Multichannel Low-Side Switches

Switching Inductive Loads

Application Note

Rev.1.0, 2011-04-19

Automotive Power

Abstract

Note: The following information is given as a hint for the implementation of the device only and shall not be regarded as a description or warranty of a certain functionality, condition or quality of the device.

This Application Note is intended to provide the right knowledge and tools to evaluate and/or measure the energy to be dissipated at the switch-OFF of an inductive load driven by a Low-Side Switch which implements an Active Clamping circuitry. That energy, namely the Clamping Energy (E_{CL}), within a well defined operating scenario, will be then used for a comparison with the Multichannel Low-Side Switch energy capabilities in order to judge whether the load can be driven by the device over life-time.

Table of Contents

1 Introduction

Today's automotive applications require more and more the ability to drive a large number of actuators. In Powertrain Applications, as Engine Management System (EMS) for example, commonly used actuators like injectors, relays, valves (purge, intake etc.) and various solenoids, are mostly showing an inductive behavior. The easiest and most common way to drive such loads is to keep them connected to the Battery Voltage (V_{BAT}) and control the flowing current through a low side switch, as illustrated in **Figure 1**.

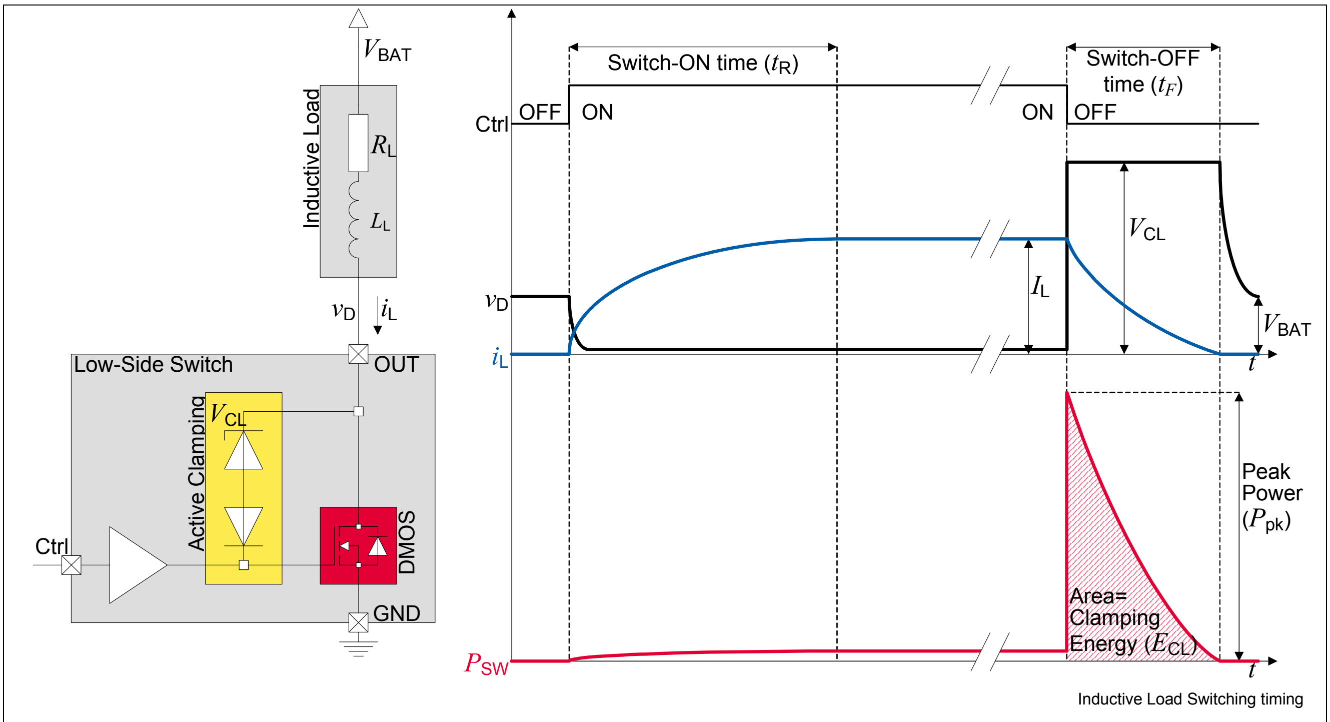

Figure 1 Inductive Load: Switch-ON, Switch-OFF timing with Active Clamping

An inductive element will naturally build up a magnetic field during the ON phase of the switch, therefore storing an amount of Energy which is related to the load ON current (I_L) and inductance (L_L) by the following:

$$E_L = \frac{1}{2}L_L I_L^2 \tag{1}$$

At the OFF phase of the switch, the load current will decrease to zero and the previously stored energy plus the energy generated by V_{BAT} has to be dissipated at the same time: a small part will be burned into the load itself (R_L) and the remaining energy will cause an increase of the switch voltage limited by the Active Clamping circuitry, where it will be dissipated. Different techniques can be implemented in order to reduce the dissipation of such energy inside the switch (into silicon) for example by using Free-Wheeling Diode or a Parallel Dumping Branch etc., but those techniques, besides increasing the Bill of Material (BOM) cost of the application, will also increase the switch-OFF time (t_F) of the actuators.

In some cases (e.g. injectors driving, PWM-operated valves etc.) a relatively short switch-OFF time is desirable in order to achieve the required performance, for this reason the implementation of the Active Clamping makes the use of the sole switch a better and cheaper solution. In fact the higher the Clamping Voltage (V_{CL}) the shorter t_F will result. As a drawback, the energy dissipated into the DMOS during the clamping event, from now on referred to as Clamping Energy (E_{CL}), due to the high peak power (high V_{CL}) and to the large number of the actuator switching cycles, will induce a repetitive thermal stress in the silicon thus affecting the life-time.

