PROFET™ +2 12V

Repetitive energy during demagnetization

About this document

Scope and purpose

This Application Note intends to provide information how the dissipated energy during the clamping time is calculated. It also explains the threshold under which the choice of the load inductance is not causing problems in the application.

Intended audience

This document is targeted for customers who are switching inductive loads and want to know more about the maximum energy that could be dissipated during the clamping time.

Table of contents

1 Introduction

This Application Note will show you what has to be considered when switching an inductive load. An inductor is a load which stores magnetic energy and is typically described by an inductance and a resistance connected in series. Motors and relays are the most common ones.

The focus of this document is to show how to calculate the energy dissipated by the device during the switch OFF time. During this period of time the clamping circuit protects the device by clamping the voltage over the device to a safe value, leading to the dissipation of the magnetic energy during the clamping time. In most of the applications, PROFET™ +2 12V does not need any external clamping circuit.

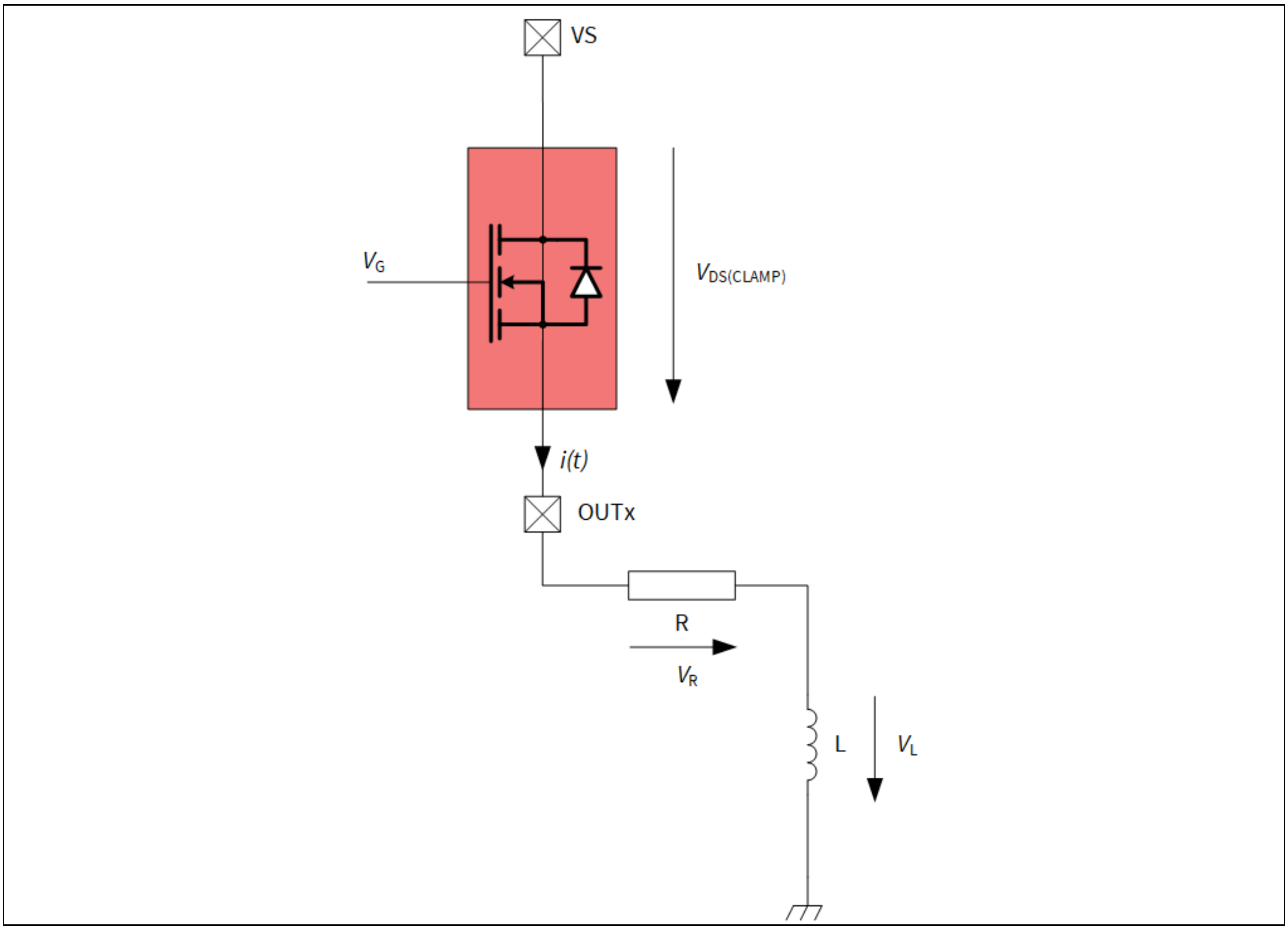

Figure 1 A PROFET™ +2 (in the red box) connected to an inductive load during clamping

2 Inductive load: motivations

An inductive load is usually described by an inductance L and a resistance R. At the switch ON, the inductive load causes a slow current ramp up, based on the time constant τ = L/R. At the switch OFF due to the inductance, the current application tempts to continue to flow in the same direction which causes the load voltage to invert. In the figure below a measurement example shows the general voltage and current characteristics of an inductive load.

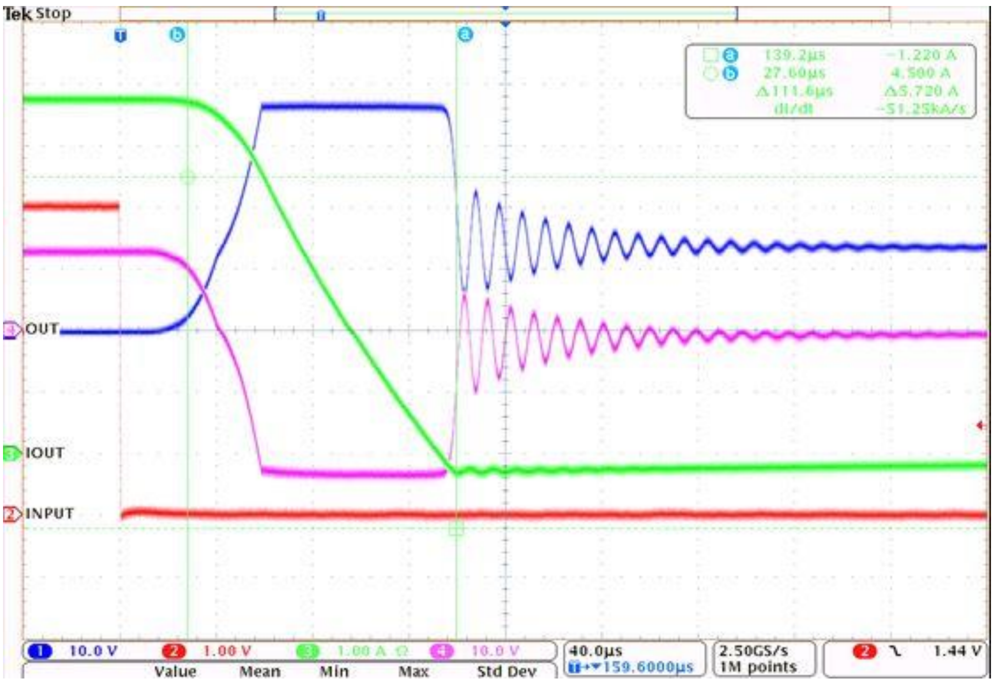

Figure 2 Switching OFF an inductive load with BTS7008-2EPA

Depending on the requirements (one direction, both directions, controlled or uncontrolled) there are different possible architectures. Some inductive loads always run in the same direction, such as wipers and water pumps, where only a single channel PROFET is required. If the load should be driven in both directions, then the H-bridge, where two single channel PROFETs are used or one double channel instead, is the right driver architecture.

3 Switch ON and switch OFF phases

When the high side switch turns on, the current through the inductor increases with a constant time given by the values of the inductance and the resistance of the load (τ = L/R)

$$i(t) = \frac{V_S}{R} \cdot (1 - e^{-\frac{t}{\tau}}) \tag{1}$$

During the switch OFF phase the load inductance generates an overvoltage which brings the output to a negative value, therefore bringing the PROFET into clamping. The DC load current is reached approximately after 3τ. The energy stored in the inductive element is calculated as follows:

$$E = \frac{1}{2} \cdot L \cdot (\frac{V_S}{R})^2 \tag{2}$$

During the switch OFF phase, the polarity of the voltage across the load is reversed. The current through the inductor will start to decrease exponentially and the PROFET goes into clamping. The calculation of the energy during the clamping is described in the following chapter.

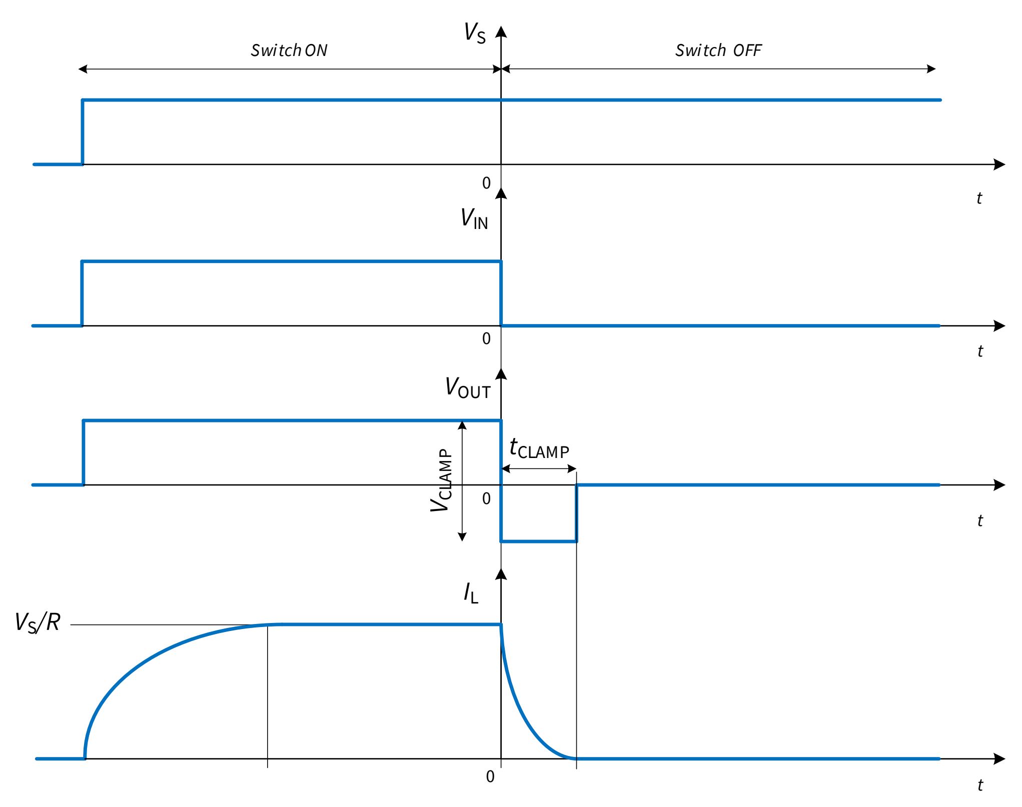

Figure 3 Waveforms of the signals of interest

3.1 Energy calculation

In order to calculate the energy during the clamping time (t_{CLAMP}), it is needed to derive the expression of the current. This is done by starting with the basic equations of the inductance and the resistance:

$$v_R(t) = R \cdot i(t) \tag{3}$$

$$v_L(t) = L \cdot \left(\frac{di(t)}{dt}\right) \tag{4}$$

Considering now $V_{\mathrm{DS(CLAMP)}}$ independent of time, it is possible to write the following relationship:

$$V_S = V_{DS(CLAMP)} + v_R(t) + v_L(t) = V_{DS(CLAMP)} + R \cdot i(t) + L \cdot \frac{di(t)}{dt} \tag{5}$$

