SIEMENS

HL application note

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Fuse Function with PROFET Highside Power Switches

Abstract:

The protection functions originally incorporated in smart power switches for self-protection have become so sophisticated that they are now capable of protecting not only themselves but also the connected load including leads and plug-in contacts. Although in the past this was primarily the task of fuses, the reduction in the number of fuses in new vehicle generations from approx. 80 to the present 40 is evidence of the trend towards replacing fuses by semiconductors.

This article shows how correct dimensioning and placement of smart power switches not only enables fuses to be replaced but can also significantly improve protection behavior. In the case of thermal operation of the protection functions, for example, a similar but in some applications more favorable behavior can be achieved than with the current vehicle fuse, whereas active current sensing allows virtually any fuse behavior to be implemented.

We then examine the various influencing factors such as manufacturing variations or temperature, but also the magnitude of the operating voltage which is important particularly for the new 42V electrical system. Finally, the unlikely event of destruction of the semiconductor and the associated failure of the protection function will be analyzed in greater detail. Correct dimensioning for lamp or motor load switching will be clarified with the aid of a number of practical examples.

CONTENTS

1 INTRODUCTION

Fuses may be generally defined as protection devices with the task of reliably breaking the circuit in the event of overloads or short circuits, thereby preventing damage to the connected equipment and cables.

The conventional fuses currently in use operate primarily on a thermal basis, and may be subdivided into two groups: blowout fuses, and respectively fuses consisting of a conductive material with a positive temperature coefficient. In both cases, the power dissipation caused by the current is converted into thermal energy, resulting in heating of the fuse. At low currents (low power dissipation) this heat energy can be dissipated to the environment and an equilibrium between absorbed and dissipated power is established causing the fuse not to heat up any further. The current at which an equilibrium of this kind is just possible is termed the "minimum fusing current" (the value of this current is a function of the electrical resistance, the thermal resistance of the fuse and the ambient temperature). It constitutes an important parameter for dimensioning. If a higher current loading occurs, heating continues until the protection function of the fuse is activated.

Another parameter is the "voltage drop" across the fuse at a particular current - generally the nominal current ($V_{drop} = f(I_{load})$). In order to ensure reliable operation, this voltage drop must not exceed a maximum voltage value (otherwise there is a risk of voltage flashovers and arcing across the fuse).

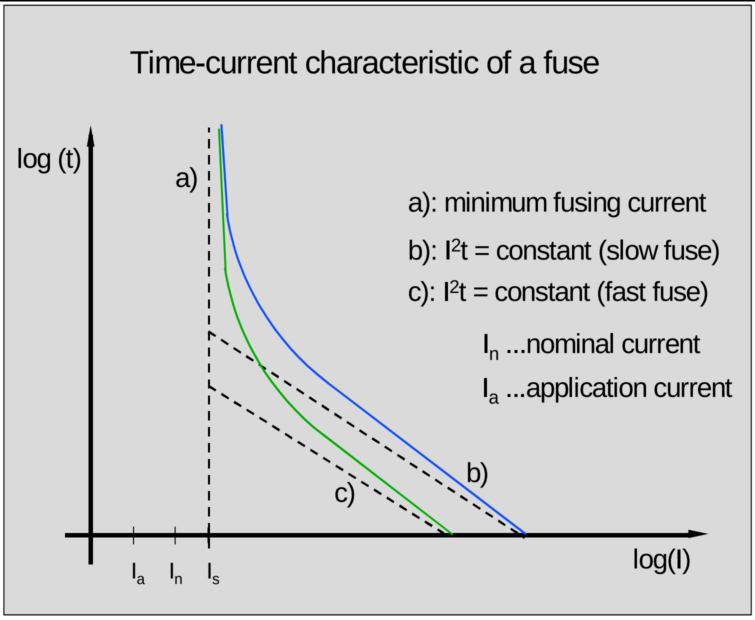


Figure 1 **Approximation of It-characteristic by two asymptotic lines**

The time taken for the fuse to operate is dependent on the amount of power dissipated and the thermal impedance (The power dissipated is always $I^2 * R_{fuse}$). At very high currents, heating takes place so rapidly that virtually no more heat energy can be dissipated to the environment. The tripping behavior is then determined solely by the thermal capacitance of the fuse. In this range $I^2 * t$ (t being the time taken by the fuse to operate) is constant. In the logarithmic current-time diagram, this produces a straight line which is a tangent of the It-characteristic. The position of this line is a measure of the "inertia of the fuse (I^2t large⇒slow-acting; I^2t small⇒quick-acting). This straight line and that of the minimum fusing current can be used to approximate the response characteristic of a fuse (Fig. 1).

