AN5146

Driving inductances for the dual 24 V high-side switch family

Rev. 1.0 — 29 July 2016

Application note

1 Introduction

This application note applies to the dual 24 V high-side SMARTMOS switch family. High-side switches are intended to cover a wide range of loads including inductances. Driving inductance leads to regular questions about capabilities to sustain energy when the device is unclamped or partially clamped. This note helps designers to be acclimated with energy in repetitive mode.

These intelligent high-side switches are designed to be used in 24 V systems such as trucks, buses and special engines. They can be used in some industrial and 12 V applications as well. The low $R_{DS(on)}$ channels can control incandescent lamps, LEDs, solenoids or DC motors. Control, device configuration and diagnostics are performed through a 16-bit SPI interface, allowing easy integration into existing applications. For a complete feature description, refer to the individual data sheets.

2 Driving inductance

With high-side configurations, driving inductances in a switching mode invariably leads to instances where the device's internal output MOSFET is surrounded on one side by an energy tank (battery or V_{PWR} of the device terminal) and on the other by an inductance strictly regulated by Lenz's law.

At switch OFF, Lenz's law is ready for action. The voltage at the inductance terminals is inverted, creating a high voltage between drain and source of the MOSFET. The load current decreases slowly until demagnetization is completed.

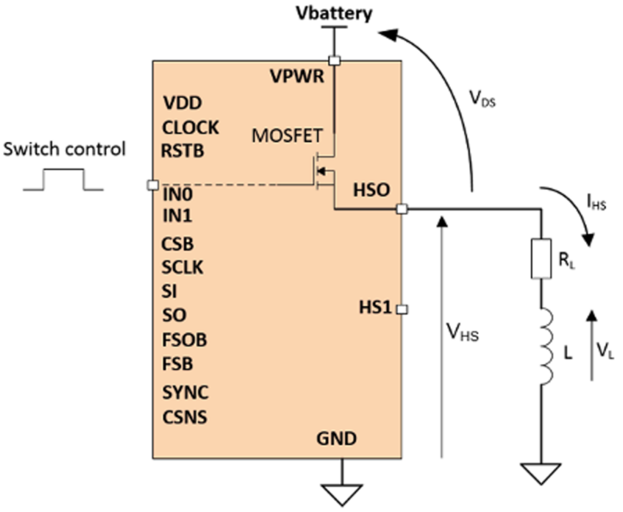

Figure 1. eXtreme switch 24 V driving inductance

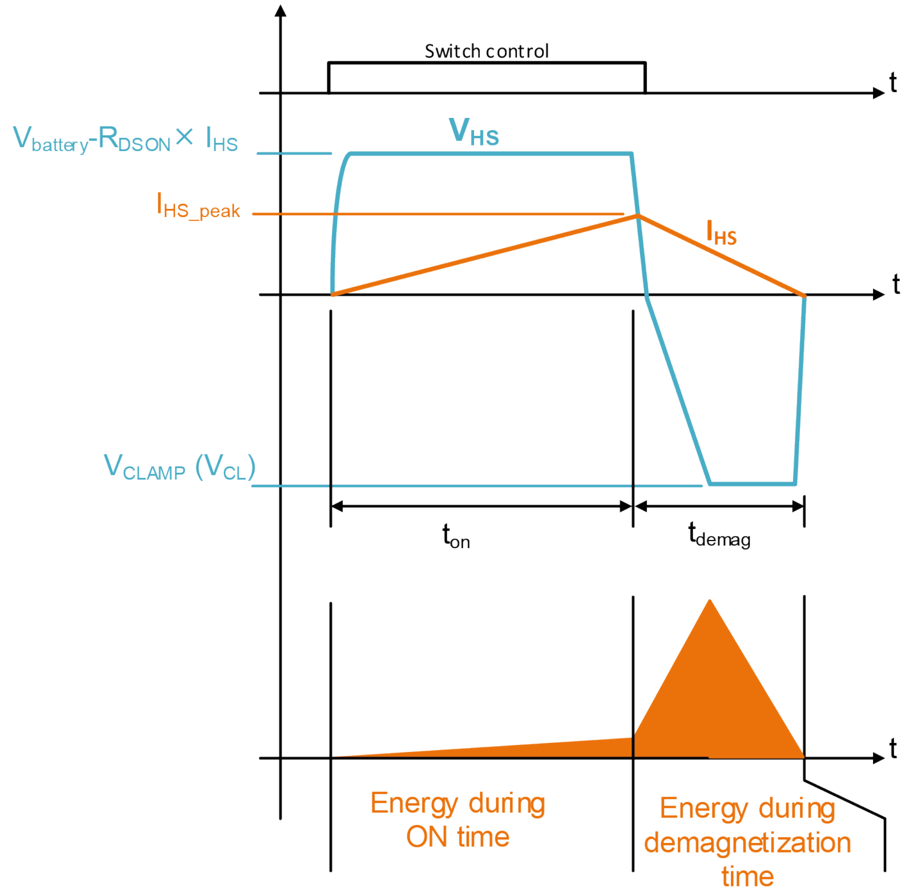

Figure 2. Device response to turn ON / OFF

The maximum energy occurs during the demagnetization time (t_{demag}) where V_{ds} is maximum and the current across the MOSFET is maximum at turn-off. The energy to be dissipated by the MOSFET during the demagnetization is expressed by the formula:

$$E_{demag} = \int_{t_{on}}^{t_{demag}} v_{DS}(t) \times i_{HS}(t)dt$$

See equation (1) in Section 4 "Appendix A" for details on how the equation was derived.

$$E_{Demag} = \frac{1}{2} \times L \times I_{HSPeak}^{2} \times \left(1 + \frac{VPWR}{|V_{CL}|}\right) \qquad (1)$$

In the above formula, the serial resistance of the inductance has been ignored to ease computations.