Note: The implementation of the Active Clamping circuitry and the Clamping Energy capabilities over life-time, as specified in the Data Sheet, makes the Infineon Multichannel Low-Side Switches very suitable for Powertrain applications.

2 Inductive Loads

In this section the setup for measuring the clamping energy on a real load will be described. A behavioral model of the actuators will be introduced in order to derive the equations for the E_{CL} calculation. Deviation of measured values from calculated ones will be explained through the introduction of non-idealities of resistance and inductance.

2.1 E_{CL} Measurement

The best approach to evaluate the real load characteristics and obtain a value of the clamping energy, dissipated in the low-side switch, is to measure it. Of course, it's important to reproduce as much as possible the operating conditions of the actuator, as they would be in the real application. In **Figure 2** a setup for the measurement is suggested where the load is kept at the expected operating temperature inside a chamber.

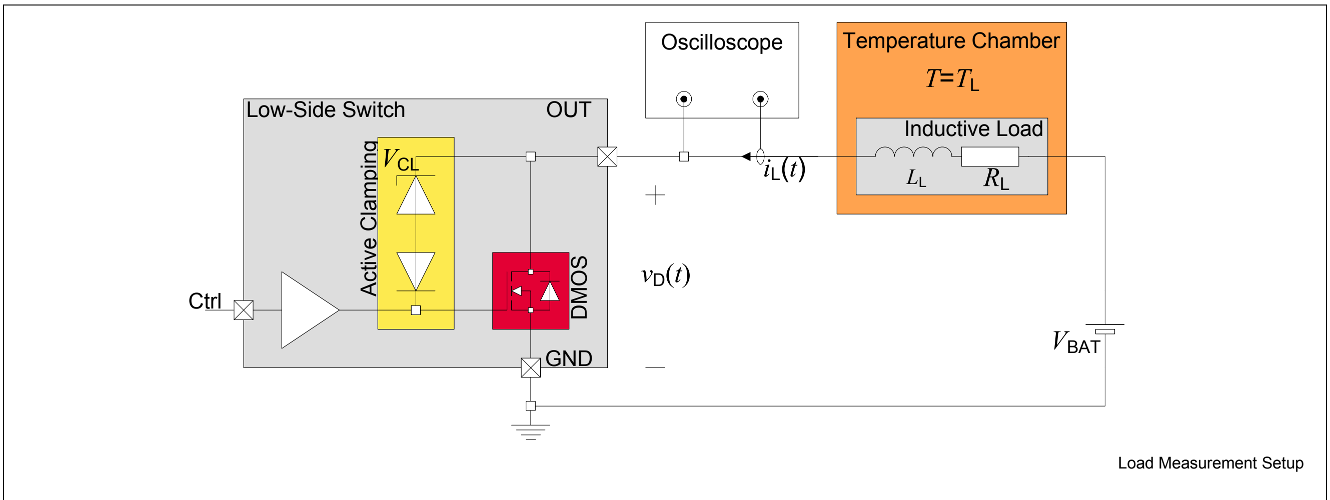

Figure 2 E_{CL} measurement setup

The clamping energy is expressed by:

$$E_{CL} = \int_0^{t_F} v_D(t) i_L(t) dt \qquad (2)$$

where v_D and i_L are, respectively, the switch voltage and load current and t_F is the time that the load current needs to reach zero after the switch-OFF event.

Let's now consider a real example:

- Load Characteristics [1)]
  - R_L=12.2Ω (@25°C)
  - L_L=13.2mH (@25°C, 1kHz)
- Switch Characteristics
  - V_{CL}=52V
  - R_{DS}=0.18Ω (@25°C)
- Expected Operating Conditions
  - V_{BAT}=14V
  - T_L=115°C

1) Nominal values confirmed by LCR measurements

Using the mathematical functions of a modern digital oscilloscope it is easy to obtain the product of the measured v_D, i_L and its integral, as shown in **Figure 3**.

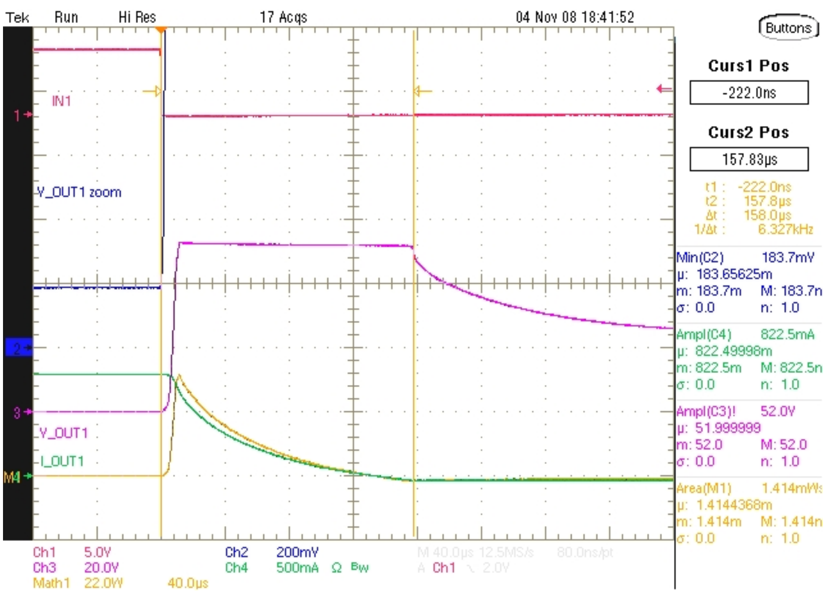

Figure 3 **E_{CL} measurement (R_L=12.2Ω, L_L=13.2mH, V_{BAT}=14V, T_L=115°C)**
Purple = Switch Voltage (v_D)
Green = Load Current (i_L)
Yellow = Switch Power (v_D•i_L)

The results are the following:

- V_{CL}=52V
- I_L=0.82A
- t_F=158µs
- **E_{CL}=1.4mJ**

If the integral function requires to much efforts as not implemented in the oscilloscope, a linear approximation of the current shape could be used, in that case the Energy would result as:

$$E_{CL} = V_{CL} I_L \frac{t_F}{2} = 52\text{V} \cdot 0.82\text{A} \cdot \frac{0.158\text{ms}}{2} = 3.3\text{mJ} \rightarrow \text{Error} > 100\% \tag{3}$$

If we compare the approximated value with the measured one it is immediately evident that we can expect an error higher then 100%.