I_n is the nominal or rated current for conventional fuses, i.e. the current that the fuse can handle continuously under specified conditions. (e.g. 23°C $T_{ambient}$ for approx.100 hours in standard holders). This rated current is the minimum fusing current of the fuse minus the so-called "minimum fusing factor" ($f=I_s/I_n$). I_a is the current during normal operation of the fuse and is normally less than the rated current. Its value is determined by the user.

However, the tripping mechanism is considerably different for the two conventional fuse types. With the blowout fuse, the conductor melts at a certain temperature, thereby breaking the circuit. This process is non-reversible and the protection device must be replaced.

With the PTC conductor, on the other hand, heating results in an abrupt increase in resistance by a factor of 10^6 to 10^7 at a certain "tripping temperature", reducing the current to a minimum (Fig.2). As long as this leakage current flows, the device remains hot and high-resistance and is also termed "self-holding".

As cooling makes this process reversible, polymeric PTC fuses are also known as "resettable fuses". However, the “polymeric positive temperature coefficient devices” (PPTC device) require a relatively long time to return to the original resistance value, and the value at $T_{ambient}$=20° measured 1 hour after tripping - "post trip resistance" - is still considerably higher than R_{max} prior to operation of the fuse.

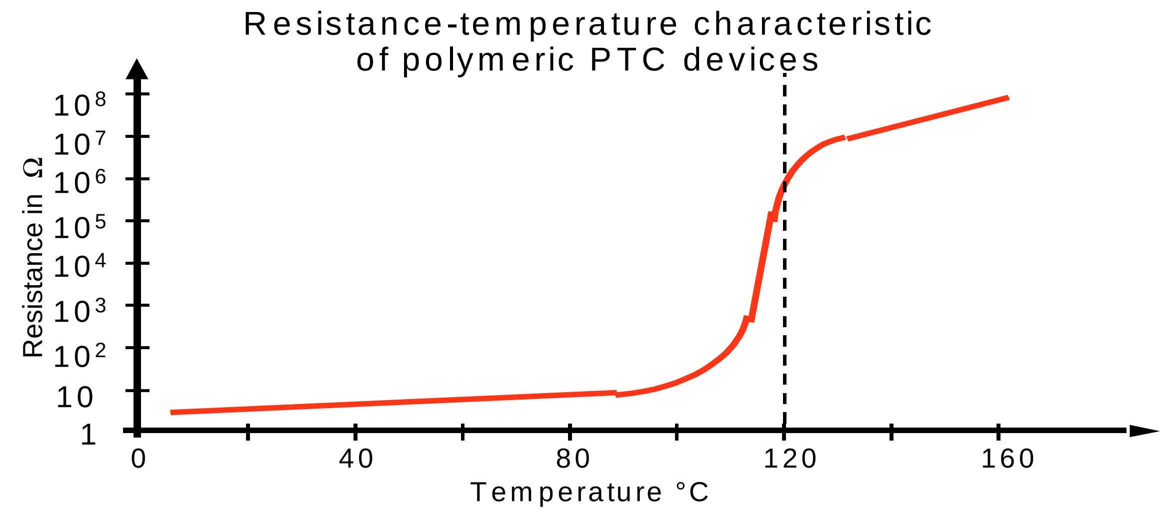


Figure 2 **polymeric PTC conductor**

In automotive applications, fuses in the 5A range and higher are mainly required, making the use of smart power highside switches possible. In addition to its switching function, a PROFET can provide protection for the entire circuit by means of the integrated protection functions originally developed for protecting the power FET (Fig. 3). Another advantage is the possibility of immediately detecting the fault indication using the status and current SENSE signals, or implementing the fuse so that it can be adjusted fully electronically. The current SENSE function allows so-called "customized fuses" to be implemented. Because of