2.1 Single pulse and repetitive pulse

When evaluating which devices are most appropriate for use in an application that incorporates solenoids, the designer may initially refer to the data sheet to determine if the device can sustain the required level of energy. The single pulse energy at T_J = 150 °C is often used to assess how robust the device is in this respect. A rapid test can be performed to verify whether the indicated value was specified with or without steroids. However, single pulse energy data does not provide enough information.

The designer must also pay attention to several parameters impacting power dissipation. Some of these parameters may be different when the device output is PWMed. For example, slew rate is a key factor for devices operating at high currents and high frequencies. In general, high current and high frequency are factors that frequently interact to influence reliability over time (that is, the average junction increase across the mission profile).

The designer must employ the appropriate tools to assure that the device is capable of maintaining frequently occurring energy levels.

This note intends to accredit or discredit the level of energy with identified conditions in repetitive mode.

2.2 Postulates

The reliability of the device across time is driven by the average junction temperature. In the automotive market, most devices are qualified up to a 150 °C junction temperature, in accordance with a mission profile. This section discusses two postulates related to junction temperature.

To assure that the device does not operate outside its intended boundaries, the first postulate maintains that the maximum junction temperature must not exceed 150 °C.

The second postulate refers to the temperature transient and maintains that, to prevent polycyclic fatigue, the junction temperature must not exceed 60 °C . This temperature transient occurs at MOSFET turn off. High energy, short duration, and poor dissipation all contribute to excessive high temperature.

Postulates :

- T_{JMAX} must not be exceeded (150 °C)
- ΔT_J must not exceed 60 °C (accelerated thermal fatigue)

Figure 3 is the thermal response of the device when driving an inductance. The time constant to reach the average temperature depends on various factors, such as frequency, load current, battery voltage, type of board and so on. In order to satisfy both of the above postulates, this application note focuses on applications in a stabilized state.

The procedure is as follows:

- Verify that the average junction temperature remains below 150 °C.
- Verify that the cumulative temperature transients of ON and the demagnetization state remains below 150 °C in addition to the average.
- Assure that the transient temperature—mainly due to demagnetization—remains within the 60 °C range.

Note:

All thermal impedance curves in this note are suited for a single active channel and a 10 mΩ device (MC10XS4200).

Impedance curves for all 24 V eXtreme switch devices are available in Appendix C, for single and dual active channels. The designer should select the appropriate curve with respect to their application.