2.2 Behavioral Model and Equations

A behavioral model of the load can also be considered to obtain a mathematical expression which predicts the value of the clamping energy. Let's now consider the simplified equivalent circuit as shown in **Figure 4**. As we are interested in the clamping event, our focus is on the OFF phase of the switch. What we need to take into account is the value of the load current at the end of the ON phase (I_L) expressed by:

$$I_L = \min[I_{LIM}; \frac{V_{BAT}}{R_L + R_{DS}}\left(1 - \exp\left(-\frac{t_{ON}}{\tau_R}\right)\right)] \text{ ; where } \tau_R = \frac{L_L}{R_L + R_{DS}} \tag{4}$$

τ_R is the time constant ruling the rise of the inductor current, I_{LIM}[1)] is the current limit of the switch, t_{ON} is the duration of the ON time of the actuator.

In **Equation (4)** - besides including the possible intervention of the switch current protection - we also consider the fact that a short ON time would not give enough time to the load to reach its regime current.

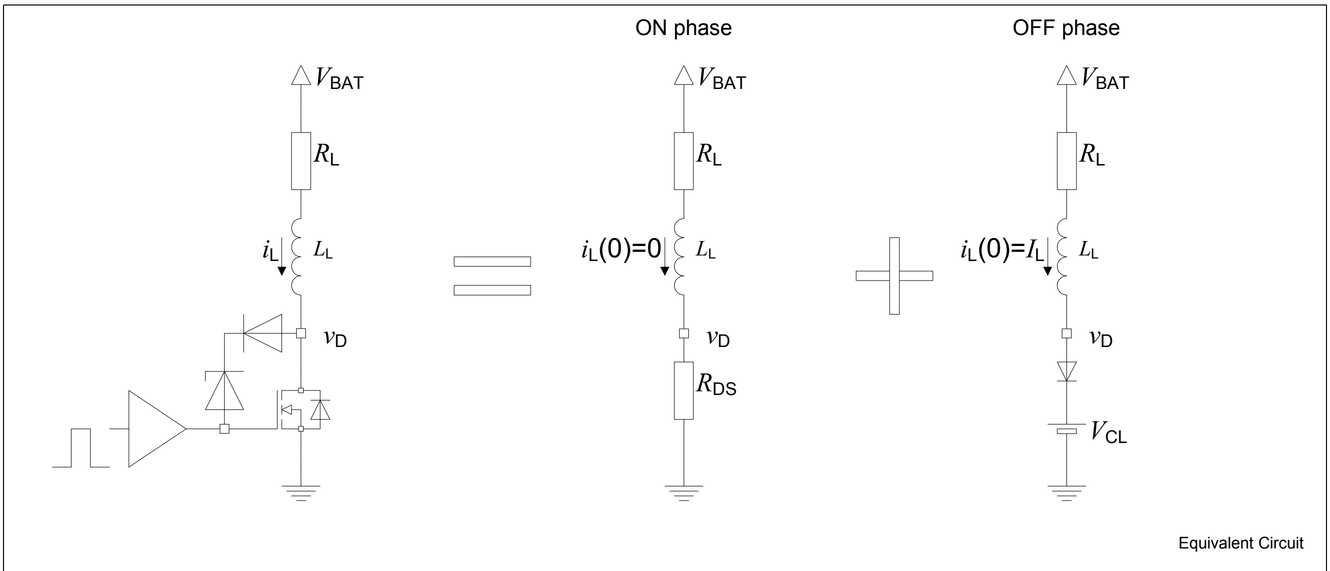

Figure 4 Equivalent Circuit

The differential equation ruling the OFF phase circuit is:

$$L_L\frac{di_L}{dt} + R_L i_L = V_{BAT} - V_{CL} \tag{5}$$

solving the **Equation (5)** with $i_L(0)=I_L$ as initial condition we obtain an expression for the inductor current:

$$i(t) = \left(I_L + \frac{V_{CL} - V_{BAT}}{R_L}\right)\exp\left(-\frac{t}{\tau_F}\right) - \frac{V_{CL} - V_{BAT}}{R_L} \text{ ; where } \tau_F = \frac{L_L}{R_L} \tag{6}$$

τ_F is the time constant ruling the fall of the inductor current.