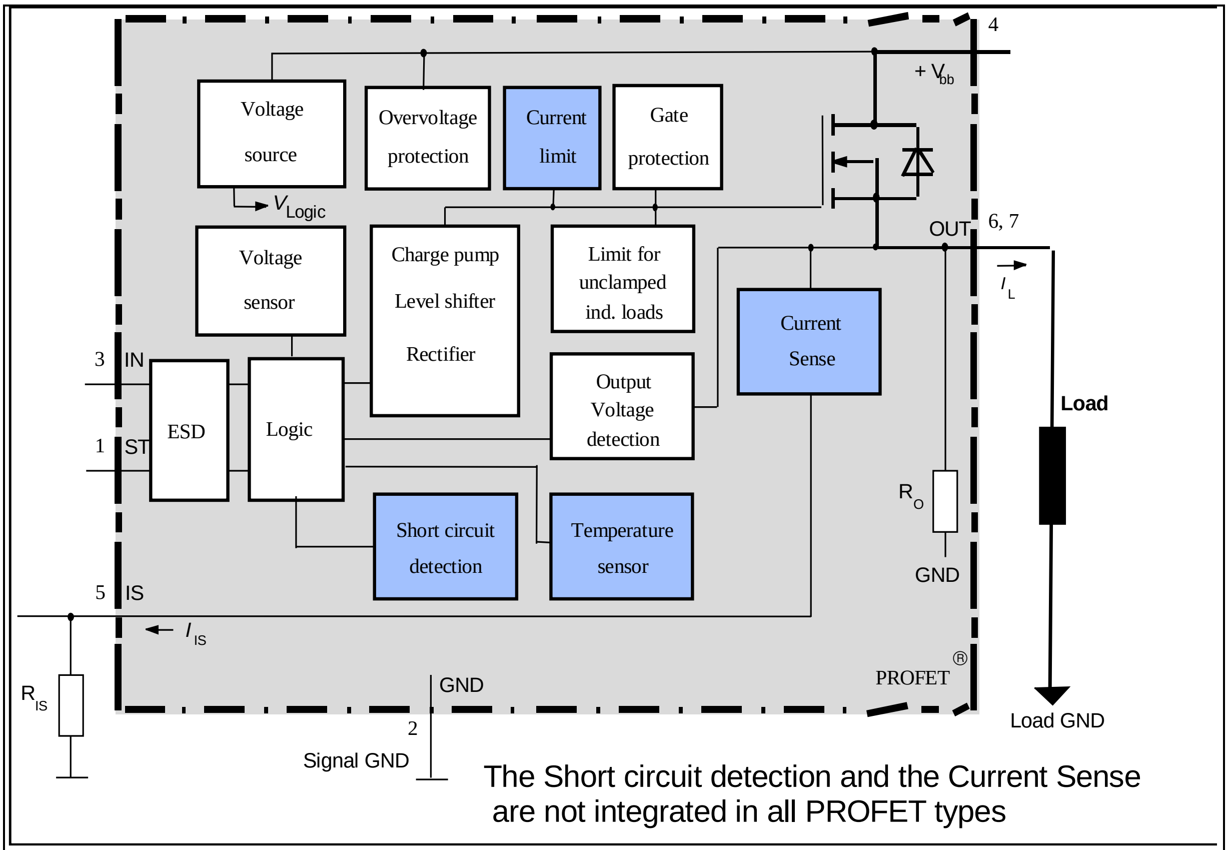


Figure 3 **Block diagram of PROFET highside switches**
The marked blocks can be used for fuse functions

the different protection mechanisms, the greater thermal capacitance and active current limiting, the PROFET's current-time characteristic differs considerably in certain areas from that of the fuses, although this can be a definite advantage.

2 GENERAL

2.1 Basic test setup and explanation

Unlike a fuse whose resistance is solely dependent on temperature, the on-state resistance of a PROFET is variable in the current limiting region (pentode branch of the FET output characteristic). For a test setup with a current source, the source would continuously increase the voltage in this region in order to be able to impress the current value set. This would result in the PROFET being loaded with the maximum output voltage of the source for any current value set greater than $I_{L(SCp)}$.