Solving for *i(t)* it follows that:

$$i(t) = \frac{V_S}{R} \cdot e^{-\frac{t}{\tau}} + \frac{V_S - V_{DS(CLAMP)}}{R} \cdot \left(1 - e^{-\frac{t}{\tau}}\right) \tag{6}$$

In the switch OFF phase, the DMOS goes into clamping and it could be modelled by a voltage generator with opposite polarity with respect to the battery with amplitude $V_{\mathrm{DS(CLAMP)}}$. If the circuit stayed in this clamping state, the current would reach the value $I = \frac{V_S - V_{DS(CLAMP)}}{R}$. This model is valid as long as there is current flowing in the branch.
After a certain time, there will be no current flowing (DMOS opened) because the energy in the inductance has been completely dissipated.

Equation (6) shows that the current decays exponentially and is valid until *i(t)* ≥ 0.

By solving $i(t_{\mathrm{CLAMP}}) = 0$ it is possible to find when the energy through the inductance vanishes:

$$t_{CLAMP} = \tau \cdot ln\left(\frac{V_{DS(CLAMP)}}{V_{DS(CLAMP)} - V_S}\right) \tag{7}$$

Switch ON and switch OFF phases

The clamping or demagnetization time is proportional to τ and shows that the higher the battery voltage, the slower the demagnetization is.
The energy dissipated by the MOSFET during t_{CLAMP} can be calculated as follows:

$$\mathrm{E} = \int_0^{t_{CLAMP}} V_{DS(CLAMP)}\, i(t)dt \tag{8}$$

By replacing *i(t)* with ***Equation (6)*** the following expression can be written:

$$E = V_{DS(CLAMP)} \cdot t_{CLAMP}\left(I_0 - \frac{V_{DS(CLAMP)}}{R}\right) - \tau\frac{V_{DS(CLAMP)}^2}{R} \cdot \left(e^{\frac{-t_{CLAMP}}{\tau}} - 1\right) \tag{9}$$

By noting that

$$e^{\frac{-t_{CLAMP}}{\tau}} = \frac{V_{DS(CLAMP)} - V_S}{V_{DS(CLAMP)}} \tag{10}$$

$$V_S = R \cdot I_L \tag{11}$$

it is possible to come to the same expression of the Datasheet for the energy dissipated by the DMOS:

$$E = V_{DS(CLAMP)}\left(\frac{V_S - V_{DS(CLAMP)}}{R} ln\left(1 - \frac{R \cdot I_L}{V_S - V_{DS(CLAMP)}}\right) + I_L\right) \cdot L/R \tag{12}$$

But what is the difference between single pulse (E_{AS}) and repetitive energy (E_{AR})?

E_{AS} refers to an isolated clamping event that can potentially be destructive by inducing high currents. In the case of E_{AR}, the energy per event is lower than the one considered for a single event. As the name implies, its occurrence is characterized by a repetition rate, which is typically the same as the switching frequency of the application circuit. In this case, due to the low energy of each event, the silicon temperature rises slowly when compared to the single pulse event.

4 Selection criteria based on I-L plots

The energy capability of the device during the demagnetization phase is an important factor to consider during the design of the application. Let's take BTS7008-2EPA as a reference for this introduction. The magenta point in ***Figure 4*** on the left represents the energy value specified in the Datasheet (see parameter E_{AR} in chapter 4.2.1). The datasheet value was obtained through characterization of several devices from different production lots. On the other hand, the curve is the outcome of simulations performed by using an electro-thermal model of the device. It would not be practical to perform extensive characterization of all devices across all energy levels and current levels therefore simulations with more conservative criteria were used.
For some products it may happen that the Datasheet point stays exactly on the curve. In this case simulations and measurements give the same results, meaning that the used characteritazion conditions were the same used for simulations.

In the low current region the behavior of energy vs load current was modeled through the following equation:

$$E = \frac{1}{2} V_{DS(CLAMP)} I_L t_{CLAMP} \tag{13}$$

where the term $\frac{1}{2} V_{DS(CLAMP)} t_{CLAMP}$ is taken as constant. The energy decreases linearly with the load current.

The behavior of the inductance vs the load current was modeled using the following relationships, starting from the E_{AR} expression of the datasheet:

$$E = V_{DS(CLAMP)} \left(\frac{V_S - V_{DS(CLAMP)}}{R} ln \left(1 - \frac{R \cdot I_L}{V_S - V_{DS(CLAMP)}} \right) + I_L \right) \cdot L/R \tag{14}$$

with $\frac{1}{R} = \frac{I_0}{V_S}$, this becomes

$$E = L{I_L}^2 \frac{V_{DS(CLAMP)}}{V_S} \left[1 + \frac{V_{DS(CLAMP)} - V_S}{V_S} ln \left(1 - \frac{V_S}{V_{DS(CLAMP}} \right) \right] \tag{15}$$

This energy equals the area of a 90°-triangle with height $V_{CLAMP} I_L$ and length t_{CLAMP}, for example

$$\frac{1}{2} V_{DS(CLAMP)} I_L t_{CLAMP} = E = L{I_L}^2 \frac{V_{DS(CLAMP)}}{V_S} \left[1 + \frac{V_{DS(CLAMP)} - V_S}{V_S} ln \left(1 - \frac{V_S}{V_{DS(CLAMP)}} \right) \right] \tag{16}$$

Selection criteria based on I-L plots

from which one could deduce the inductance as

$$L = t_{CLAMP}\,\frac{V_S}{2I_L}\left[1 + \frac{V_{DS(CLAMP)} - V_S}{V_S}\ln\left(1 - \frac{V_S}{V_{DS(CLAMP)}}\right)\right]^{-1} \tag{17}$$

making use of

$$\ln(1+x) = x - \frac{x^2}{2} + \frac{x^3}{3} - \cdots \tag{18}$$

and developing until 2nd order, the initial energy expression results in

$$E = \frac{1}{2}\,L{I_L}^2\,\frac{V_{DS(CLAMP)}}{V_{DS(CLAMP)} - V_S} \tag{19}$$

under the condition that $RI_L \ll (V_{DS(CLAMP)} - V_S)$.

By this simplification, the energy can be rewritten as

$$\frac{1}{2}V_{DS(CLAMP)}I_L t_{CLAMP} = E = \frac{1}{2}\,L{I_L}^2\,\frac{V_{DS(CLAMP)}}{V_{DS(CLAMP)} - V_S} \tag{20}$$

and hence

$$L = t_{CLAMP}\,\frac{V_{DS(CLAMP)} - V_S}{I_L} \tag{21}$$

Although the formula suggests that an infinitely big inductive load can be demagnetized by using an infinitely small current, it is necessary to consider that this operation area implies currents much smaller than $I_{L(NOM)}$. For simplicity it is considered that the switchable inductance reaches its maximum when the current is decreasing, and then remains constant even when the current decreases furthermore.

In ***Figure 4*** you can see how to read the two curves. Infineon recommends the usage of the product in application conditions so that the resulting load current, energy and inductance are within the green area as indicated. Different products have different curves therefore it is possible to select the curve for each device used in the application. The figures are valid for a total clamping time up to 360 seconds over device lifetime and a number of cycles up to 1M.

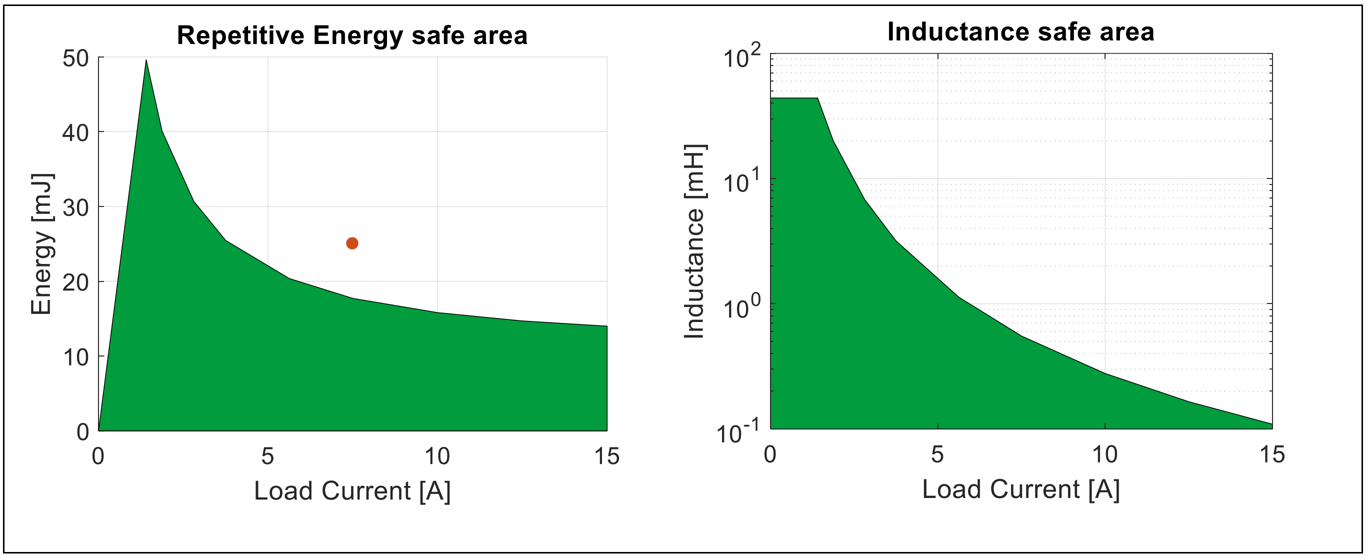

Figure 4 **BTS7008-2EPA inductance and repetitive energy safe areas as a function of the load current for $T_{J(0)}$ = 85°C**

The following example, using the E_{AR} value of BTS7008-2EPA as specified in the Datasheet (see P_4.2.1.2, 25 mJ with $I_L = I_{L(NOM)}$ = 7.5 A, $T_{J(0)}$ = 85°C for 1M cycles), shows how the total clamping time over lifetime can be calculated:

$$t_{CLAMP(TOT)} = \frac{2\ E_{AR}}{V_{DS(CLAMP)} I_L} \cdot 1M\ cycles = 175{,}44\ s < 360\ s \tag{22}$$

All E_{AR} values specified in SMART7 PROFET™ +2 Datasheets are valid up to 1M cycles and have a total clamping time over lifetime shorter than 360 s.