Making **Equation (6)** equal to zero and solving for t, we obtain also an expression for the clamping event duration:

$$t_F = \frac{L_L}{R_L}\ln\left(1 + \frac{R_L I_L}{V_{CL} - V_{BAT}}\right) \tag{7}$$

1) Current limit protection is normally implemented in Multichannel Low-Side Switches

Since the current - once it has reached the zero value t=t_F - cannot become negative due to the diode, we can write:

$$\begin{cases} i_L(t) = \left(I_L + \frac{V_{CL} - V_{BAT}}{R_L}\right) \exp\left(-\frac{t}{\tau_F}\right) - \frac{V_{CL} - V_{BAT}}{R_L} \text{ ; for } t \le t_F \\ i_L(t) = 0 \text{ ; for } t > t_F \end{cases} \tag{8}$$

Now we have the elements we need to evaluate the integral:

$$E_{CL} = \int_0^{t_F} v_D(t) i_L(t) dt = V_{CL} \int_0^{t_F} \left[\left(I_L + \frac{V_{CL} - V_{BAT}}{R_L}\right) \exp\left(-\frac{t}{\tau_F}\right) - \frac{V_{CL} - V_{BAT}}{R_L}\right] dt \tag{9}$$

which leads to:

$$E_{CL} = V_{CL} \frac{L_L}{R_L}\left[I_L - \frac{V_{CL} - V_{BAT}}{R_L} \ln\left(1 + \frac{R_L I_L}{V_{CL} - V_{BAT}}\right)\right] \tag{10}$$

The obtained equations can be used to compare the measured values of the example in **Chapter 2.1** with the calculated ones, **Table 1** and **Figure 5**.

Table 1 Measured vs. Calculated values (R_L=12.2Ω, L_L=13.2mH, V_{BAT}=14V, V_{CL}=52V, R_{DS}=0.18Ω)

	I_L [A]	E_{CL} [mJ]	t_F [ms]
Measured Values	0.82	1.4	0.158
Calculated Values	1.13 (+37%)	9.3 (+560%)	0.335 (+110%)

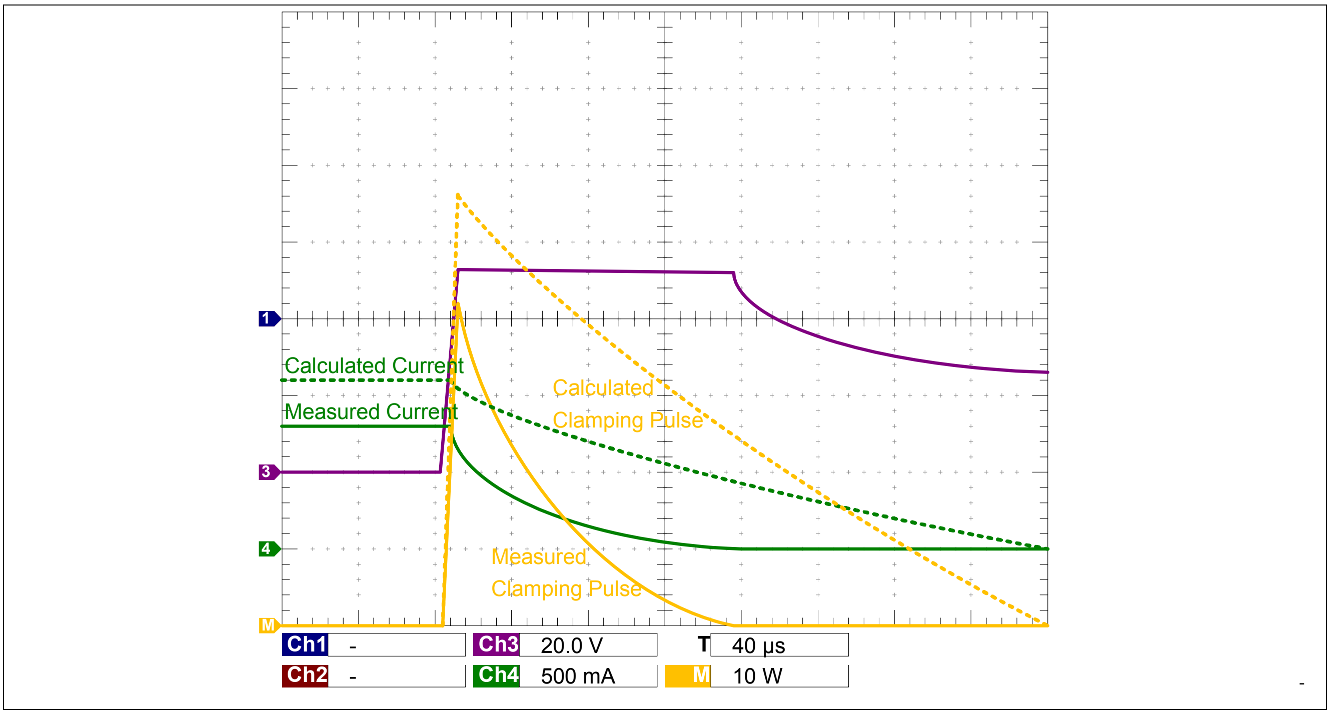

Figure 5 Measured vs. Calculated values (superposed dotted curves are the calculated ones)

Utilizing nominal load characteristics (R_L, L_L) calculated values show a strong deviation from measured ones mainly because of the following reasons:

- Load resistance (R_L) in reality changes with the load temperature T_L
- Load inductance (L_L) in reality changes with load current I_L

2.2.1 Resistance versus Temperature

The conductivity of any metal is normally affected by the temperature causing a relationship between R and T. For typical automotive temperature range [-50°C, 150°C] this relationship can be simplified as following:

$$R(T) = R(T_0)[1 + \alpha \cdot (T - T_0)] \tag{11}$$

where α is a coefficient that changes from material to material and for copper is α_{CU}=0.0039 K^{-1}. As we can predict the operating temperature of the load (T_L) it makes sense to replace R_L in **Equation (4)** and **Equation (10)** with $R_L(T_L)$ to have a better estimation of the current and the energy.