Consequently, in order to measure the current-time characteristic, a voltage source was used to which a specific resistance (as load) is connected lowside in series (Fig. 4). The maximum current is determined by the voltage of the source, the R_{on} of the highside PROFET, the resistance of the cables used (for switches with less than 100 mΩ, this must be taken into account), and the load resistance.

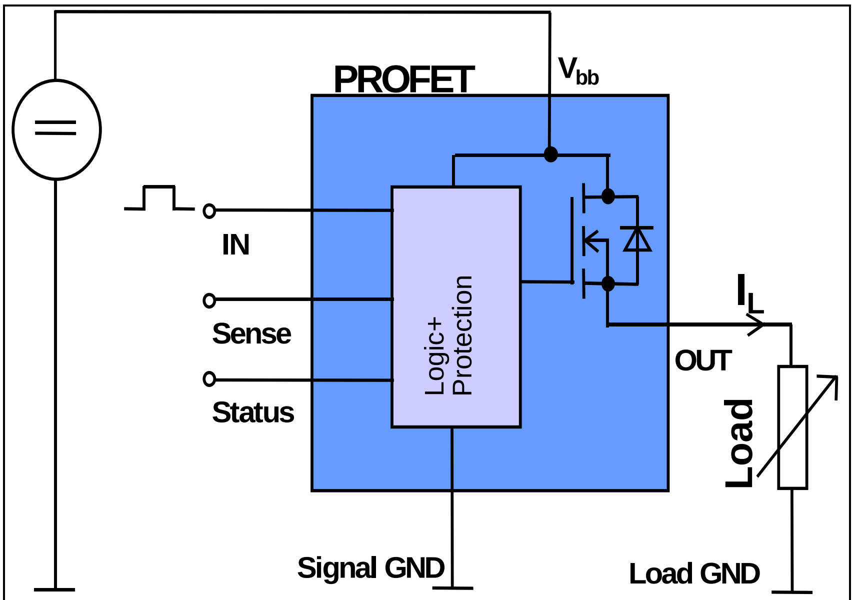


Figure 4 **Symbolic measuring arrangement for the current-time characteristic**

In order to have a means of comparison with the It-curves of a fuse, a fictitious current value must be introduced for the current limiting range. This fictitious load current is calculated as follows

$$I_L = \frac{V_{bb}}{R_{load} + R_{ON(T_A°)} + R_{wire}} . \qquad \text{[Form.1]}$$

Although this current is useful for illustration purposes, it is in fact rendered ineffective by the current limiting of the PROFET. Relevant for the tripping time is the actual current through the PROFET and the voltage drop across the device. The non-linear temperature dependence of the semiconductor makes calculating this current extremely complicated, especially for low-resistance loads and in the event of a short circuit.

The test setup employed here corresponds very closely to the practical application of power semiconductors in the automotive field. Here too the operating voltage remains approximately constant under overload or short circuit conditions, and only the load resistance is reduced by the short circuit or overload. For applications employing high-current switches (e.g. BTS 550P) the internal resistance of the voltage source (e.g. car battery) must be taken into account in order to take equally into account the dip in the supply voltage when the load is applied.

The behavior of the PROFET in response to dynamically variable loads (e.g. switching-on of a halogen lamp, startup of a motor, variable load conditions) can be reproduced with the aid of a simulation based on datasheet information.

2.2 Influencing factors:

Material and package:

The thermal capacitance of silicon is much higher than that of the fuse because of its very high mass compared to the fuse wire. This means that the PROFET must absorb more energy for its temperature to increase by a certain value. However, because of the considerably smaller temperature swing required for turn-off, the PROFET has a comparable inertia to that of a blowout fuse of the same size in spite of its higher thermal capacitance.

