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DMC4040SSD reduces MOSFET losses ensuring reliable operation of Brushless DC motors

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Introduction

When used in Brushless DC (BLDC) motor applications the MOSFETs used in the half- or full-bridge driver stages are subjected to high torque currents a few times higher than continuous operating current. Through laboratory evaluation and power loss analysis, this application note demonstrates that the DMC4040SSD, a 40V complementary pair MOSFET, remains within its maximum junction temperature rating when evaluated in the demanding environment of the consumer printer.

MOSFET full-bridge driver for printer

A simplified block diagram of a BLDC motor driver circuit for a consumer printer is shown in Figure 1, below. As can be seen three pairs of complementary MOSFETs are used to drive a three phase BLDC motor. This topology is preferred to an all N-channel MOSFET configuration as the need for more complex level shifted gate driver circuitry for the high-side N-channel MOSFETs can be eliminated.

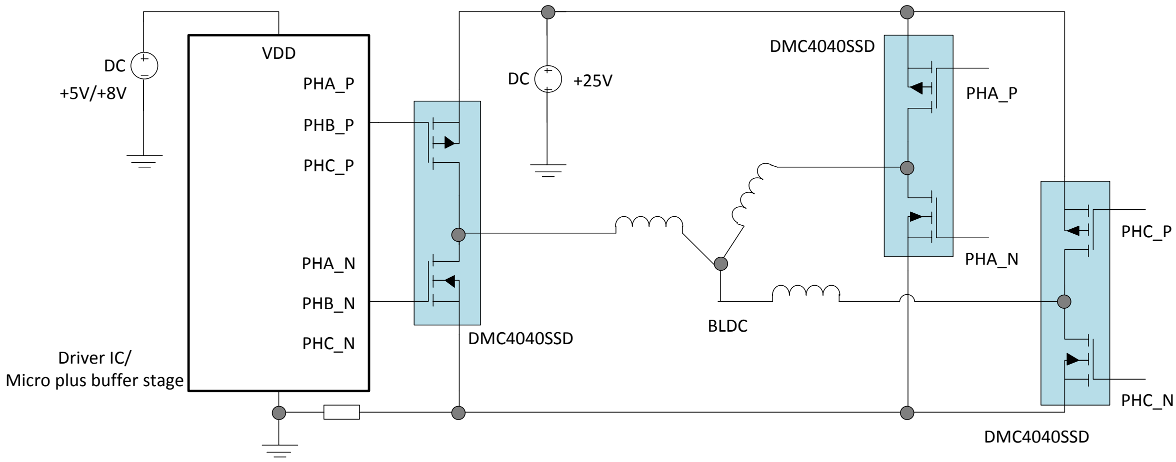

Figure 1 Block diagram of a typical BLDC motor driver

Depending on the design concept deployed, the MOSFETs are driven by either a microcontroller or low power pre-driver IC with low current, gate drive voltages of between 5V to 10V. A gate voltage amplitude above 5V is generally preferred as it ensures full enhancement of the MOSFET, reducing resistive loss during the start-up sequence.

Furthermore, it is also important that the MOSFETs have low gate charge, $Q_{G(tot)}$, in order to minimize drain voltage versus current commutation time, thereby reducing switching losses.

Power loss and device temperature analysis

During start-up condition the windings of the BLDC motor are energized by a high torque current that can be up to five times its continuous current rating. This torque current flows through the MOSFETs causing power loss and temperature rise in the devices.

Care therefore must be taken in selecting a suitable MOSFET to ensure that power losses are minimized, and that the peak instantaneous device temperature does not exceed the maximum junction temperature of the MOSFET during motor start up.

In order to calculate the instantaneous rise in junction temperature it is necessary to measure/calculate the switching and conduction losses within the MOSFET during motor start up and operation.

A mid-range consumer printer was chosen as the test platform as the high ambient temperature within the printer provides a challenging operating environment for the MOSFETs. The device selected for evaluation was the DMC4040SSD, a complementary 40V MOSFET that has matched $R_{DS(ON)}$ ensuring better distribution of the conduction loss between the high and low-side MOSFET in the motor driver circuit.

The evaluation was carried out in an ambient temperature of 30ºC. Under these conditions the PCB board inside the printer reached a steady state temperature of 85ºC. A print request initiated motor start-up/operation. Voltage and current waveforms, shown in figure 2, were measured during this activity. The waveform can be divided into two distinct periods: 1) the initial current torque sequence, T_1, lasting 80 milliseconds and, 2) sinusoidal current sequence that ends after 2 second.