Looking at the curves in ***Chapter 5***, the magenta point represents the E_{AR} parameter in the Datasheet at $T_{J(0)}$ = 85°C, except for Grade0 devices (-EPZ), where the point at $T_{J(0)}$ = 125°C is shown. The curves are drawn as well at $T_{J(0)}$ = 125°C for Grade0 devices.

5 I-L and E_{AR} plots of the PROFET™ +2 12V portfolio

5.1 BTS70012-1ESP

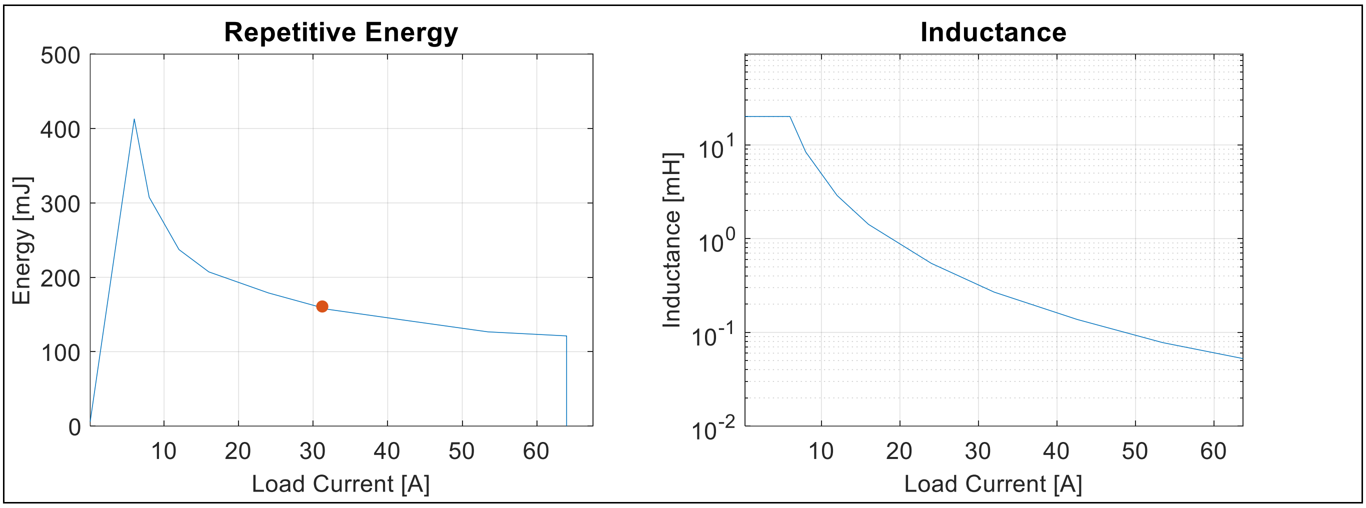

Figure 5 BTS70012-1ESP repetitive energy and inductance as a function of the load current

5.2 BTS70015-1ESP

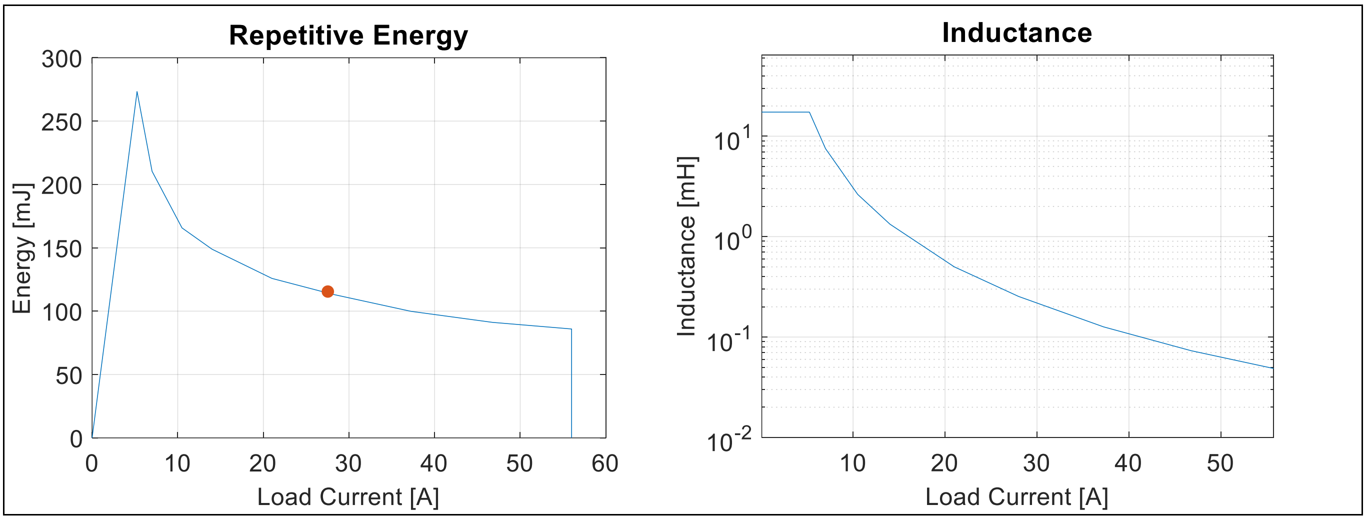

Figure 6 BTS70015-1ESP repetitive energy and inductance as a function of the load current

5.3 BTS70020-1ESP

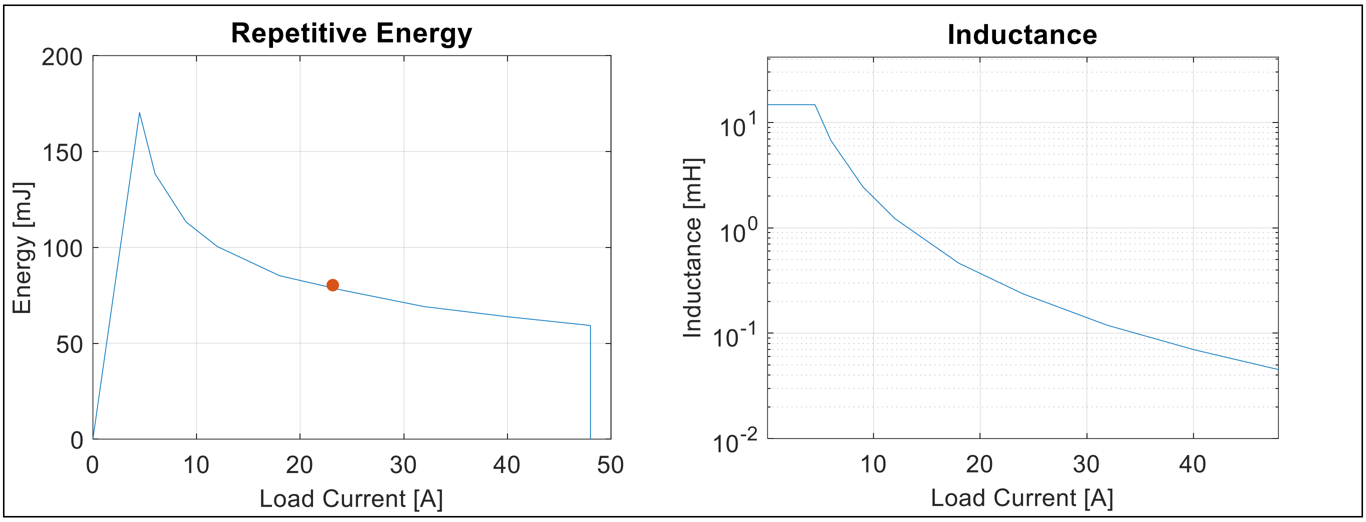

Figure 7 BTS70020-1ESP repetitive energy and inductance as a function of the load current

5.4 BTS7002-1EPP

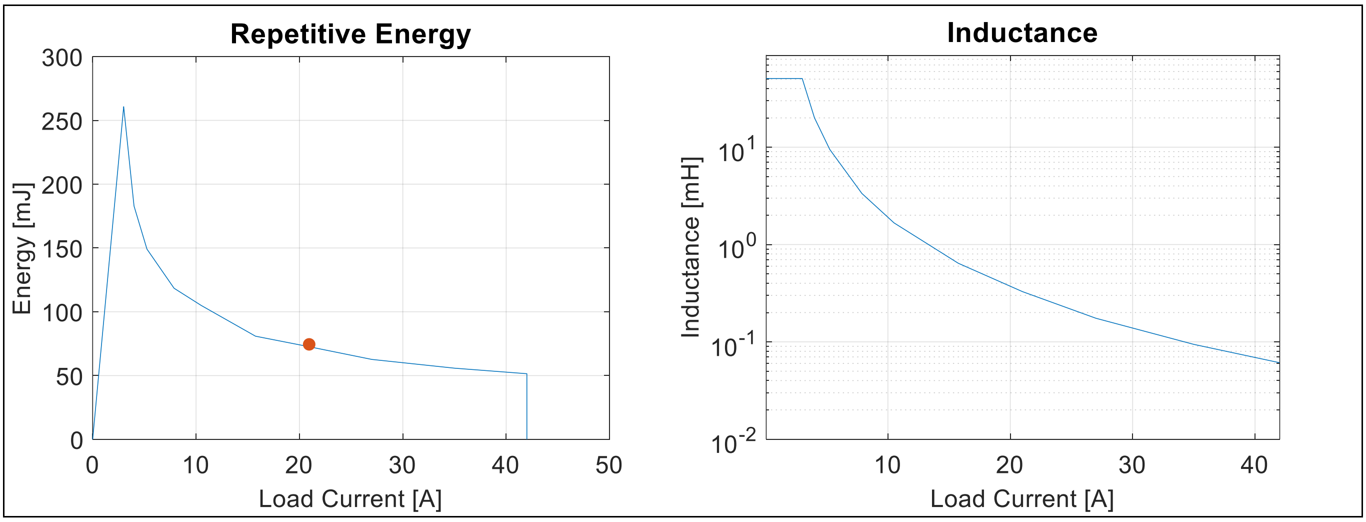

Figure 8 BTS7002-1EPP repetitive energy and inductance as a function of the load current

