the acquired data, a transient response curve is obtained, as shown in Figure 13. This curve can be used for other calculations.

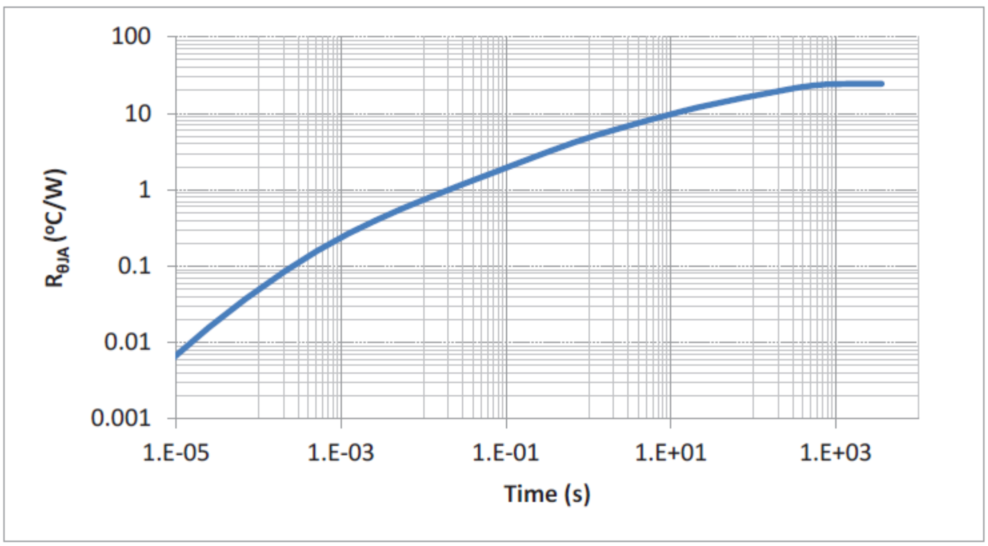


Figure 13. Experimentally obtained transient thermal curve

5.3 Junction temperature estimation by simulation

For simulation results to be accurate, accurate power dissipation calculations are essential. Refer to Power dissipation calculation on page 4 for more details. Several tools are available online performing thermal calculations based on numerical methods, such as the Boundary Element Method, Finite Difference Method, Finite Element Method, and Finite Volume Method. Full system level thermal simulations with forced convection may be done using computational fluid dynamics (CFD) software tools. An example of thermal simulation results for a test case is shown by the following:

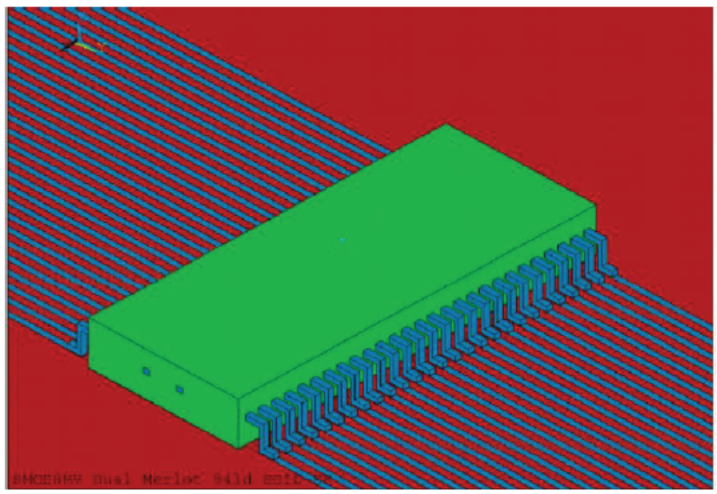
5.3.1 Simulation conditions

- 2s2p - 1.0 oz. Cu top and bottom signal layers, 1.0 oz. Cu internal power and ground planes, PTH connected to all internal planes, 76 mm^2 x 76 mm^2, 1.4 mm total thickness
- Model includes thermal radiation, horizontal natural convection, and heat conduction
- Temperature and power for transient thermal simulation
- T_{AMB} = 120 °C, T PCB back 115 °C
- LS1-HS2, LS3-HS4 powered at 2.0 A to steady state
- Inputs connected to PWM signal at 3.0 kHz
- $R_{DS(on)}$ = 195 mΩ
- V_{PWR} = 16 V
- Power in POWERFET HS2 at 2.0 A (using 195 m) = 0.78 W
- Power in POWERFET LS2 while switching at 2.0 A = 0.67 W
- Power in POWERFET HS1 at 2.0 A (using 195 mΩ) = 0.38 W

Total power dissipated on each of the two H-bridges = 1.83 W.