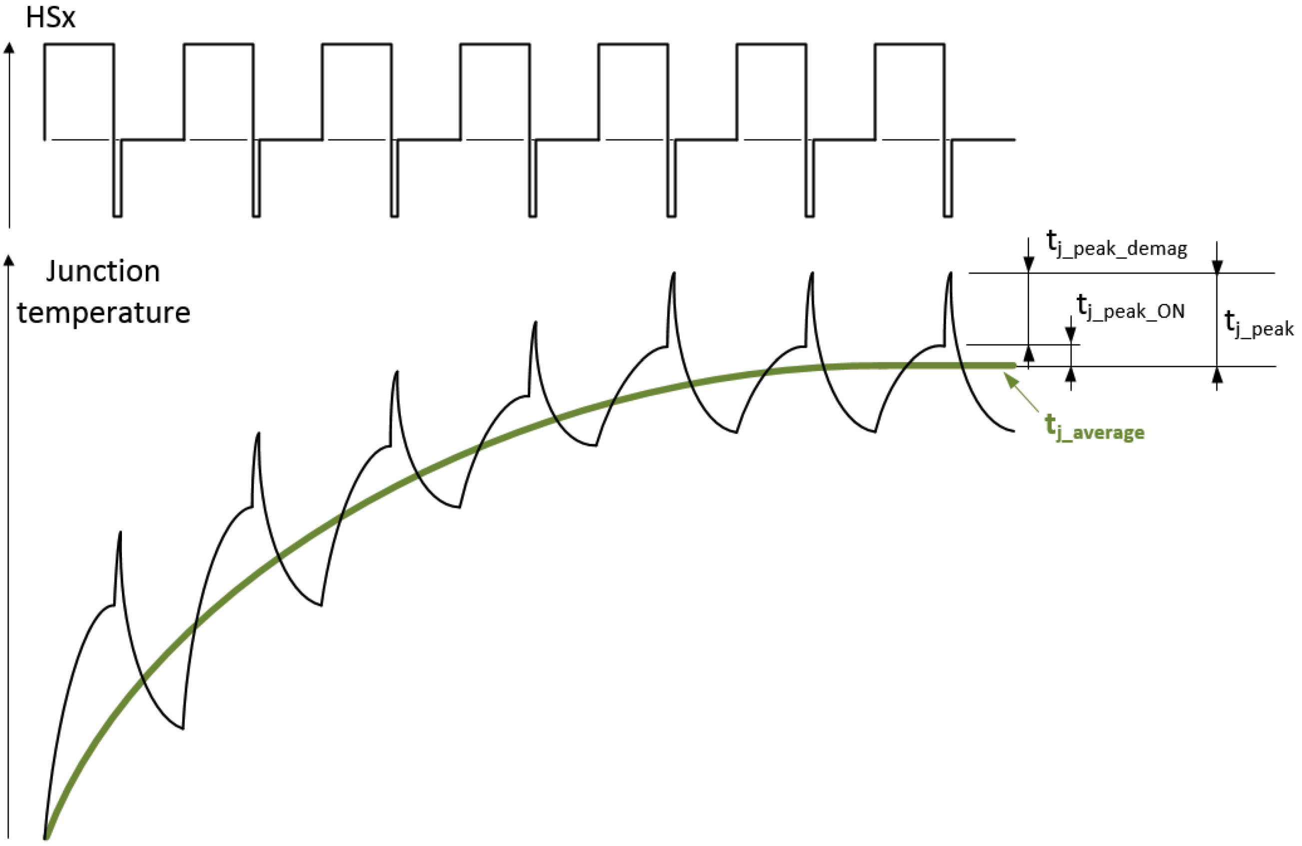

Figure 3. Thermal response

3 Procedures to assure that the device can sustain an identified energy

3.1 Safety area

As previously mentioned, the device is usually specified with a maximum energy of 150 °C junction temperature prior to energy pulse application.

This condition violates the first postulate, because any additional power across the device makes the junction temperature rise above the specified maximum.

The following curves are drawn at different temperatures (Figure 4) of the maximum allowed energy versus the current across the MOSFET and the inductance used. These curves were constructed using the single pulse method. The curves are boundaries which must not be crossed. If so, the designer has to investigate alternative solutions to exhibit the device with different conditions. When the energy levels involved are too high, alternate solutions with external freewheeling diodes are depicted in the Application Note AN4858 *Inductive Switching for Dual 24V and 36V High-side Switch Families* http://www.nxp.com/files/analog/doc/app_note/AN4858.pdf.

25 °C is the ambient temperature, 85 °C represents a high value of a mission profile and 125 °C represents the maximum allowed temperature to fulfill the second postulate up to the thermal shut down of the device. The violation of the first postulate is tolerated as the device must comply with the thermal protection. This excursion of 125 °C + 60 °C must not be repetitive.

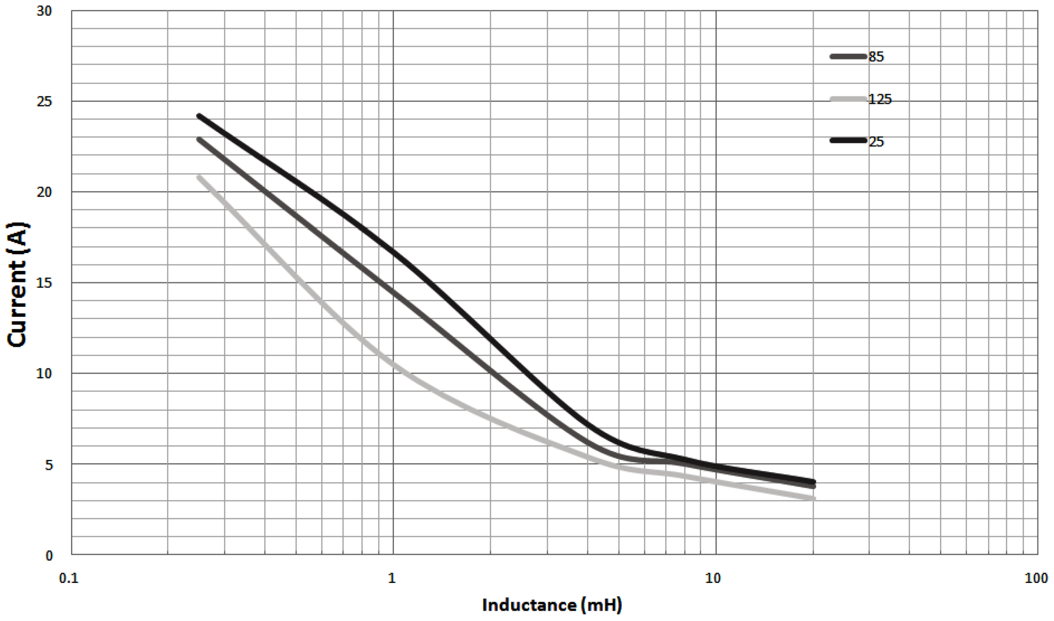

Figure 4. MC10XS4200 current versus inductance, single pulse operation

3.2 Energy across the MOSFET

The designer must compute the energy across the MOSFET for both ON state (during t_{on}) and during demagnetization time (t_{demag}).

For demagnetization time, the energy E_{demag} can be either calculated by equation (1) or directly measured on the boards by using the Scope energy measurement feature.

$$E_{Demag} = \frac{1}{2} \times L \times I^2_{HS_{Peak}} \times \left(1 + \frac{VPWR}{V_{CL}}\right) \qquad (1)$$

For ON time, the energy E_{on} can be either calculated by equation (2) or directly measured on the boards by using the Scope energy measurement feature.

$$E_{ON} = R_{DSON} \times \frac{I_{HS_{Peak}}}{2}^{2} \times t_{ON} \qquad (2)$$

3.3 Parameters involved to be gathered

Once the energy is identified, either by computation or measurement, a few parameters are required to pursue the process of temperature elevation assessment:

- V_{PWR}: Voltage on VPWR terminal
- V_{DD}: Voltage on VDD terminal
- I_{VPWR}: Current consumption on VPWR terminal (either using data sheet information or through measurement on VPWR terminal minus load current)
- I_{VDDON}: Current consumption on VDD terminal (either using data sheet information or through measurement)
- t_{Demag}: Demagnetization time
- t_{ON}: Duration of ON state
- Freq: Frequency of switching