5.5 BTS7004-1EPP

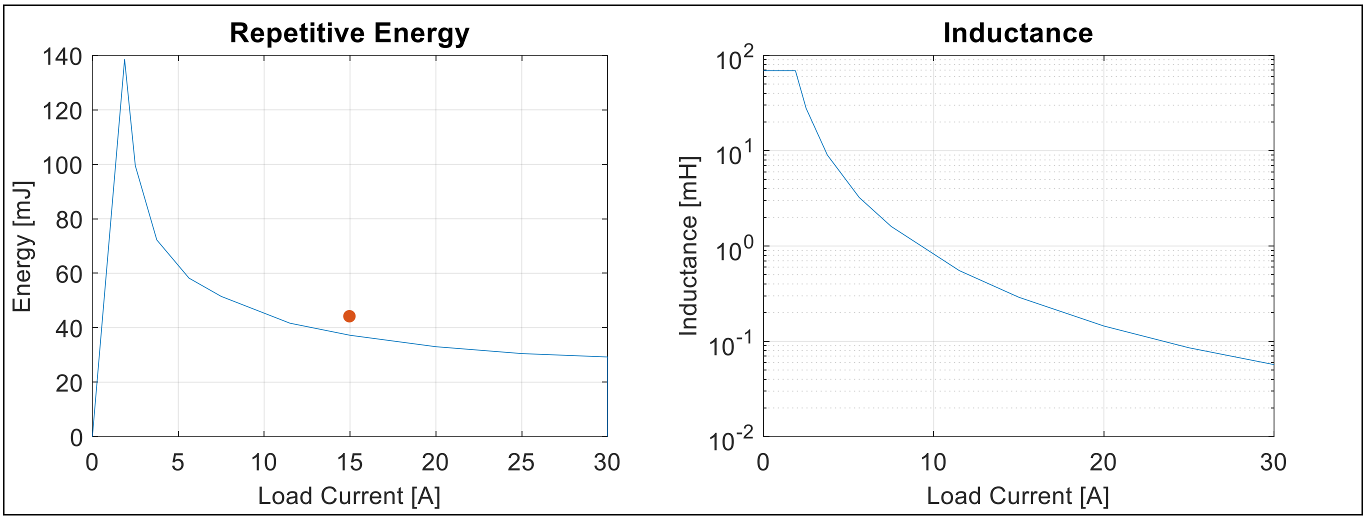

Figure 9 BTS7004-1EPP repetitive energy and inductance as a function of the load current

5.6 BTS7004-1EPZ

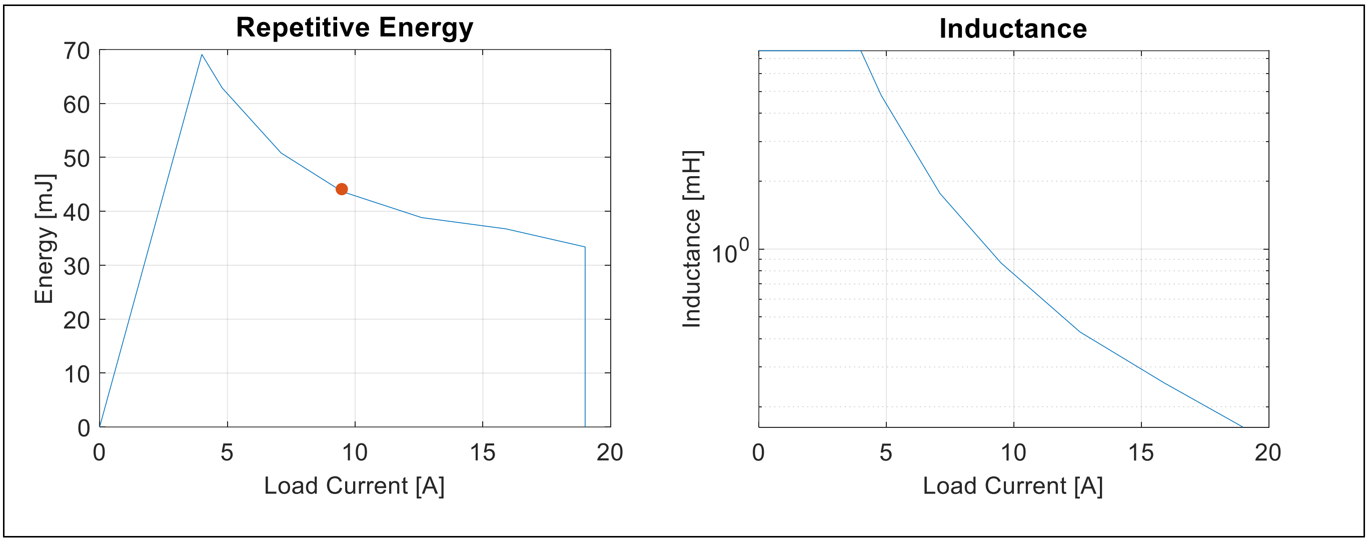

Figure 10 BTS7004-1EPZ repetitive energy and inductance as a function of the load current

5.7 BTS7006-1EPP

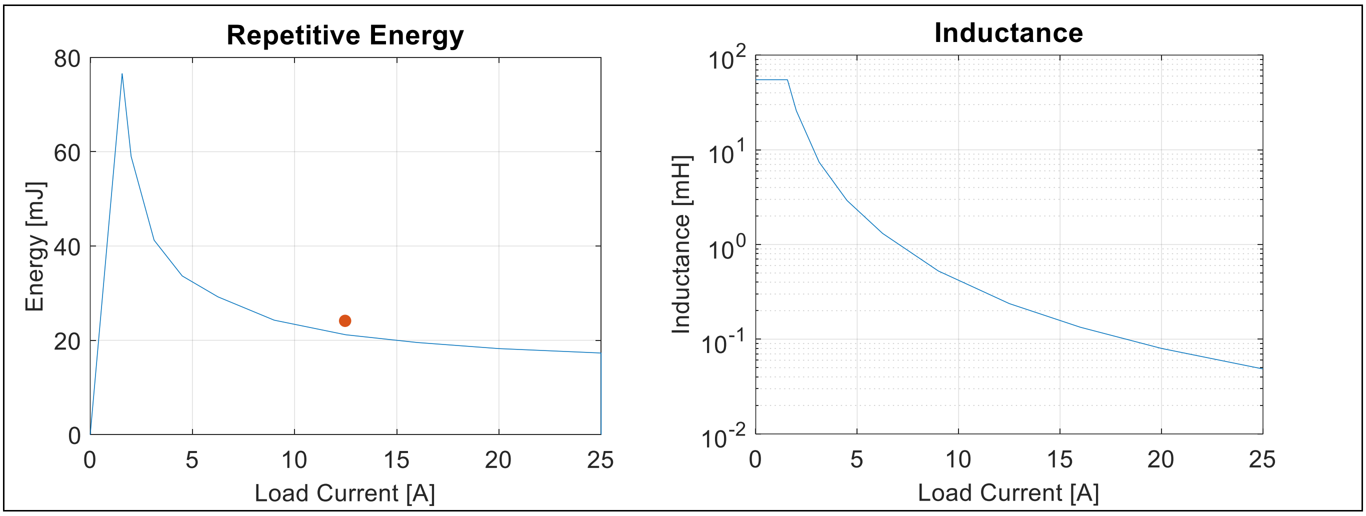

Figure 11 BTS7006-1EPP repetitive energy and inductance as a function of the load current

5.8 BTS7006-1EPZ

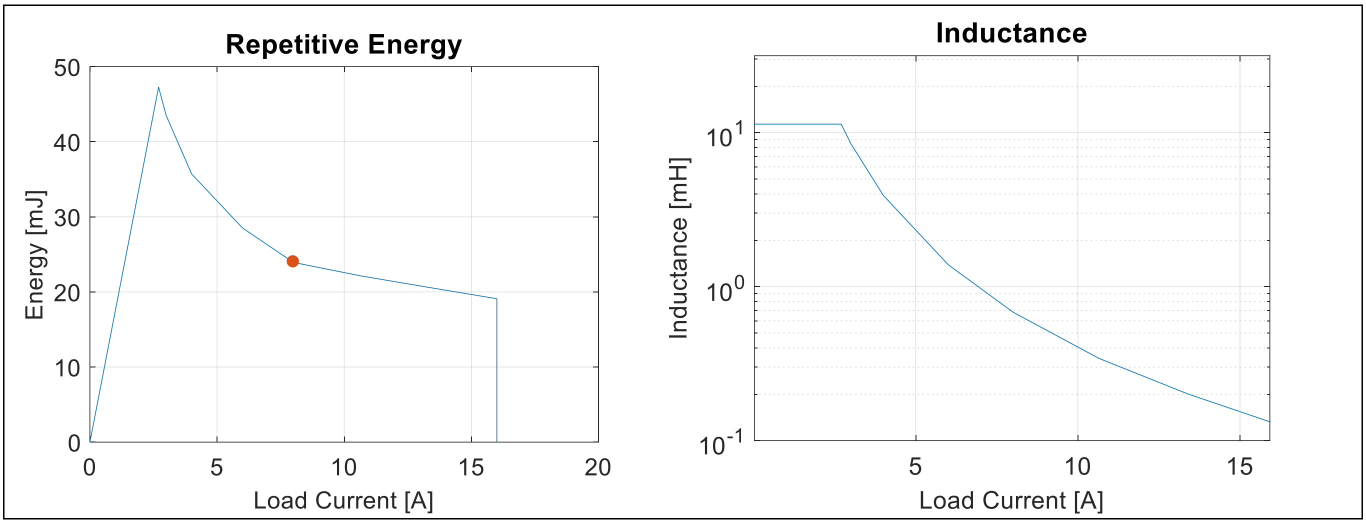

Figure 12 BTS7006-1EPZ repetitive energy and inductance as a function of the load current