A thermal model used for thermal simulation of the MC33932, according to the conditions mentioned previously, is shown in Figure 14.

a) Die layout


b) Package layout

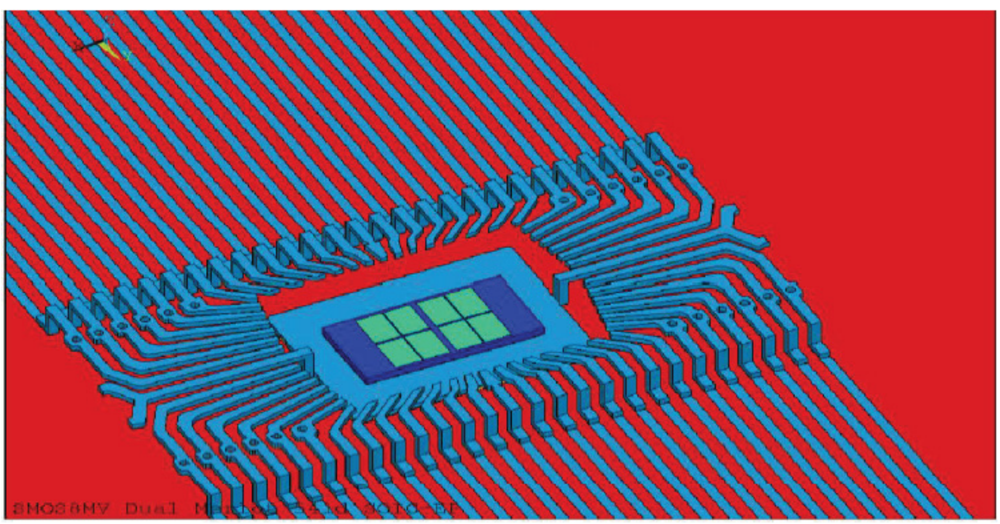

c) Die Inside the Package with Lead Frame Structure

Figure 14. Thermal model of the MC33932

Once the model is set up and the MOSFETs are powered up according to the application requirements, the expected ambient conditions to run simulations are ready. Provided the model is built correctly and the power dissipation calculations are precise, accurate monitoring of the temperature of each MOSFET on the die can be made. Simulation condition results for the conditions cited previously should look as follows:

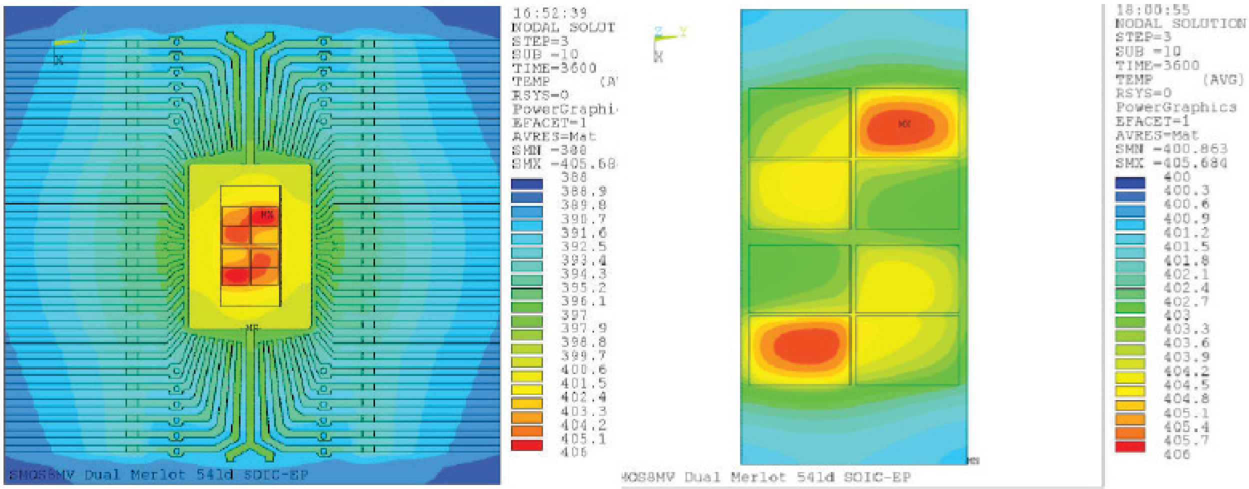


Figure 15. Simulation results - temperature distribution around the die

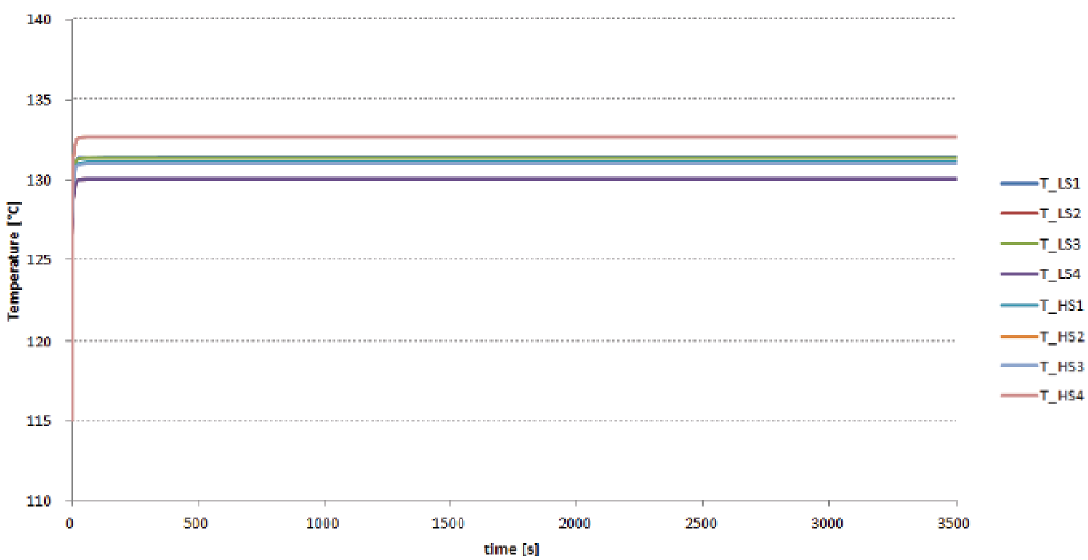


Figure 16. Simulation results - temperature of each MOSFET on the die

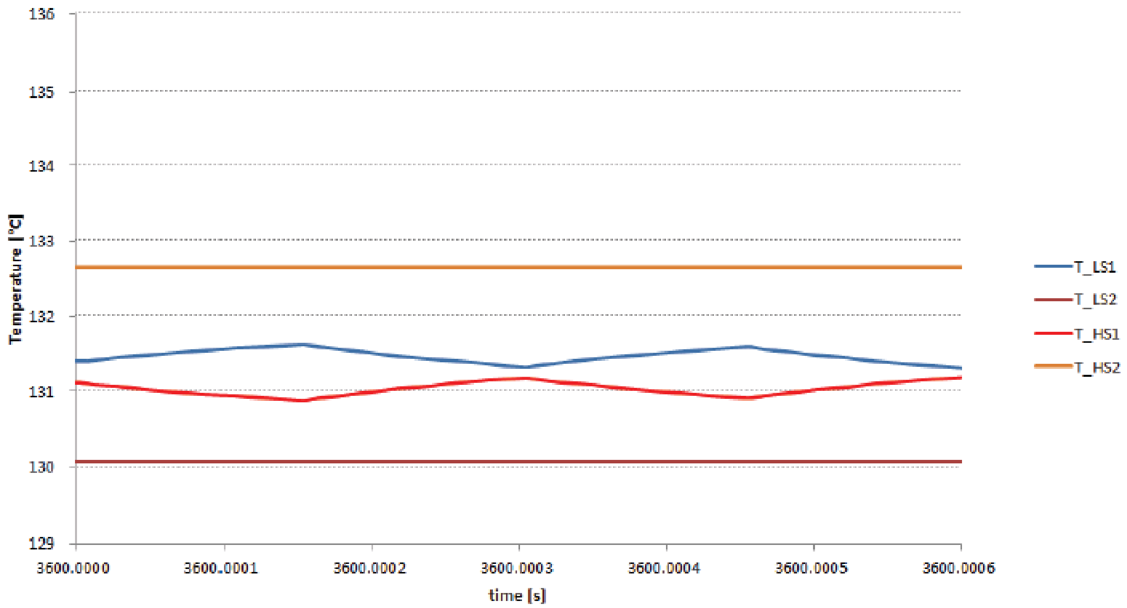


Figure 17. Simulation results - zoomed section showing temperature variation among MOSFETs due to switching

6 Conclusion

Thermal management is critical in motor drive applications because motors can bind, stick, and stall. The optimization of thermal performance must be an integral part of device and system design. NXP products are based on extensive experience in thermal management. NXP thermal packages achieve exceptionally low thermal resistance at an attractive price.The innovative thermal management scheme in the MC33932 and the MC34932 motor drivers monitors temperature, self-regulates device thermals and provides safeguards against device and motor damage. To get more insight on thermal performance of such devices, contact your local sales or field application engineer.

7 References

Following are URLs where you can obtain information on NXP products and application solutions:

Document Number and Description		URL
MC33932	Data Sheet	www.nxp.com/files/analog/doc/data_sheet/MC33932.pdf
MC34932	Data Sheet	www.nxp.com/files/analog/doc/data_sheet/MC34932.pdf
Support pages		**URL**
Analog Home Page		www.nxp.com/analog

8 Revision history

Revision	Date	Description
1.0	10/2015	• Initial release
	7/2016	• Updated to NXP document form and style

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