If the current sense feature is activated:

- R_{SENSE}: Sense resistor value (Ω)
- V_{CSNS}: Voltage at sense resistor terminal

3.4 Power assessment

All factors contributing to power dissipation must be calculated. Each factor has its own weight in the power assessment. Do not neglect any of them. Three powers must be computed:

Power dissipation during demagnetization time:

$$P_{Demag} = \frac{E_{Demag}}{t_{Demag}} \qquad (3)$$

Power dissipation during ON time:

$$P_{ON} = \frac{E_{ON}}{t_{ON}} \qquad (4)$$

All other power dissipations involved called facilities. Those powers are due to biasing on each power feed and current sensing:

$$P_{Facilities} = P_{VPWR} + P_{VDD} + P_{CSNS} \qquad (5)$$

with:

Power dissipation on the power path (VPWR):

$$P_{VPWR} = VPWR \times I_{VPWR}$$

Power dissipation on SPI interface supply (VDD):

$$P_{VDD} = VDD \times I_{VDDON}$$

Power dissipation on current sense path (CSNS):

$$P_{CSNS} = \left(\frac{V_{CSNS}}{R_{Sense}}\right) \times (VPWR - V_{CSNS}) + VPWR \times (1 + K_1) \times (\frac{V_{CSNS}}{R_{Sense}} \times K_2)$$

With a dependency of the current ratio used:

- CSNS_ratio = 0: K1 = 9 K2 = 0.1
- CSNS_ratio = 1: K1 = 3 K2 = 0.1

3.5 Average temperature elevation

Each power dissipation factor contributes individually to the overall device temperature elevation. Therefore, temperature elevation is determined by first calculating the temperature elevation of each individual power dissipation factor and then summing the results.

Each power component is assigned an identified time slot across the switching period. For each component, a duty cycle (DC) is allocated with respect to the time of operation within the switching period.

Example:

$$DC_{Demag} = t_{Demag} \times Freq$$

Based on duty cycle data and time of occurrence, the thermal impedance Zth is extracted from 'Temperature rise at repetitive pulse' curve (see Figure 5).

Each junction temperature is calculated with the generic formula:

$$Tj = P \times Zth$$

Then the final temperature elevation is:

$$Tj_{Average} = Tj_{Ambient} + Tj_{Demag} + Tj_{ON} + Tj_{Facilities}$$

With powers computed in Section 3.4 "Power assessment" equations (3), (4) and (5)

$$Tj_{Demag} = P_{Demag} \times Zth_{JA\_Demag}$$
$$Tj_{ON} = P_{ON} \times Zth_{JA\_ON}$$
$$Tj_{Facilities} = P_{Facilities} \times Zth_{JA\_Facilites}$$

Duty cycle formulas:

For the demagnetization time slot:

$$DC_{Demag} = t_{Demag} \times Freq$$

With:

- DC_{Demag}: duty cycle of demagnetization
- t_{Demag}: duration of demagnetization
- Freq: frequency of output switching

For the ON time slot :

$$DC_{ON} = t_{ON} \times Freq$$

- DC_{ON}: duty cycle of ON state
- t_{ON}: duration of ON state
- Freq: frequency of output switching

For facilities:

$$DC_{Facilities} = 100\%$$

The power involved for facilities is not subject to output switching events. The duty cycle is therefore 100 %.