5.9 BTS7008-1EPP

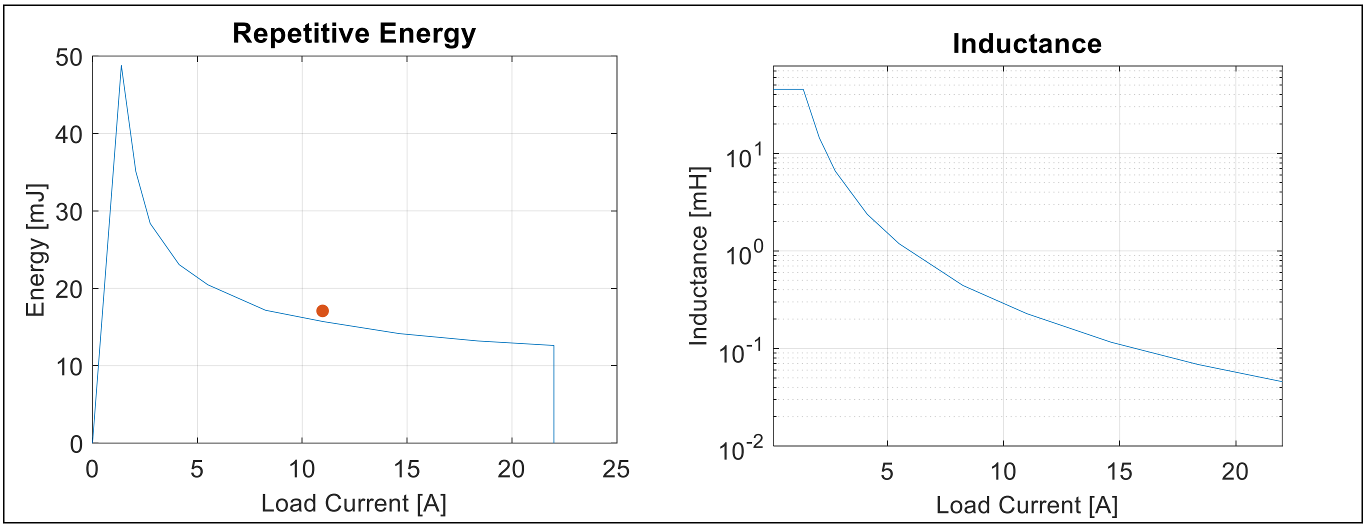

Figure 13 BTS7008-1EPP repetitive energy and inductance as a function of the load current

5.10 BTS7008-1EPZ

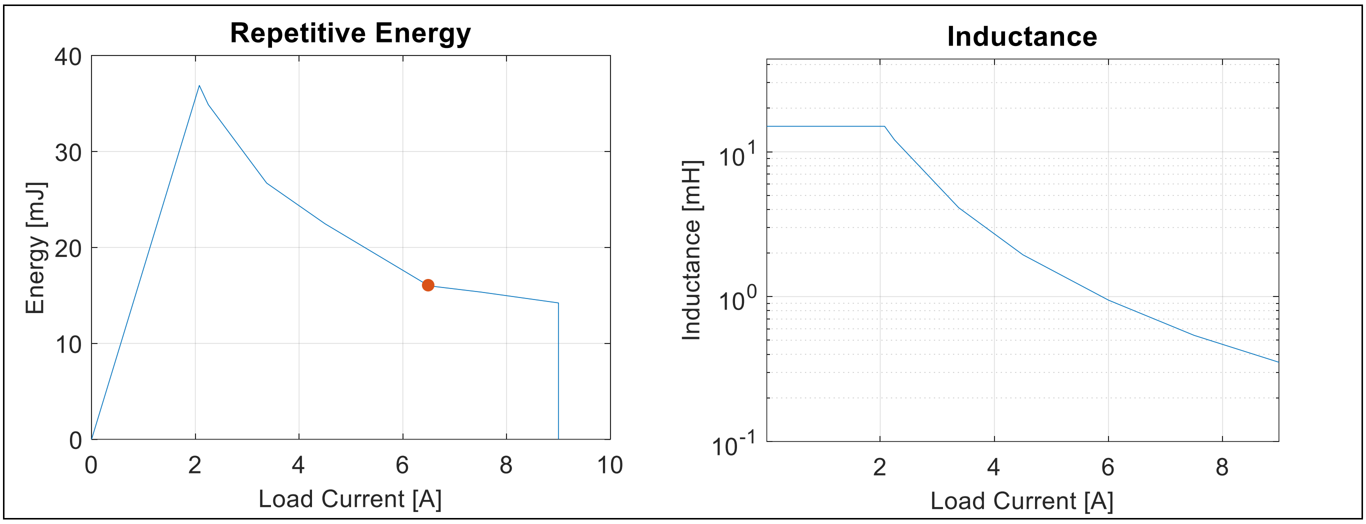

Figure 14 BTS7008-1EPZ repetitive energy and inductance as a function of the load current

5.11 BTS7008-1EPA

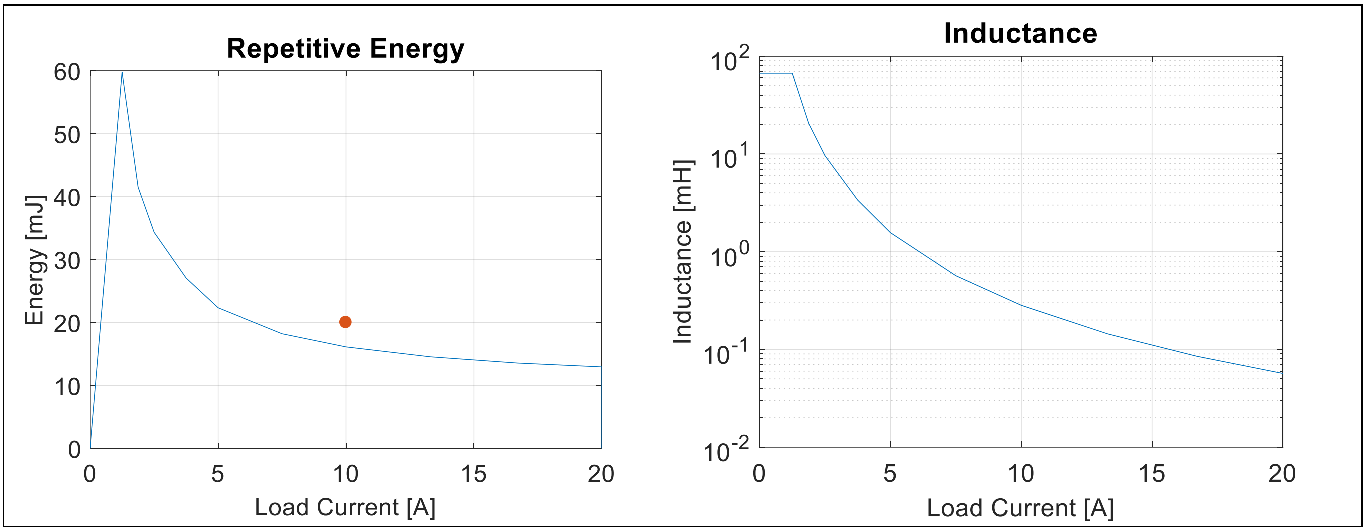

Figure 15 BTS7008-1EPA repetitive energy and inductance as a function of the load current

5.12 BTS7010-1EPA

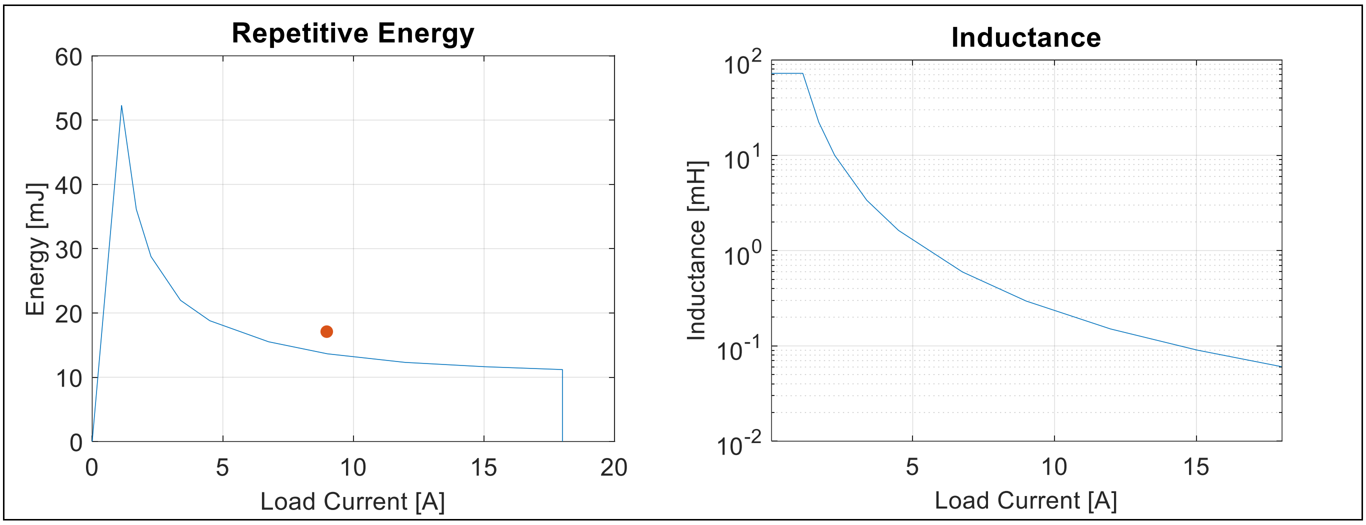

Figure 16 BTS7010-1EPA repetitive energy and inductance as a function of the load current

5.13 BTS7010-2EPA

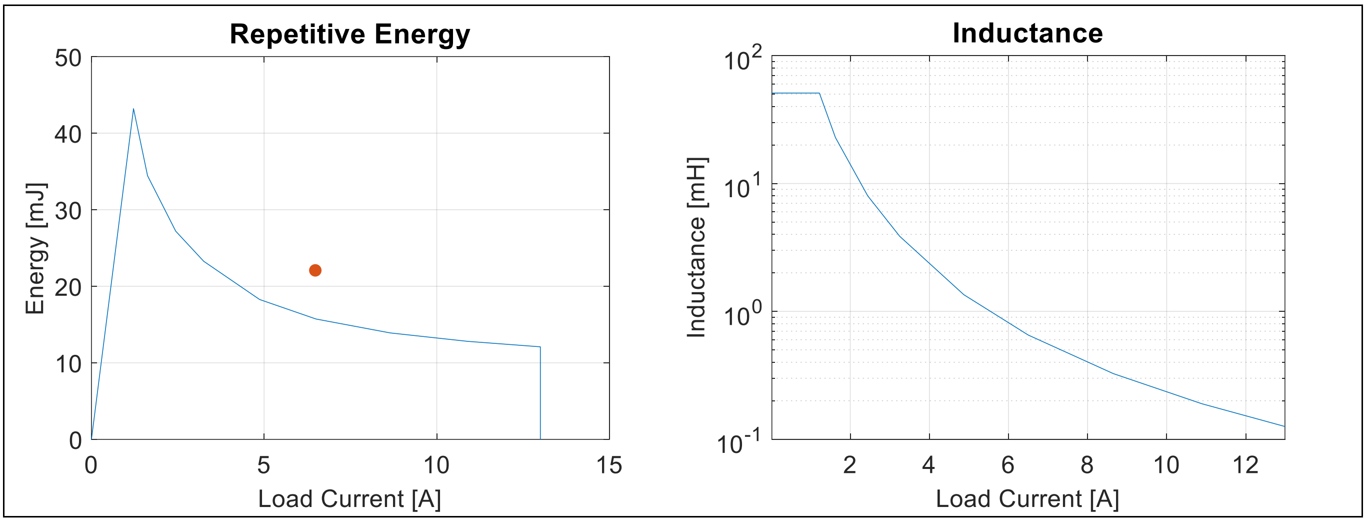

Figure 17 BTS7010-2EPA repetitive energy and inductance as a function of the load current