2.2.2 Inductance versus Current

Ferromagnetic materials which compose the core of any coil show a dependency from the magnetic field. Therefore the inductance of the coil shows a dependency from the current flowing through it. In general, at a certain current level, namely the saturation current, the inductance starts to decrease with a trend that depends on the material, and the saturation current itself decreases also with temperature, see **Figure 6**. Additionally we need to consider that many actuators (e.g. Relays) change the morphology of their core due to a mechanical switch, namely changing the permeability (μ) of the core and thus the resulting inductance.

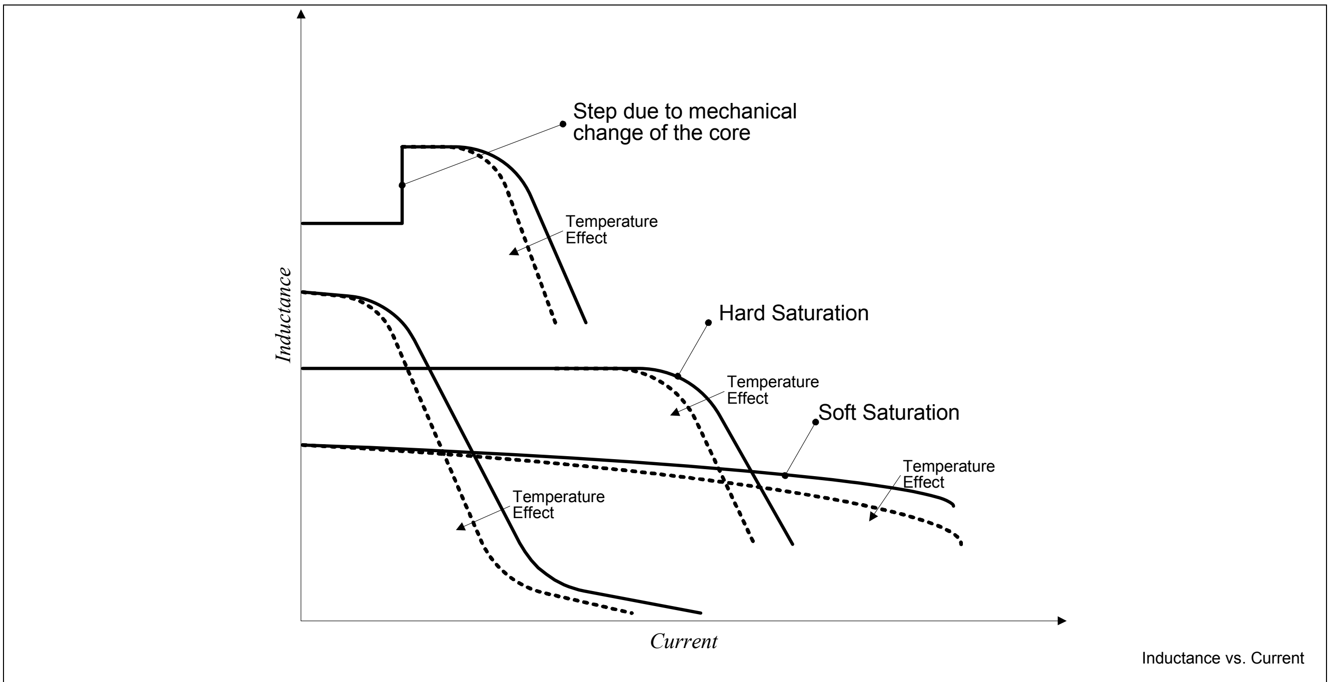

Figure 6 Inductance vs. Current (different types of materials)

Unfortunately the behavior of the actuators cannot be easily ruled out neither classified. For this reason the dependency of the inductance from the current is hard to be included in the **Equation (10)**. Nevertheless it is important to know that the real clamping energy of the load will be heavily influenced by this effect, as shown in the comparison of **Figure 5**.

In conclusion we can expect strong deviations from the calculated value of the clamping energy to the real one depending on the actuator type and on the operating conditions (V_{BAT}, T_L), moreover the calculated one not always represents the worst case approximation. In fact, as mentioned before, some load types (e.g. relays and some kind of valves) could show an increased inductance due to an increase of current beyond the switching threshold. A short summary is shown in **Figure 7**.

Note: It is strongly recommended to base any assessment on the real load measurement data.