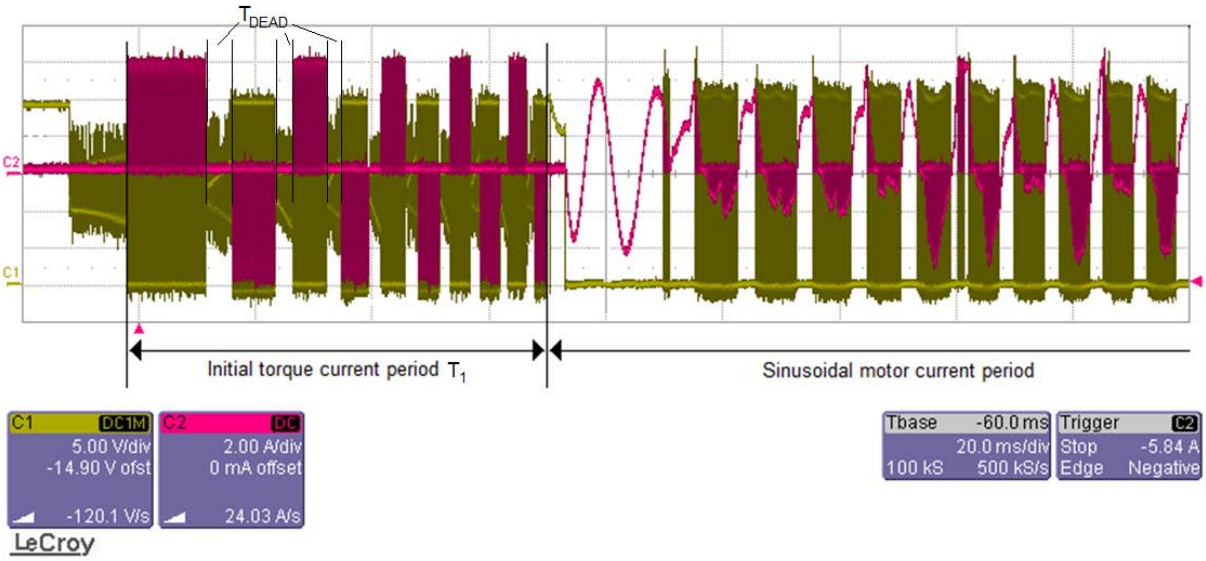

Figure 2 - Operating waveform of the low-side MOSFET in the full bridge driver. CH1: drain voltage; CH2: drain current

Calculations – Torque current period

This section now analyzes the power loss within the first period, T_1, when the MOSFET delivers torque current to energize the winding. The control IC drives the MOSFETs at 45KHz switching frequency. The switching loss can be estimated by

$$P_{swi} = 0.5 \times V_{DS} \times I_D \times (t_{rise} + t_{fall}) \times f_{swi}$$

$$= 25V \times 6.5A \times 150ns \times 45KHz$$

$$= 1.1W$$

where

V_{DS} is the measured drain-source voltage

I_D is the measured drain current

f_{swi} is the switching frequency

t_{rise} and t_{fall} are the measured gate rise and fall time respectively

The gate voltage rise and fall time of the DMC4040SSD is measured at 150ns in the evaluation. However, the commutation times can vary depending on the printer driver IC and MOSFET gate charge.

In the evaluation, the peak gate voltage amplitude, V_{GS}, of 8V is applied by the motor driver IC to the high and low side MOSFETs. The conduction losses can therefore be calculated by:

$$P_{on} = (I_D)^2 \times R_{DS(ON)} \times 0.5 \times (K_{factor(1)} + K_{factor(2)}) \times (T_1 - T_{DEAD})$$

$$= (6.5A)^2 \times 27m\Omega h m \times 0.5 \times (1.3 + 1.4) \times 0.8$$

$$= 1.23W$$

where $R_{DS(ON)}$ is the worse-case device on-resistance at 25°C, V_{GS}=8V specified in the DMC4040SSD datasheet.

However, $R_{DS(ON)}$ varies with temperature. An increase in temperature above 25°C causes a corresponding increase in conduction loss. As shown in Figure 3 – On state resistance variation with temperature - $K_{factor(1)}$ and $K_{factor(2)}$ are the normalized MOSFET's on-state resistance ratio at 85ºC and 110ºC respectively. These ratios are then averaged to account for temperature rise from 85°C to 110°C.

T_{DEAD} is the MOSFET conduction dead time during the motor's phase current change-over as shown in Figure 2. In the evaluated equipment, T_{DEAD} is approximately 20% of total T_1 period.

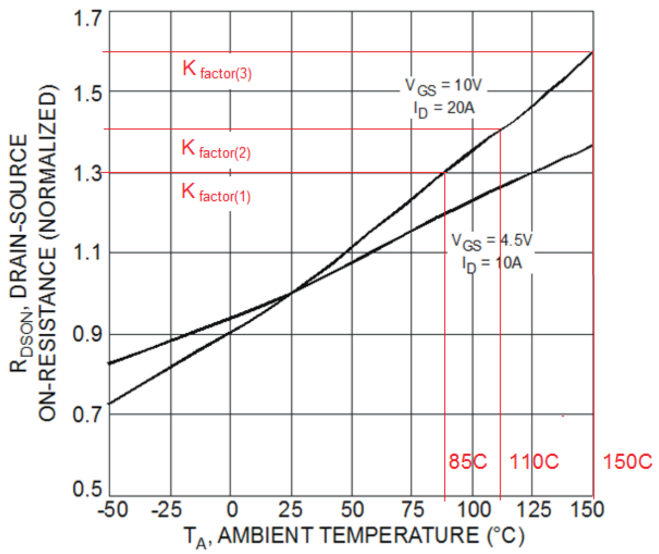

Figure 3 - On-resistance variation with junction temperature

The MOSFET power loss, P_{TOTAL}, is the sum of conduction and switching loss. The total power loss is equal to 2.33W.