5.14 BTS7012-1EPA

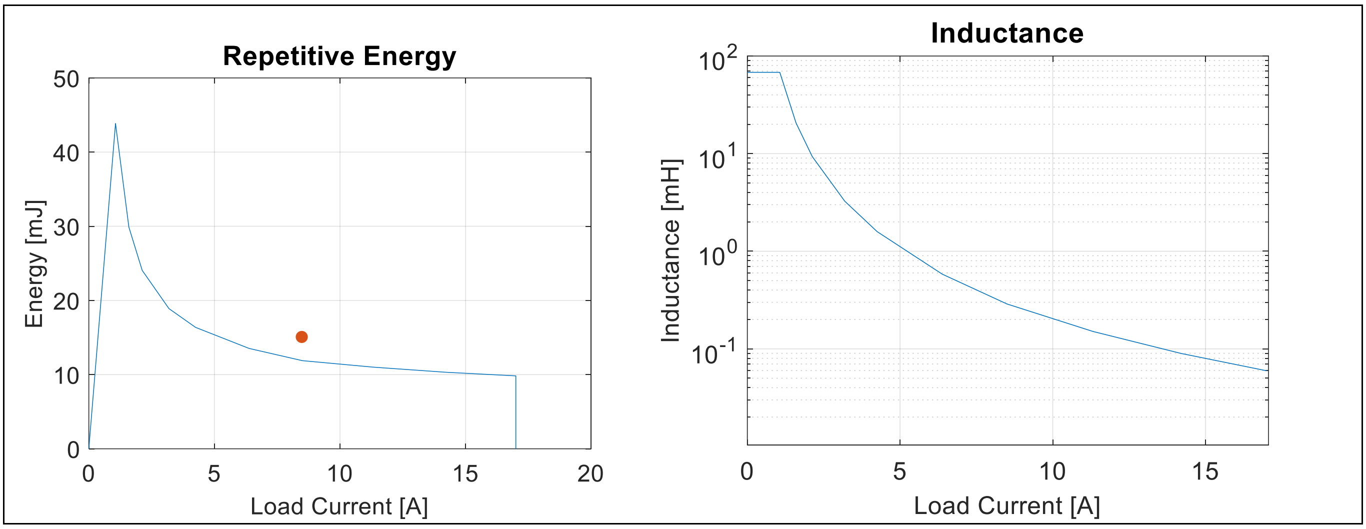

Figure 18 BTS7012-1EPA repetitive energy and inductance as a function of the load current

5.15 BTS7012-2EPA

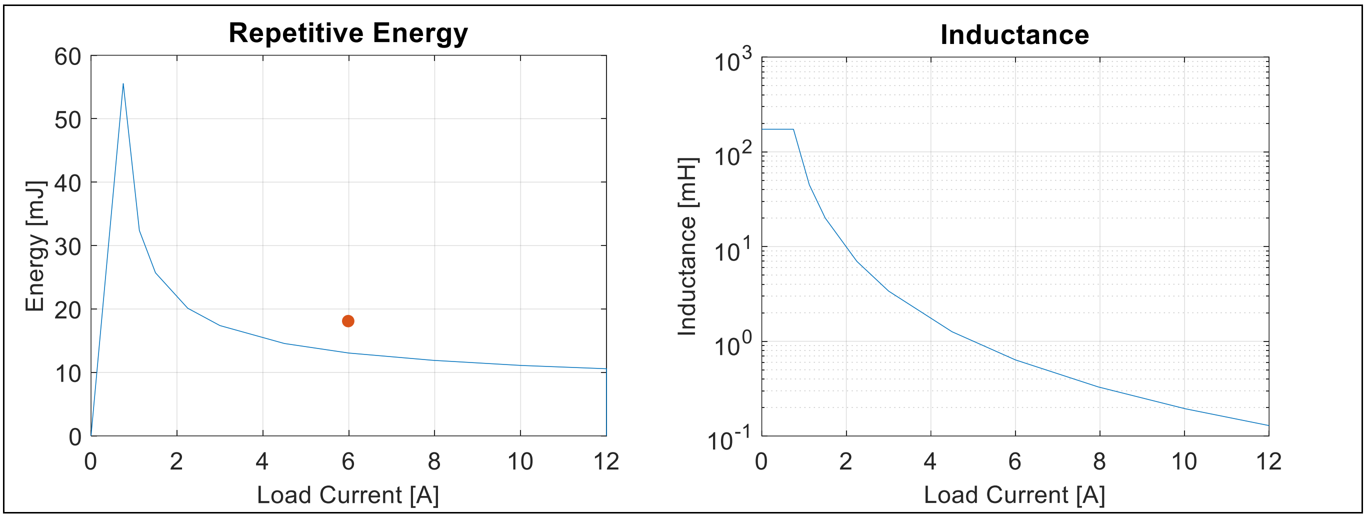

Figure 19 BTS7012-2EPA repetitive energy and inductance as a function of the load current

5.16 BTS7020-2EPA

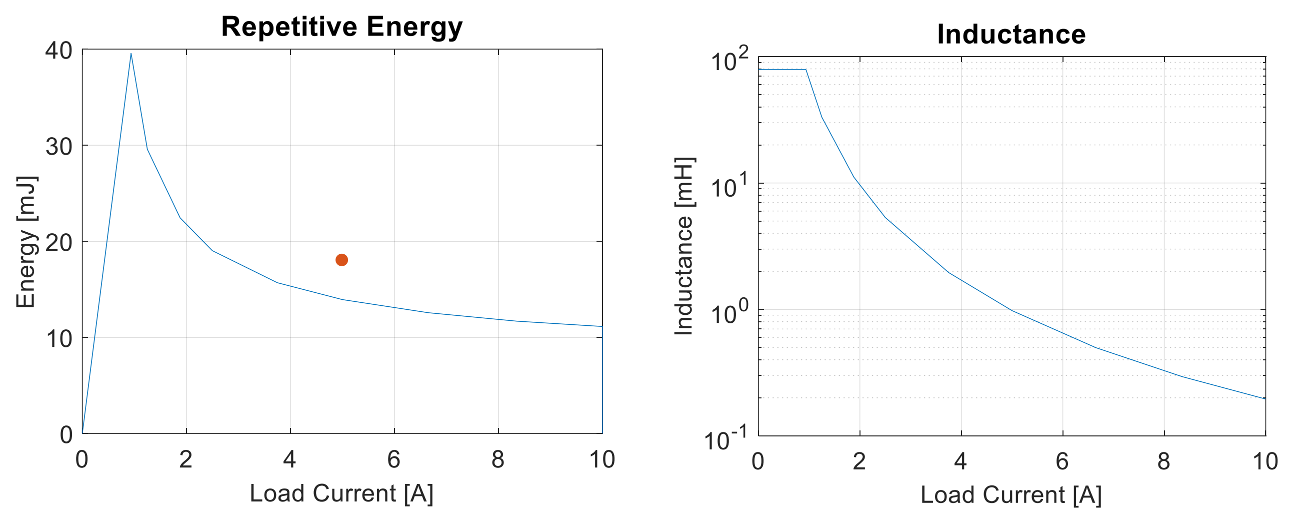

Figure 20 BTS7020-2EPA repetitive energy and inductance as a function of the load current

5.17 BTS7030-2EPA

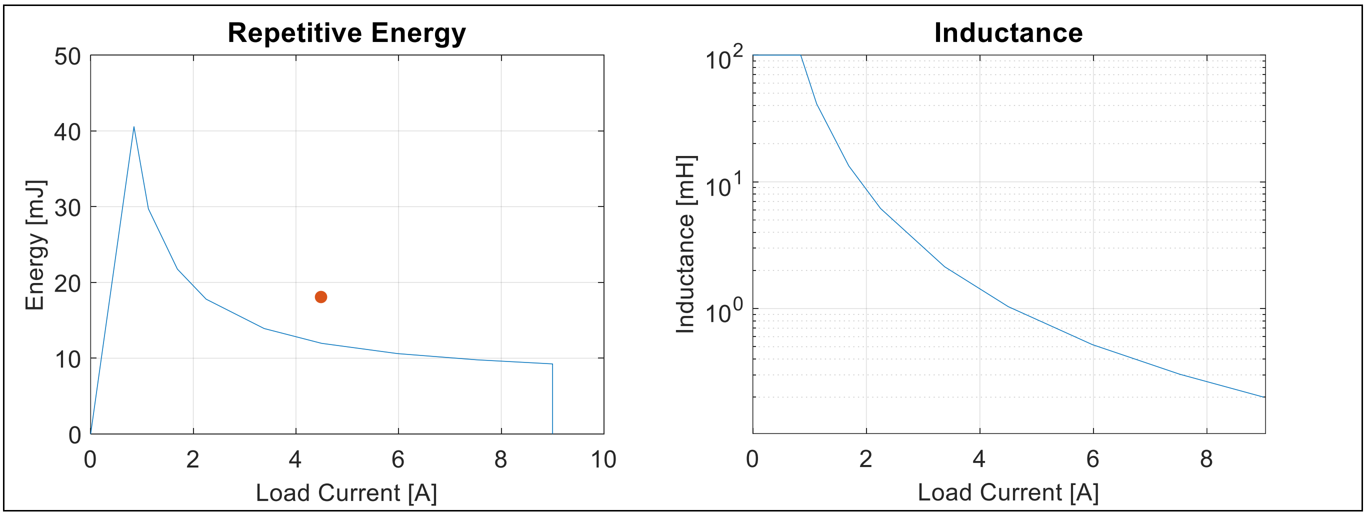

Figure 21 BTS7030-2EPA repetitive energy and inductance as a function of the load current