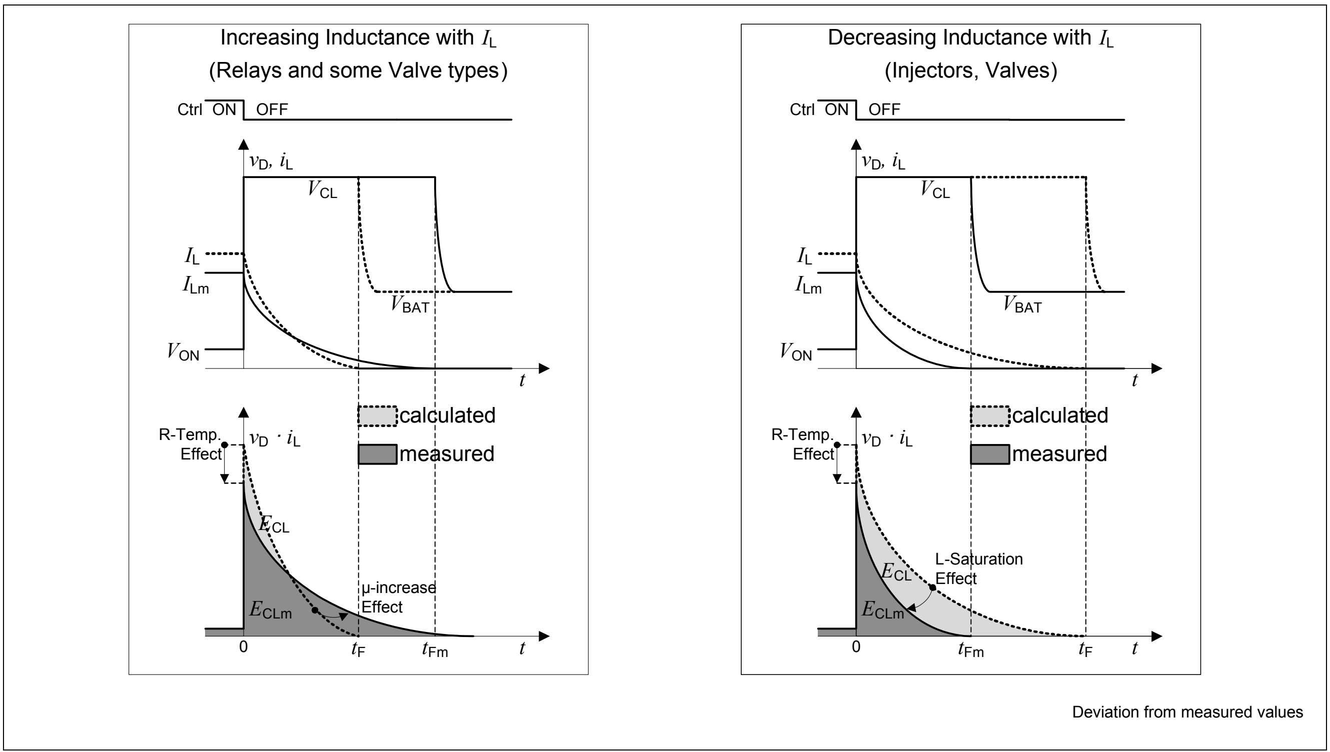

Figure 7 Deviation of calculation from measurement

3 Energy Capabilities of the Device

In the application is important to estimate the capabilities of the stressed switch over life-time. In this document an approach based on the *Energy vs. Current* safe operating area (SOA) of the device is presented, where each load, in a specific operating condition, defines an operating point also for the switch.

The variable parameters which determine the operating conditions of the load are:

- Battery Voltage (V_{BAT})
- Temperature of the load (T_L)

In fact we have already shown that:

- $R_L = R_L(T_L)$
- $L_L = L_L(I_L) = L_L(T_L, V_{BAT})$

which lead to the operating conditions of the DMOS:

- $I_L = I_L(R_L, V_{BAT}) = I_L(T_L, V_{BAT})$
- $E_{CL} = E_{CL}(R_L, I_L, V_{BAT}, V_{CL}) = E_{CL}(T_L, V_{BAT})$

where dependencies on constant parameters (e.g. V_{CL}, R_{25}, L_0) have been omitted and influence of the DMOS channel resistance (R_{DS}) has been neglected as well as the influence of the clamping voltage variations (V_{CL}).

On the other hand the variables affecting the clamping energy SOA of the device are:

- Number of operation cycles (N_C)
- Starting Junction Temperature (T_J)

the higher the required number of cycles and the higher the T_J, the lower will be the device capability in terms of clamping energy, **Figure 8**.

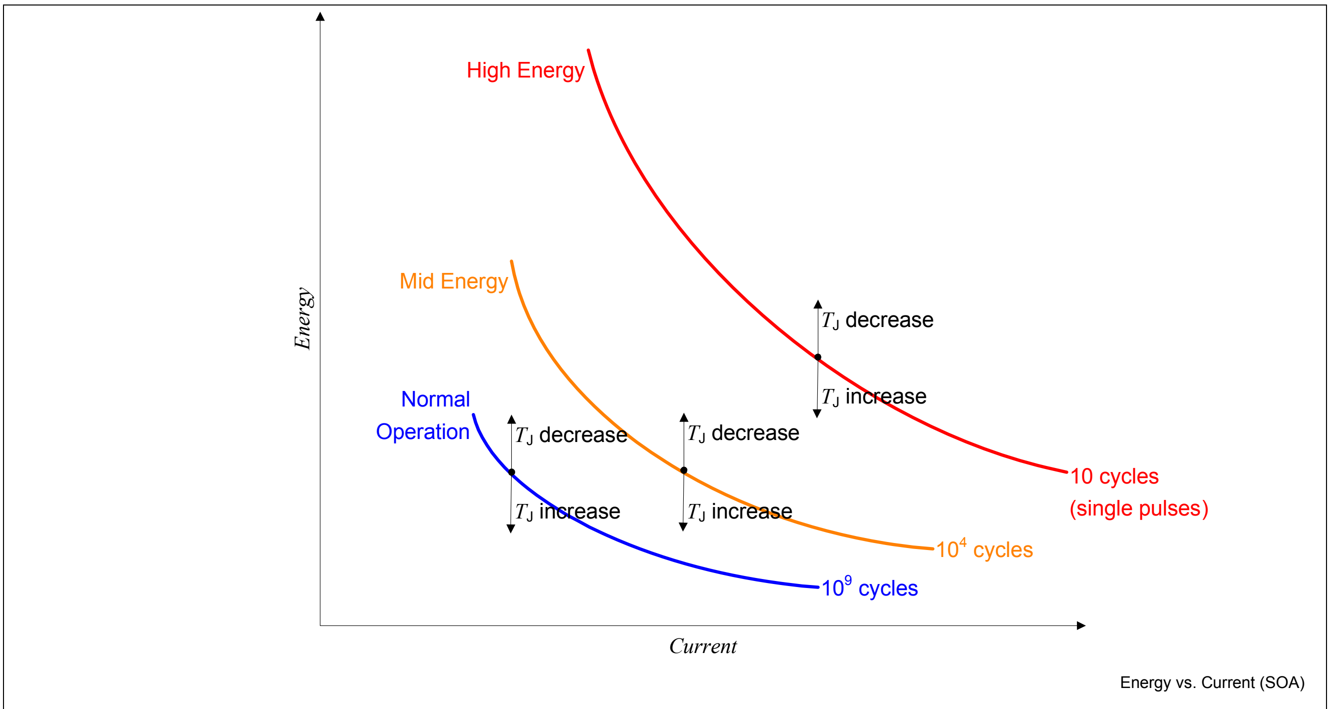

Figure 8 Energy vs. Current (SOA)