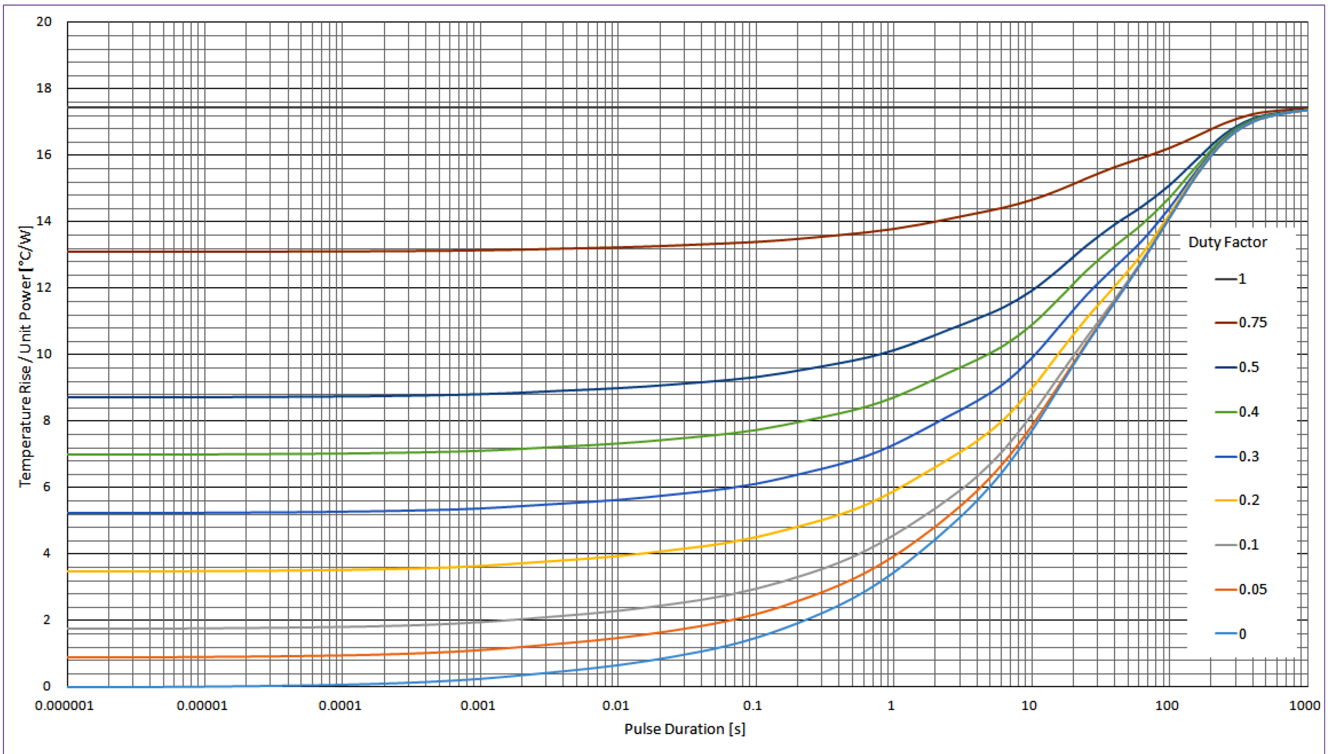

Figure 5. Temperature rise at repetitive pulse

3.6 Peak temperature elevation

This section verifies the postulate N°2, such as the temperature transient, must not exceed 60 °C. The sanity check is done based on the impedance curve in single pulse mode (Figure 6), powers and duration of events (t_{ON}, t_{DEMAG}, P_{ON}, P_{DEMAG}).

Most of the time, the demagnetization is worse case, as the peak power is the highest and as energy is highest with the shortest time (equation (3)).

$$Tj_{Peak\_Demag} = P_{Demag} \times Zth_{JA\_Peak\_Demag}$$

$$Tj_{Peak\_ON} = P_{ON} \times Zth_{JA\_Peak\_ON}$$

$$Tj_{Peak} = Tj_{Peak\_Demag} + Tj_{Peak\_ON}$$

The impedance value is extracted on Y axis from the thermal impedance curve with the event duration on X axis.

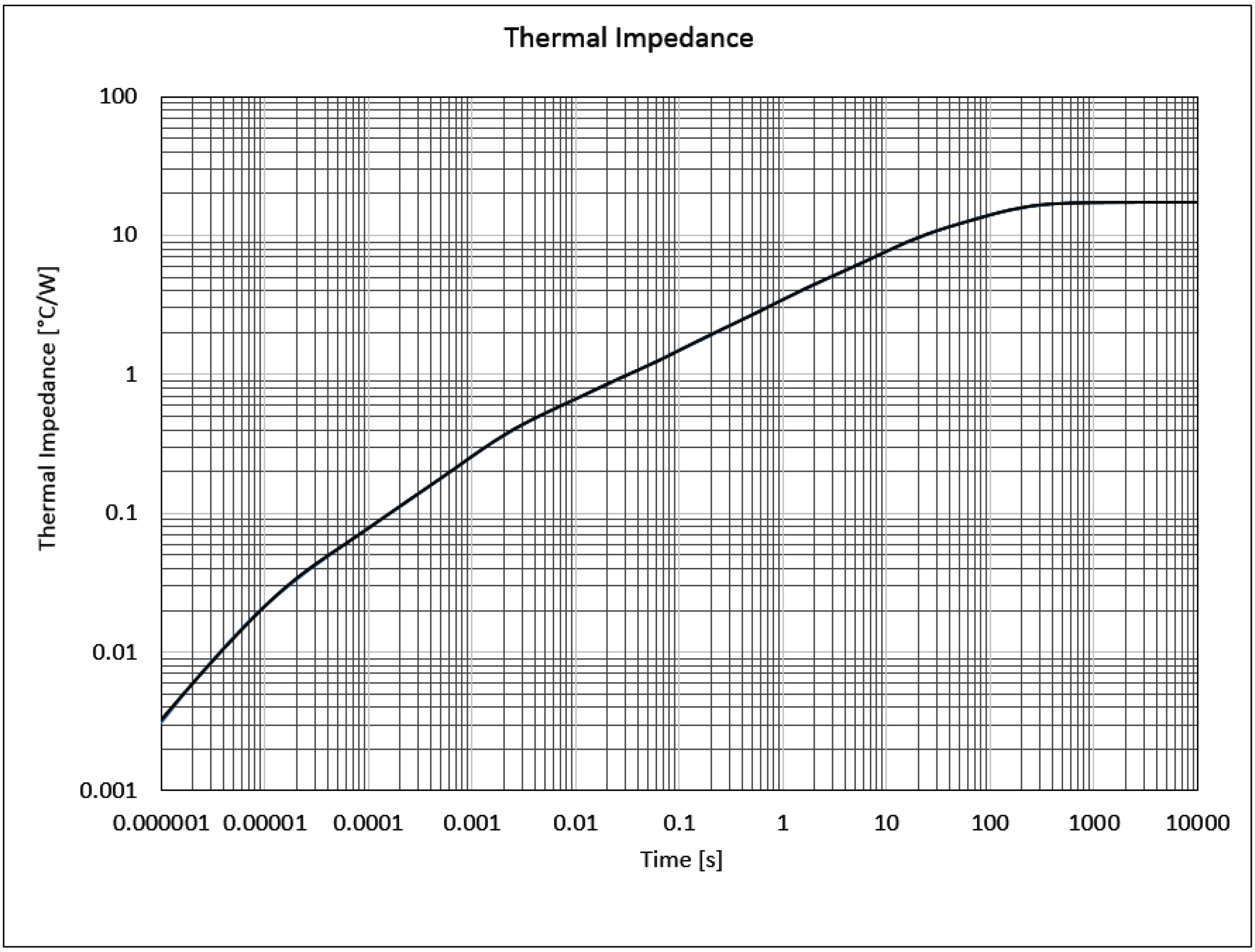

Figure 6. Thermal impedance – single pulse

3.7 Example

The following is an example that illustrates the methodology. The example uses an 8.0 mH air inductance switched at 100 Hz. The device used is a 10 mΩ MC10XS4200.