5.18 BTS7040-1EPA

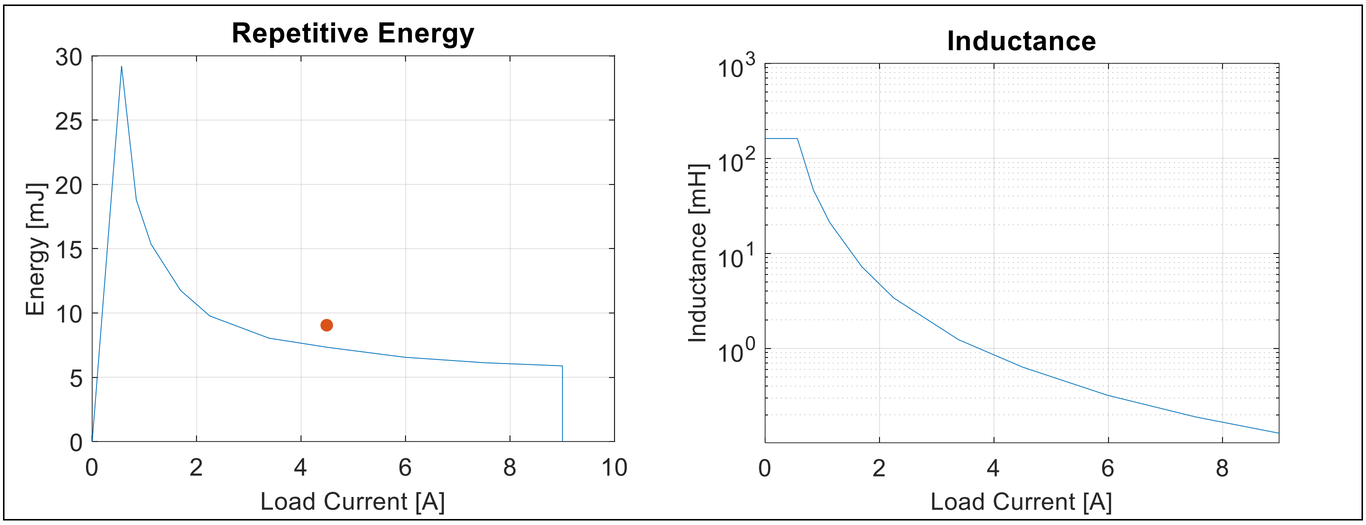

Figure 22 BTS7040-1EPA repetitive energy and inductance as a function of the load current

5.19 BTS7040-1EPZ

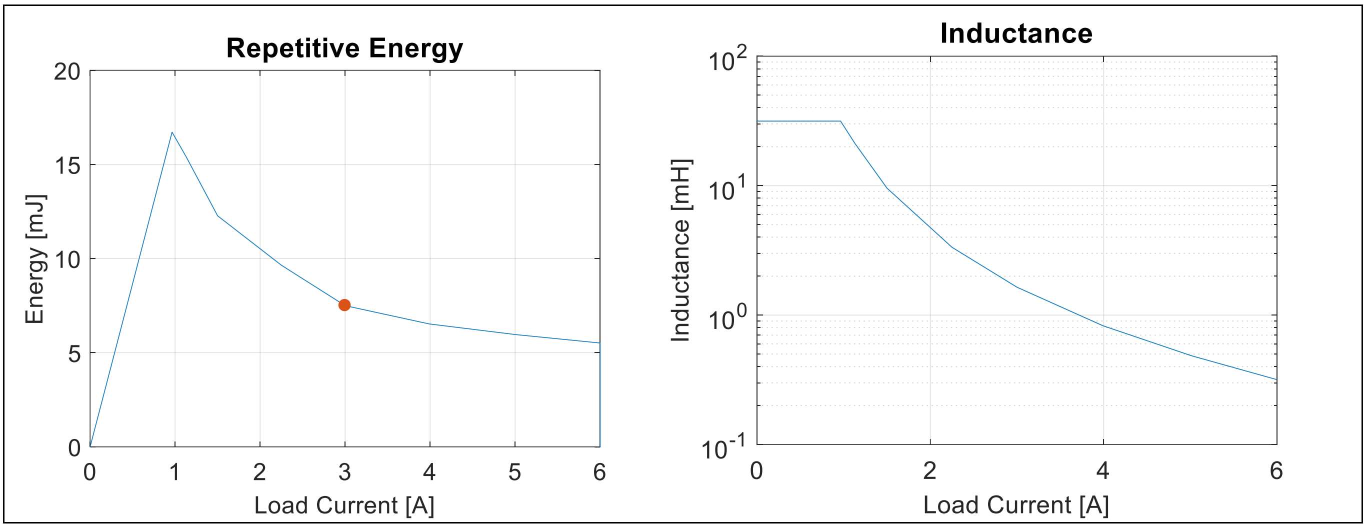

Figure 23 BTS7040-1EPZ repetitive energy and inductance as a function of the load current

5.20 BTS7040-2EPA

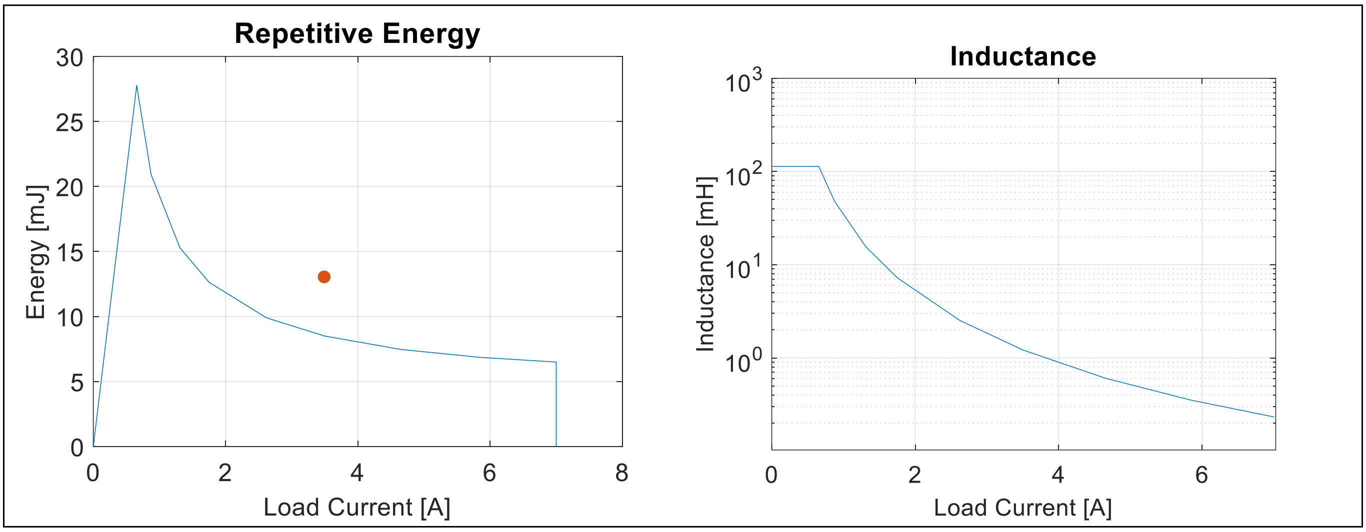

Figure 24 BTS7040-2EPA repetitive energy and inductance as a function of the load current

5.21 BTS7080-2EPA

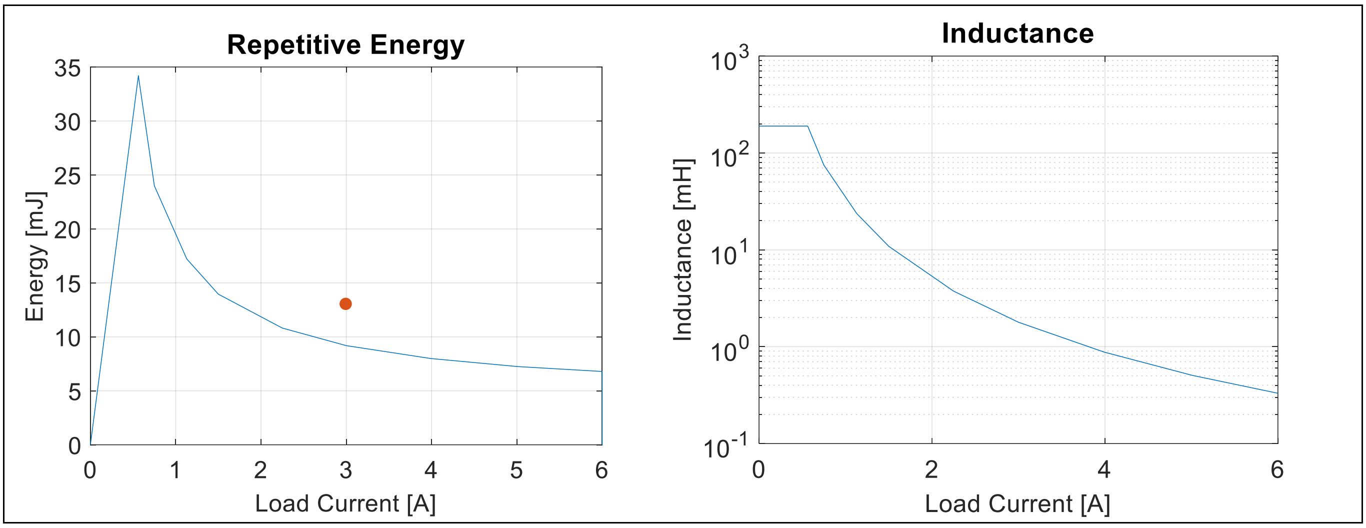

Figure 25 BTS7080-2EPA repetitive energy and inductance as a function of the load current

5.22 BTS7080-2EPZ

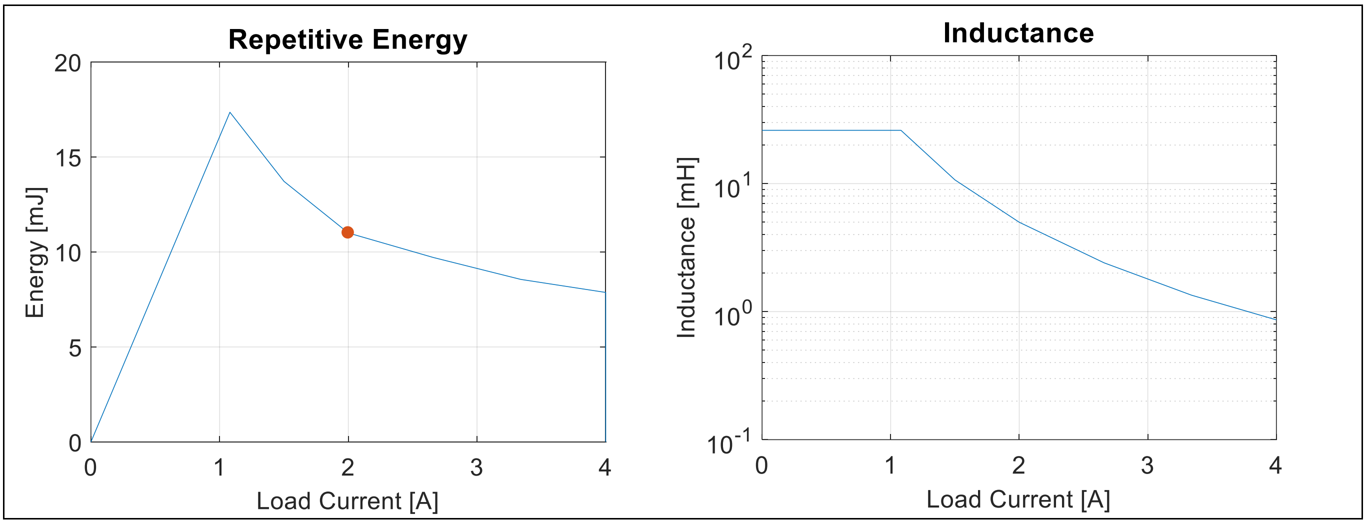

Figure 26 BTS7080-2EPZ repetitive energy and inductance as a function of the load current