The junction temperature rise associated with the above power loss is

$$T_{J(rise)} = (P_{swi} + P_{on}) \times Z_{th(1)}$$

$$= 2.33W \times 9^{o}C/W$$

$$= 21^{o}C$$

where $Z_{th(1)}$ is the transient thermal impedance of the DMC4040SSD in SO-8 package at 80millisecond pulse width as shown in Figure 4.

In order to achieve good thermal efficiency, the four drain pins of the DMC4040SSD should be connected in common. Sufficient PCB via holes should be used to connect top and bottom copper heat sink areas.

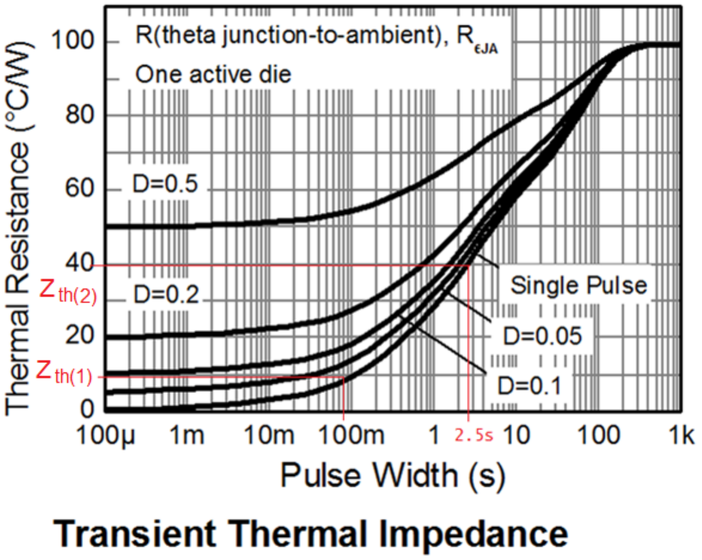

Figure 4 Transient thermal impedance variation with pulse width

Since the PCB board temperature prior to the torque current sequence was 85ºC, the MOSFET junction temperature will reach $T_{J(1)}$ = 106ºC at the end of T_1.

Calculations – Sinusoidal motor current period

As is shown in Figure 2, as the high torque current expires, the motor current transitions into the sinusoidal state – sinusoildal motor current period. The power loss in this stage is less than its predecessor. The RMS MOSFET current amplitude in the evaluated printer during this time was estimated to be 3.25A.

So, the worse-case conduction loss due to the sinusoidal motor current is

$$P_{on} = (I_{D(RMS)})^2 \times R_{DS(ON)} \times K_{factor(3)}$$

$$= (3.25A)^2 \times 27mOhm \times 1.6$$

$$= 0.43W$$

where $K_{factor(3)}$ is the normalized on-state resistance ratio at 150ºC (worst case scenario).

Similarly, the worst-case switching losses can be calculated as follows:

$$P_{swi} = 0.5 \times V_{DS} \times I_{D(RMS)} \times (t_{rise} + t_{fall}) \times f_{swi}$$

$$= 25V \times 3.25A \times 150ns \times 45KHz$$

$$= 0.55W$$

Once the printer completes printing a test page the sinusoidal current phase expires after 2 seconds. From the transient thermal impedance curve, the associated ttranisient thermal impedance $Z_{th(2)}$ is 40ºC/W. The device temperature rise due to the sinusoidal current mode of the waveform is

$$T_{J(rise)} = (P_{swi} + P_{on}) \times Z_{th(2)}$$

$$= 0.98W \times 40ºC/W$$

$$= 39.2ºC$$

The instantaneous rise in device junction temperature is the sum of the temperature rise during start up period T1 and the temperature rise during sinusoidal motor period T2. The rise in junction temperature is therefore 85ºC (starting temperature) + 21ºC + 39.2ºC = 145.2ºC. The DMC4040SSD rises to 145.2°C which is still within the maximum permissible device junction temperature.

It is important that MOSFETs are operated with some margin over the operating limit. Exceeding the maximum junction temperature will result in degradation of device and with time device failure.

The same methodology can be used to calculate losses in the P-channel of the DMC4040SSD. However, as their $R_{DS(ON)}$ are matched the losses in the P-channel will be the same as that observed in the N-channel side.

Conclusion

Using a combination of laboratory measurement data and theoretical analysis, it has been demonstrated that the temperature of the DMC4040SSD will stay within its max junction temperature when subjected to high torque current several times higher than its nominal operating current. The DMC4040SSD is therefore suitable for use in high torque current Brushless DC motor applications