VPWR = 24 V

t_{ON} = 5.0 ms

t_{Demag} = 680 µs

Freq = 100 Hz

DC_{ON} = 50 %

DC_{Demag} = 6.8 %

E_{demag} = 28 mJ (measured)

E_{ON} = 3 mJ (measured)

Computation of powers:

$$P_{Demag} = \frac{E_{Demag}}{t_{Demag}} = \frac{28\ mJ}{680\ us} = 41\ W$$

$$P_{ON} = \frac{E_{ON}}{t_{ON}} = \frac{3\ mJ}{5\ ms} = 0.6\ W$$

$$P_{Facilities} = 201.8\ mW$$

Note:

For $P_{Facilities}$ details, see Section 5 "Appendix B"

Thermal impedance extracted from Figure 7 with duty cycle and timing data:

- $Zth_{JADemag}$ (t_{demag}) = 1.2 °C/W
- Zth_{JAON}(t_{ON}) = 9 °C/W
- $Zth_{JA\_Facilities}$ = 17 °C/W

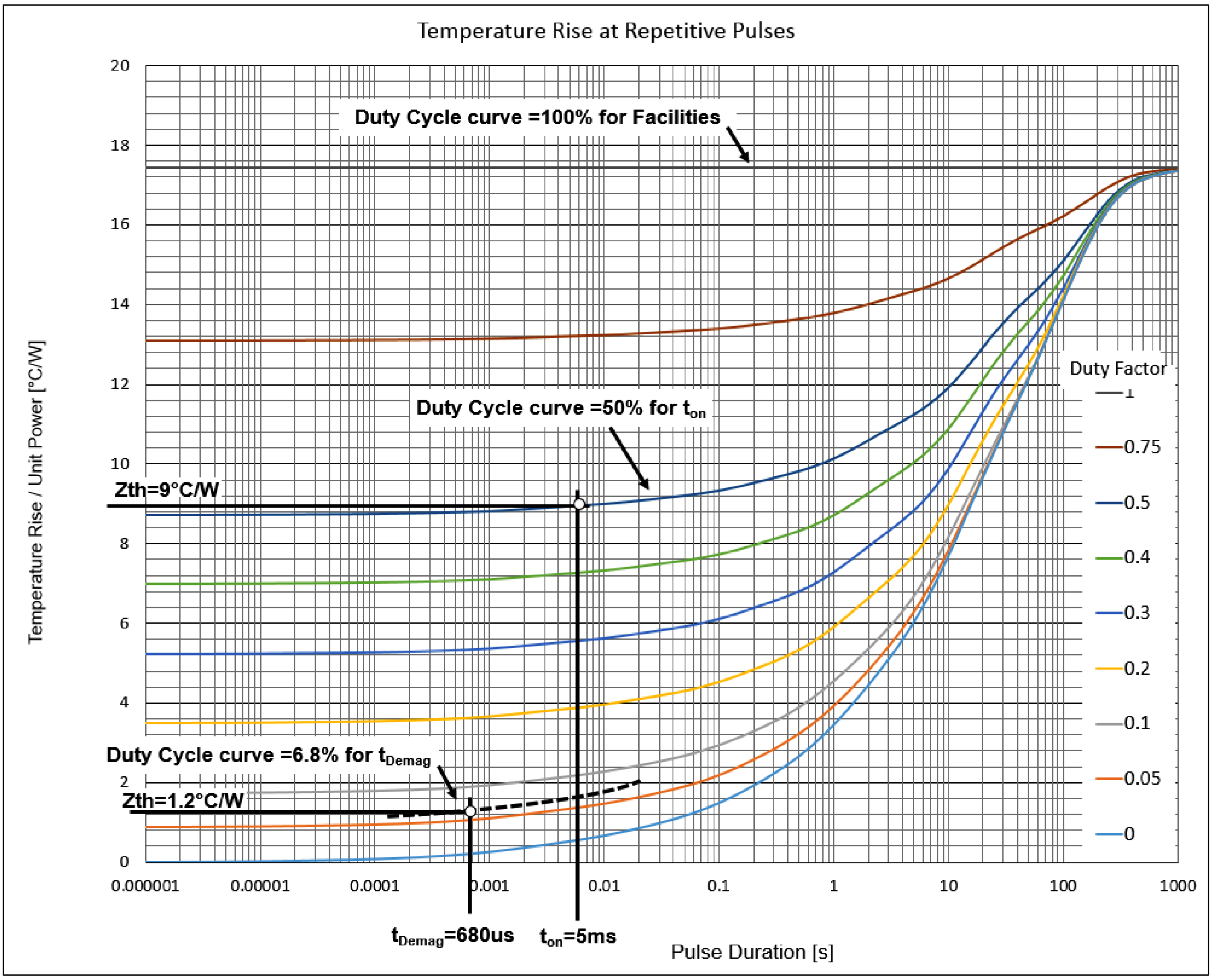

Figure 7. Temperature rise example

Junction temperature based on power dissipation and thermal impedance:

$$Tj_{Demag} = P_{Demag} \times Zth_{JA\_Demag} = 41W \times 1.2°\frac{C}{W} = 49.2°C$$

$$Tj_{ON} = P_{ON} \times Zth_{JA\_ON} = 0.6W \times 9°\frac{C}{W} = 5.4°C$$

$$Tj_{Facilities} = P_{Facilities} \times Zth_{JA\_Facilites} = 0.201W \times 17°\frac{C}{W} = 3.4°C$$