3.1 Operating conditions and cumulative scenario

Depending on the load type and the application, different operating scenarios can be identified. For example an injector for Multi Port (MPI) could operate according to a System Temperature Profile, as shown in **Figure 9**, over a life-time of 10’000 hours, which means about 10^9 operation cycles[1]. For a relay the operating temperature would probably be lower and not more than 10^6 cycles over life-time could be expected. In addition to that also variations of the battery voltage over car life-time needs to be taken into account as well as Jump Start or Load Dump events, deviations over temperature and other generator defects. The Engine Control Unit (ECU) itself will also operate at a temperature according to the profile of **Figure 9**, affecting the starting T_J of the device (Multichannel Low-Side Switch in this case).

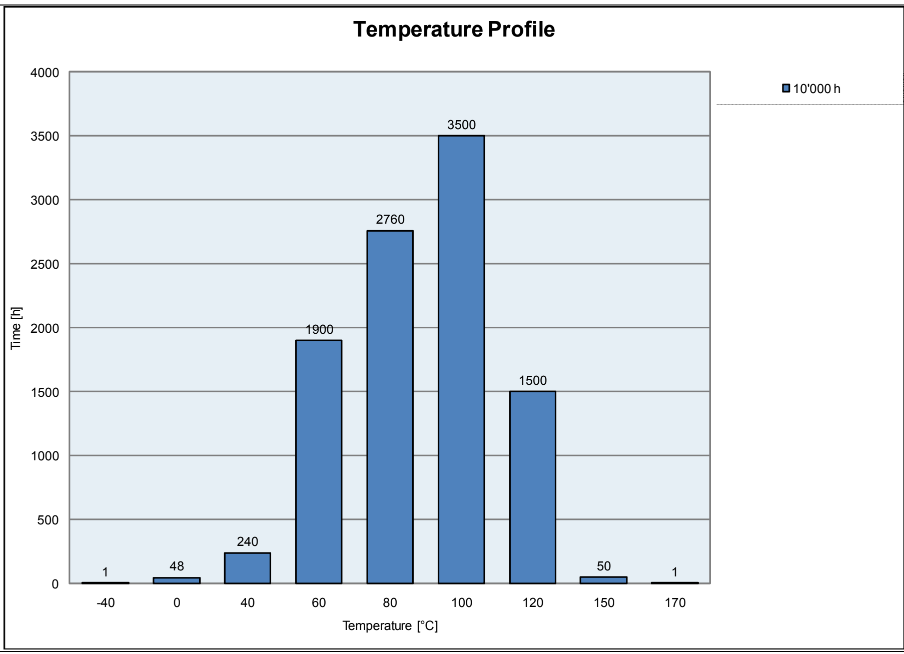

Figure 9 Temperature Profile example

In order to ease the evaluation of such wide range of operating conditions of the load and the switch device, we propose an approach where an average starting temperature T_J=110°C is assumed (justified by the temperature profile), and three different areas or energy levels (and according N_C) are defined, see **Figure 8** and **Table 2**. An operation of the device is contemplated in a combination of the defined areas as a Cumulative Scenario.

Table 2 Energy Levels

Energy Level	N_C[1)]	Operation	Description
Normal Operation	10^9	Repetitive	Nominal Average System Conditions (V_{BAT}, T_L, T_J)
Mid Energy	10^4	Repetitive	Exceptional Fault Condition, low occurrence rate
High Energy	10	Single Pulses[2)]	Exceptional Fault Condition, rare event

1) Number of cycles here defined are only an example for injectors and may vary depending on device and application case.

2) For high energy pulses a repetitive operation is not contemplated as the heat dissipation could eventually be not enough to keep the device at the specified starting T_J. In case of high energy event, it is strongly recommended an immediate switch OFF strategy.

1) For an injector: N_{cycles}= $T_{life\text{-}time}$ * (RPM*60) * $Injections\text{-}per\text{-}cycle$ = 10’000h * (3000*60) * 1/2 = $9*10^8$

4 Application Check Example

In this section an example of application check will be presented showing also the differences we could expect between calculated values and measured ones. Let's assume a clamping energy SOA of the switch device (it normally varies channel to channel for Multichannel Low-Side Switches) as shown in **Figure 10**, and consider the following load conditions (same load as in **Chapter 2.1**):

Injector: R_{25}=12.2Ω, L_0=13.2mH

- Normal Operation
  - V_{BAT}=16V (chosen higher then 14V to include also temperature deviations and generator defects)
  - T_L=115°C (average operating temperature according to Temperature profile)
- Mid Energy
  - V_{BAT}=28V (Jump Start event)
  - T_L=50°C (Considering a 25°C starting temperature plus short time for heating up)
- High Energy
  - V_{BAT}=40V (Load Dump event)
  - T_L=115°C (Considering the highest probability of Load Dump during normal operation)

According to mentioned conditions, measured and calculated values are summarized in **Table 3**.