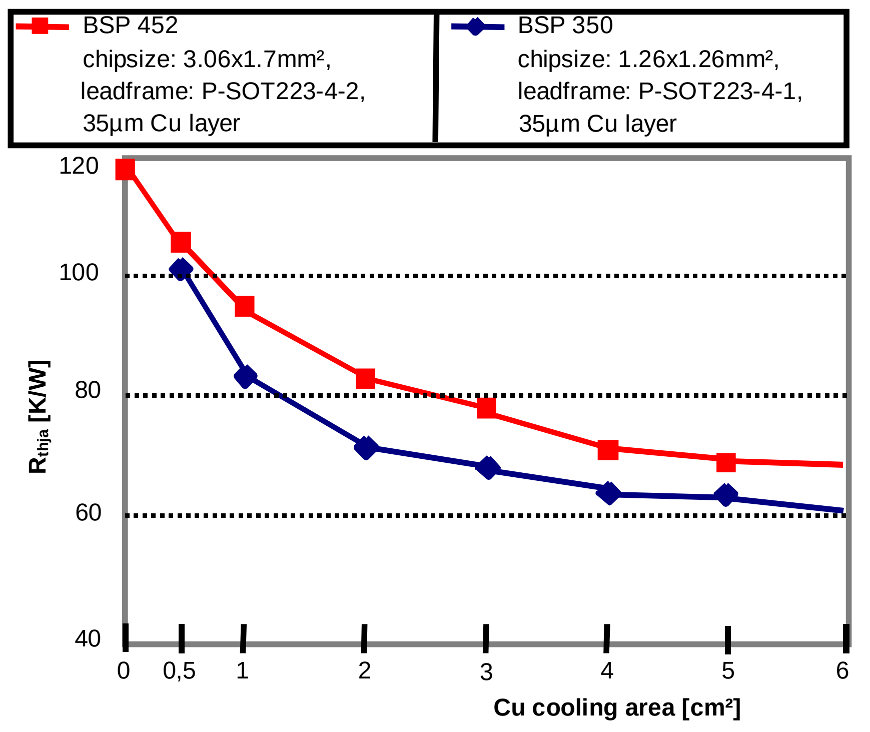


Figure 5 **Influence of copper area on the R_{th}**

By suitable choice of package, chip size and cooling for the PROFET, the thermal resistance or the thermal impedance (thermal conductivity) can be varied within certain limits (with fuses the rated current cannot be subsequently varied). This allows the current at which the absorbed power loss and dissipated heat are balanced - minimum fusing current - to be varied in defined ranges even with an identical chip. Fig. 5 shows the relationship between cooling surface area and R_{th} using the example of two miniPROFETS.

With the BSP 452, a rated current of 0.9A (at 70 K/W) to 0.5A (at 120 K/W) can be implemented by means of the different R_{th}, for example for $T_{junction}$ =100°C and $T_{ambient}$ =85°C. The mounting and heat sink have no great effect on the short-circuit behavior, as they do not become thermally active within such short times (heat sink <100ms or package <10ms).

Temperature:

A temperature of around 1000°C is necessary for a blowout fuse to melt. The effect of temperature on fuses in their operating range of approximately –40°C to 85°C is correspondingly low, unlike the PROFET and the polymeric PTC fuses.

Tripping here occurs at 120°C (PTC fuses) or at 175°C (PROFET). The small temperature swing and the low R_{th} of the PROFET compared to the blowout fuses make the ambient temperature a factor that must be taken into account for dimensioning.
For further details see Section 6.

2.3 Protection structures for fuse applications:

2.3.1 Temperature tripping:

If a certain semiconductor temperature ($T_j \approx 175°C$) is exceeded, the PROFET automatically turns off in order to prevent destruction of the power semiconductor.

It is turned on again either automatically after cooling of the semiconductor with a certain temperature hysteresis or only when a new ON-signal is applied to the input of the PROFET (latching function). Temperature tripping does not distinguish between load-induced heating and heating due to other influences.