Average temperature:

$$Tj_{Average} = T_{Ambient} + Tj_{Demag} + Tj_{ON} + Tj_{Facilities} = 25°C + 49.2°C + 5.4°C + 3.4°C = 82.7°C$$

With $T_{Ambient}$ = 25 °C

Peak temperature check using Single pulse curve (see Figure 8):

t_{ON} = 5.0 ms

t_{Demag} = 680 µs

$$Tj_{Peak\_Demag} = P_{Demag} \times Zth_{JA\_Peak\_Demag} = 41W \times 0.2°\frac{C}{W} = 8.2°$$

$$Tj_{Peak\_ON} = P_{ON} \times Zth_{JA\_Peak\_ON} = 0.6W \times 0.55°\frac{C}{W} = 0.33°$$

$$\Delta Tj_{Peak} = 8.2°C + 0.33°C = 8.55°C$$

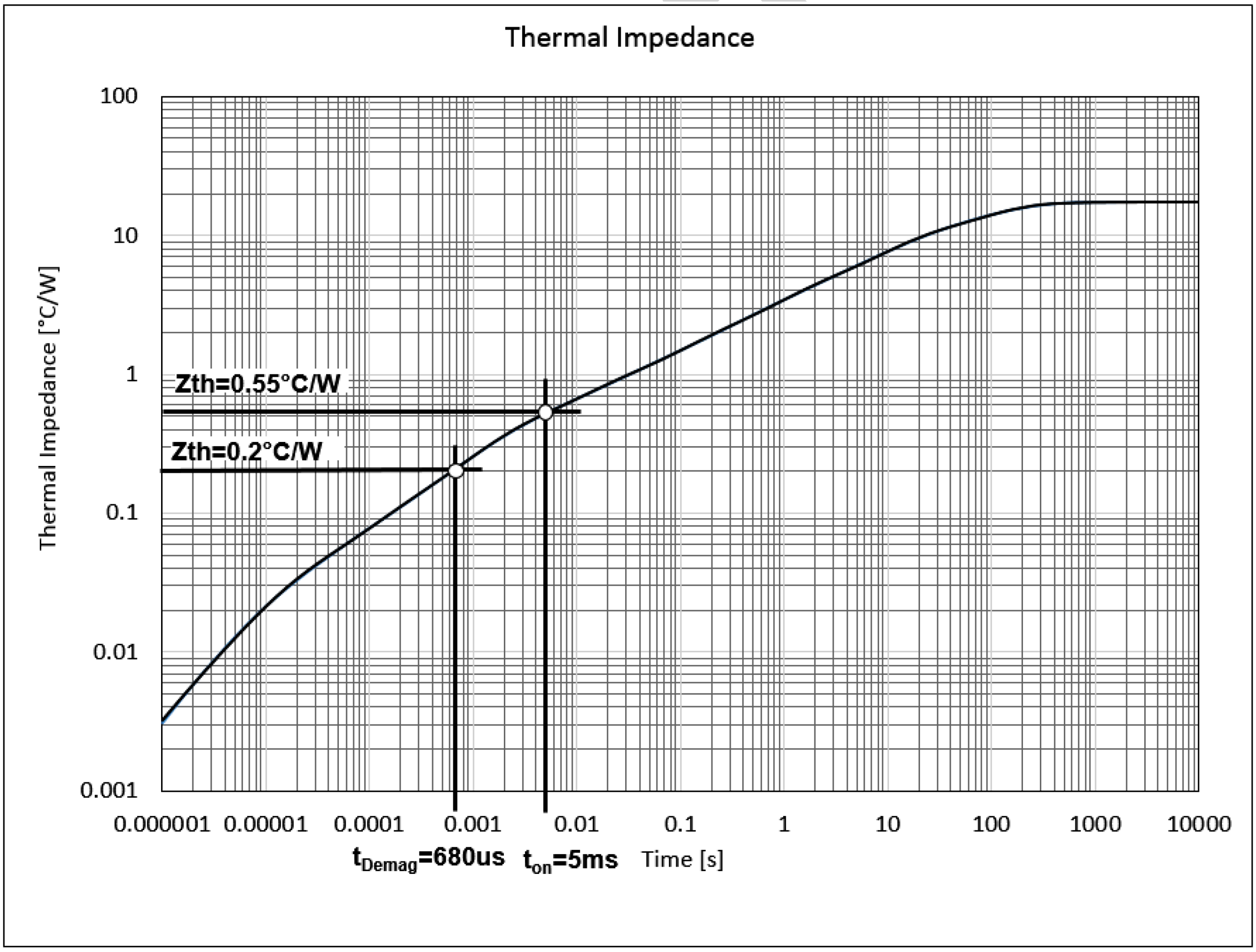

Figure 8. Thermal impedance – single pulse example

Therefore:

$$Tj_{Max} = Tj_{Average} + \Delta Tj_{Peak} = 82.7°C + 8.55°C = 91.25°C$$

$$Tj_{Max} < 150°C$$

$$\Delta Tj_{Peak} < 60°C$$

4 Appendix A

Development details of equation (1)

Formula of Energy:

$$E_{demag} = \int_{t_{on}}^{t_{demag}} v_{DS}(t) \times i_{HS}(t) dt \quad (1)$$