5.23 BTS7120-2EPA

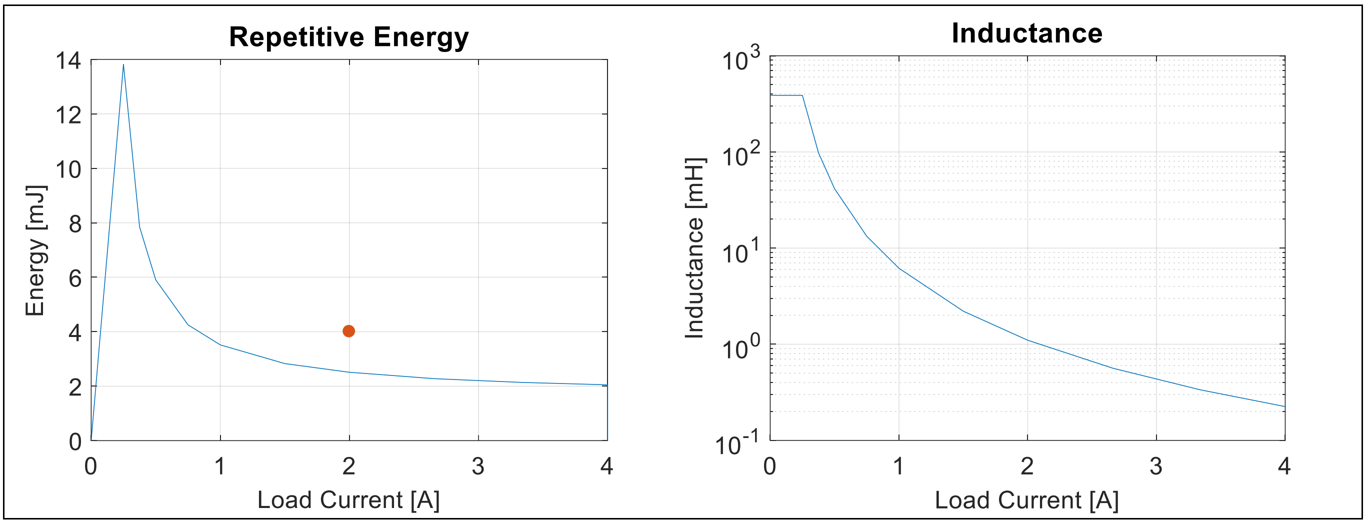

Figure 27 BTS7120-2EPA repetitive energy and inductance as a function of the load current

5.24 BTS7200-2EPA

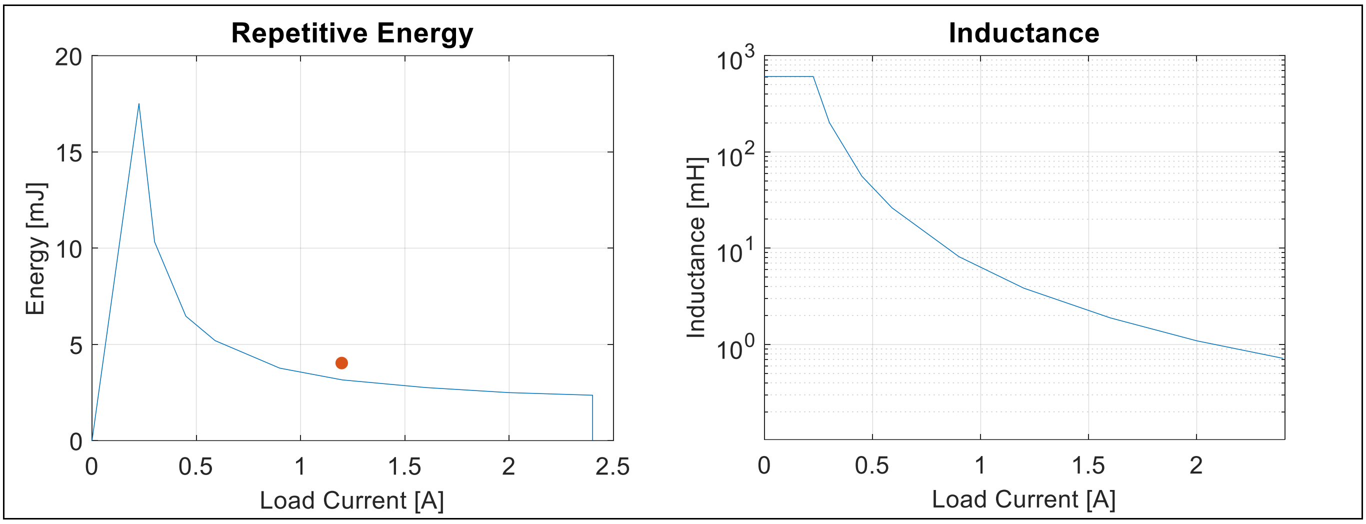

Figure 28 BTS7200-2EPA repetitive energy and inductance as a function of the load current

5.25 BTS7200-2EPC

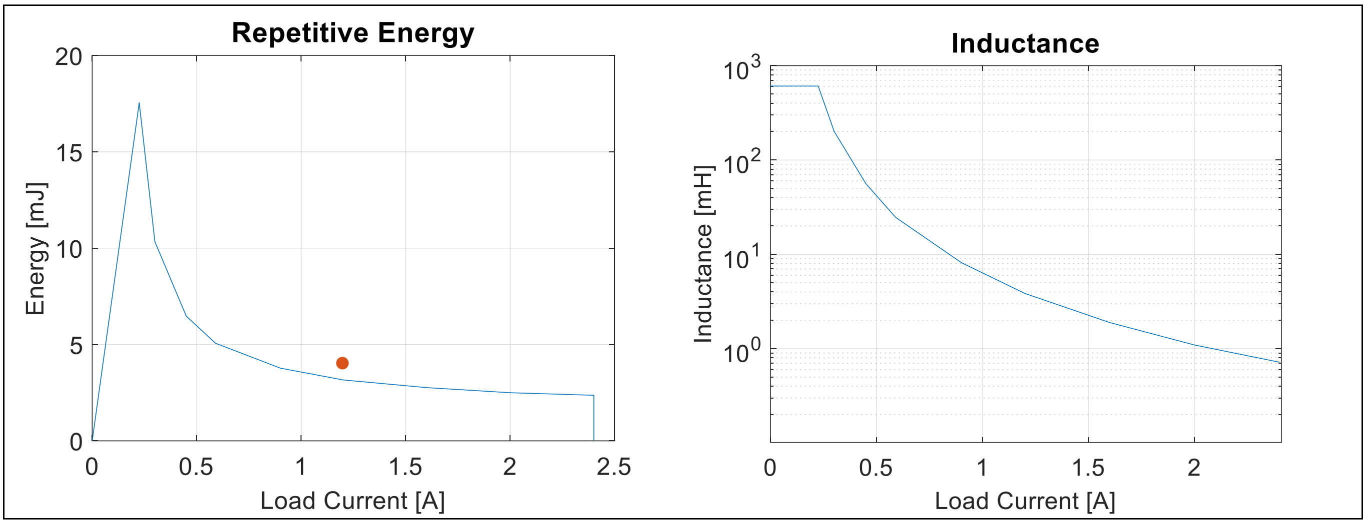

Figure 29 BTS7200-2EPC repetitive energy and inductance as a function of the load current

5.26 BTS7200-4EPA

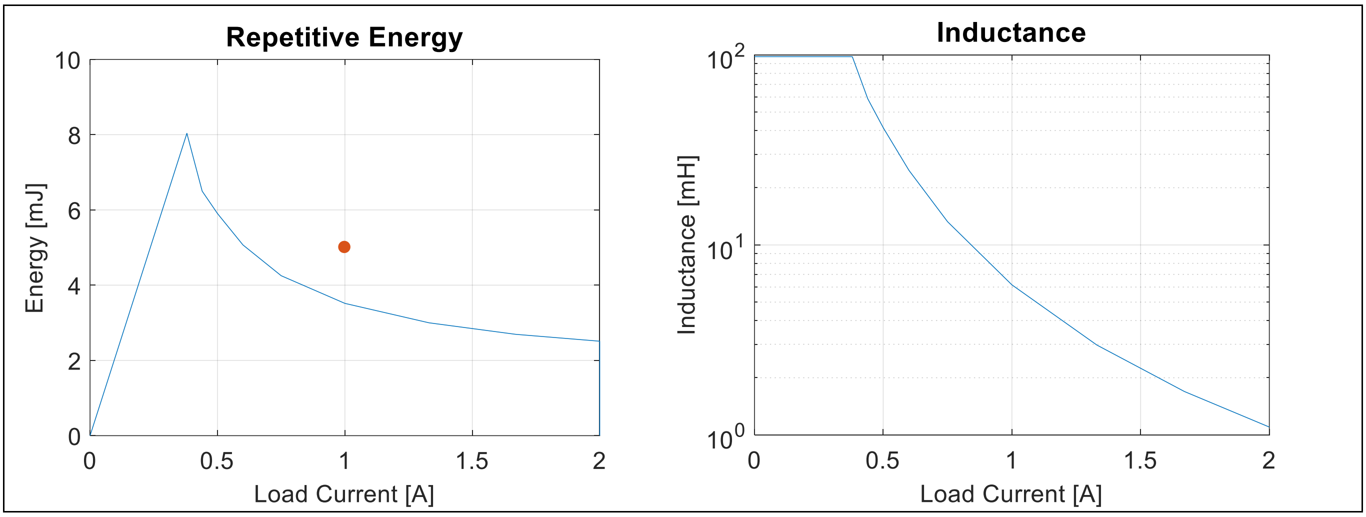

Figure 30 BTS7200-4EPA repetitive energy and inductance as a function of the load current

6 Conclusion

This document explains how to calculate the energy during demagnetization and recommends for each product which value of inductance has to be chosen in order to drive the device without damaging.

Revision history

Document version	Date of release	Description of changes
v01.00	2021-04-21	Application Note available
v01.10	2021-05-11	Typos corrected

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