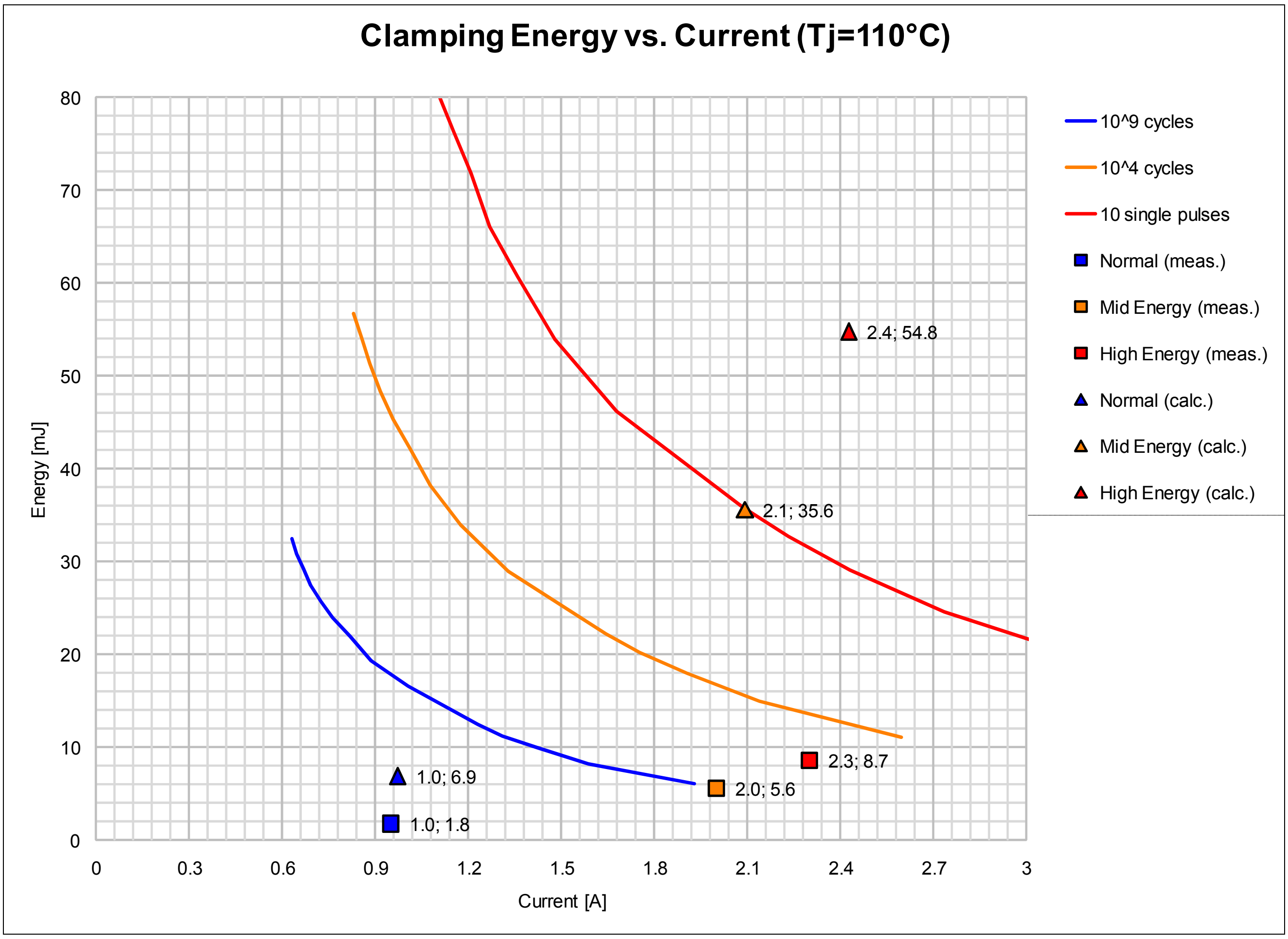

Figure 10 Application Check Example

Note: Similar curves as shown in ***Figure 10****. are provided in separate document for specific Multichannel Low-Side Switches.*

Table 3 Application Check - Operating Values

	Measured Values		Calculated Values 1) 2)	
	I_L [A]	E_{CL} [mJ]	I_L [A]	E_{CL} [mJ]
Normal Operation	0.95	1.8	1.0	6.9
Mid Energy	2	5.6	2.1	35.6
High Energy	2.3	8.7	2.4	54.8

1) Calculated values are obtained using **Equation (4)**, **Equation (10)** including temperature effect on R_L

2) Deviation from measured values is treated in **Chapter 2.2**

As we can see from **Figure 10**, each one of the three measured operating points (square markers) are below the relative curve meaning that, assuming a starting T_J=110°C:

- 10^9 cycles allowed for normal operation
- + 10^4 cycles allowed for mid energy condition
- + 10 single pulses allowed at high energy

As also shown on the plot, the calculated values (triangular markers) are still within the SOA for Normal Operation but completely unacceptable for the higher energy areas. For this reason it is always strongly recommended to base any assessment on load measurement data rather than on calculated ones.

5 Conclusion

In this document the driving of inductive loads through low-side switches has been considered and the related clamping event occurring during switch-off has been described. It was explained how to measure the clamping energy and a formula for its evaluation has been proposed. The comparison of measured values with calculated ones was shown to point out the deviations due to non-idealities of the load. It was introduced a practical way, proposed by Infineon, of describing the energy capabilities of Multichannel Low-Side Switches in a realistic application scenario. At the end has been shown an example of application check where current end energy values of a load - measured and calculated ones - were projected into the Safe Operating Areas of a switch according to the load operating conditions.

This application note, together with the addenda containing the clamping energy SOAs of specific devices, represents a guide-line for safe and efficient design using Infineon Multichannel Low-Side Switches.

6 Additional Information

- For further information you may contact **http://www.infineon.com/**

7 Revision History

Revision	Date	Changes
1.0	2011-04-19	Release of the Document

Edition 2011-04-19

Published by
Infineon Technologies AG
81726 Munich, Germany