Energy to be considered here is restricted to the range t_{ON} to t_{DEMAG}.

$$v_{DS}(t) = VPWR + V_{CL} \quad (2)$$

$$i_{HS}(t) = I_{HS_{Peak}} - \frac{I_{HS_{Peak}}}{t_{Demag}} t \quad (3)$$

Replace both $v_{DS}(t)$ and $i_{HS}(t)$ in equation (1)

$$E_{Demag} = (VPWR + |V_{CL}|) \times I_{HS\_Peak} \int_{t_{ON}}^{t_{Demag}} \left(1 - \frac{t}{t_{Demag}}\right) dt$$

$$E_{Demag} = (VPWR + |V_{CL}|) \times I_{HS_{Peak}} \times \left[t - \frac{t^2}{2 \times t_{Demag}}\right]_{t_{ON}}^{t_{demag}}$$

$$E_{Demag} = \frac{1}{2} \times I_{HS_{Peak}} \times t_{Demag} \times (VPWR + |V_{CL}|) \quad (4)$$

In an inductance

$$e = L\frac{di}{dt}$$

then:

$$t_{Demag} = L \times \frac{I_{HS_{Peak}}}{|V_{CL}|} \quad (5)$$

Replace t_{Demag} equation (5) in equation (4)

$$E_{Demag} = \frac{1}{2} \times I_{HS_{Peak}}^2 \times L \times \left(\frac{VPWR + |V_{CL}|}{|V_{CL}|}\right)$$

5 Appendix B

Details of $P_{FACILITIES}$ computation:

$$P_{Facilities} = P_{VPWR} + P_{VDD} + P_{CSNS} \quad (5)$$

VPWR = 24 V

Power dissipation on the power path (on VPWR):

$$P_{VPWR} = VPWR \times I_{VPWR}$$

Per data sheet of MC10XS4200 (typ.):

$$I_{VPWR} = 6.5\ mA$$
$$P_{VPWR} = 24V \times 6.5mA = 0.144\ W$$

Power dissipation on SPI interface supply (VDD):

$$P_{VDD} = VDD \times I_{VDDON}$$

Per data sheet of MC10XS4200 (typ.):

$$I_{VDDON} = 1\ mA$$
$$P_{VDD} = 5V \times 1mA = 5mW$$

Power dissipation on current sense path (CSNS):

$$P_{CSNS} = \left(\frac{V_{CSNS}}{R_{Sense}}\right) \times (VPWR - V_{CSNS}) + VPWR \times (1 + K_1) \times (\frac{V_{CSNS}}{R_{Sense}} \times K_2)$$

With:

- V_{CSNS} = 1.2 V
- R_{CSNS} = 1060 Ω
- $CSNS_{ratio}$ = 0
- K1 = 9

- K2 = 0.1

$$P_{CSNS} = (\frac{1.2\,V}{1060\,\Omega}) \times (24\,V - 1.2\,V) + 24\,V \times (1+9) \times (\frac{1.2\,V}{1060\,\Omega} \times 0.1)$$

$$P_{CSNS} = 25.8\,mW + 27\,mW = 52.8\,mW$$

Note:

When current sense is not used, it is recommended to de-activate the feature. It can also be de-activated between current measurements.

$$P_{Facilities} = P_{VPWR} + P_{VDD} + P_{CSNS} \;= 144mW + 5mW + 52.8mW = 201.8mW$$

6 Appendix C

Table 1. Plots for MC06XS4200

Revision	Plots	Links
1.0	Max current versus inductance Thermal Impedance – Single channel Thermal Impedance – Dual channel Temperature Rise at Repetitive Pulses – Single channel Temperature Rise at Repetitive Pulses – Dual channel	The plots for MC06XS4200 device can be downloaded from the associated archive file AN5146SW.zip at www.nxp.com

Table 2. Plots for MC10XS4200

Revision	Plots	Links
1.0	Max current versus inductance Thermal Impedance – Single channel Thermal Impedance – Dual channel Temperature Rise at Repetitive Pulses – Single channel Temperature Rise at Repetitive Pulses – Dual channel	The plots for MC10XS4200 device can be downloaded from the associated archive file AN5146SW.zip at www.nxp.com

Table 3. Plots for MC20XS4200

Revision	Plots	Links
1.0	Max current versus inductance Thermal Impedance – Single channel Thermal Impedance – Dual channel Temperature Rise at Repetitive Pulses – Single channel Temperature Rise at Repetitive Pulses – Dual channel	The plots for MC20XS4200 device can be downloaded from the associated archive file AN5146SW.zip at www.nxp.com

Table 4. Plots for MC22XS4200

Revision	Plots	Links
1.0	Max current versus inductance Thermal Impedance – Single channel Thermal Impedance – Dual channel Temperature Rise at Repetitive Pulses – Single channel Temperature Rise at Repetitive Pulses – Dual channel	The plots for MC22XS4200 device can be downloaded from the associated archive file AN5146SW.zip at www.nxp.com

Table 5. Plots for MC50XS4200

Revision	Plots	Links
1.0	Max current versus inductance Thermal Impedance – Single channel Thermal Impedance – Dual channel Temperature Rise at Repetitive Pulses – Single channel Temperature Rise at Repetitive Pulses – Dual channel	The plots for MC50XS4200 device can be downloaded from the associated archive file AN5146SW.zip at www.nxp.com

7 Revision history

Table 6. Revision history

Revision	Date	Description
1.0	7/2016	Initial public release

8 Legal information

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Tables

Figures

Contents

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