2.3.2 Current limiting:

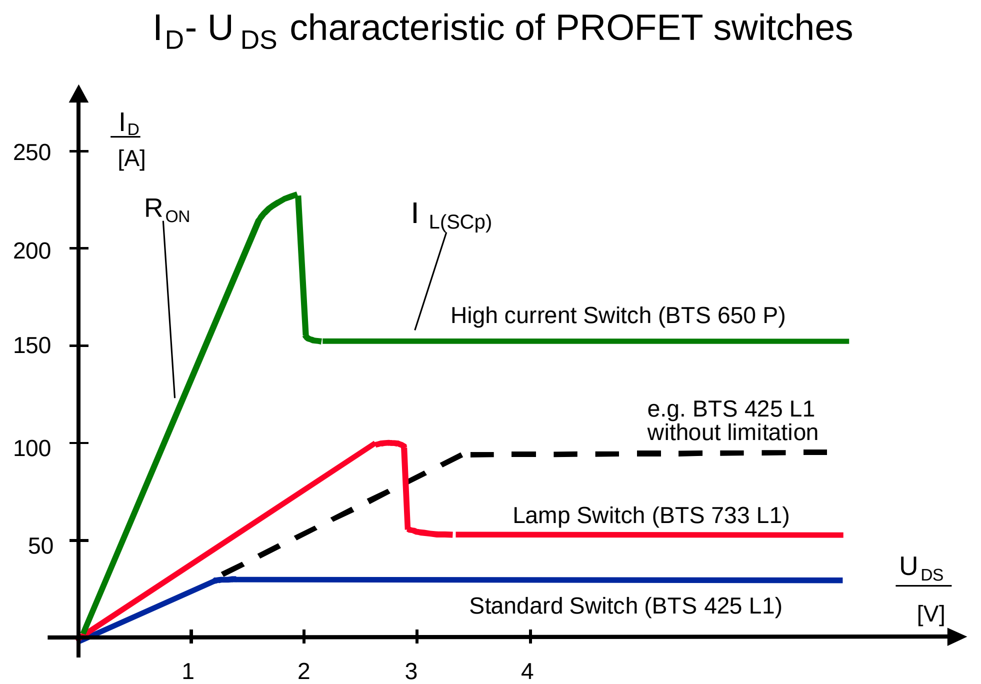


Figure 6 **Example for different PROFET output characteristics (T_j=20°C)**

Current limiting used for overload and short-circuit protection of the PROFET, and is activated if voltage U_{DS} exceeds a certain type-dependent value (fold back voltage). The gate voltage of the power FET is reduced until a new lower characteristic of the transistor obtains (from approx. 8V U_{DS} the current is constant and independent of the voltage →pentode branch of characteristic).

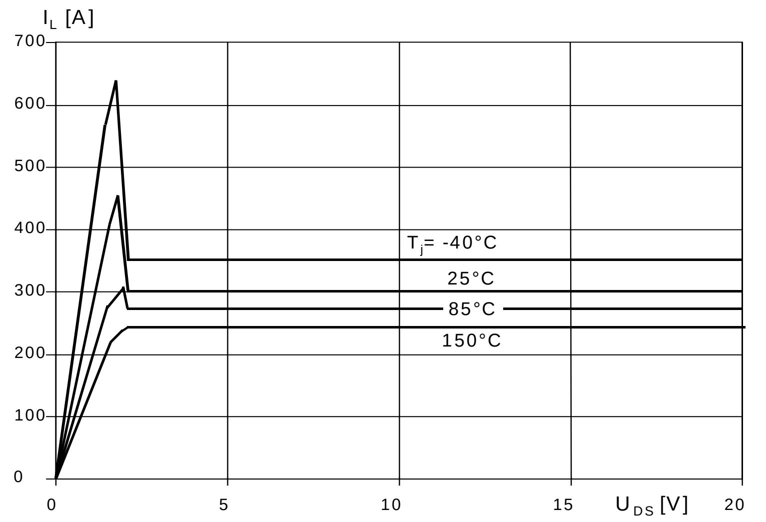


Figure 7 **Temperature dependent output characteristic (BTS 550 P PROFET)**

Consequently, the power dissipation no longer increases as the square of the current but merely linearly with the voltage across the transistor. The heating therefore remains within controllable limits and "hot spots" in the silicon can be prevented in this way (Fig. 7). Particularly in the case of the high-current PROFET, the low R_{ON} (<10mΩ) and low U_{DS} make very large currents possible.

Current limiting at this level (up to 600A) would, however, result in uncontrollably high power dissipations and therefore to damage. It is necessary to reduce the current by reaching the tripping threshold at a much lower, safe value (example BTS 550 P and BTS 650 P in Figs.7 and 8). It should also be noted that the threshold voltage for the onset of current limiting and the size of the limited current may vary greatly from one type of PROFET to another[1)].

2.3.3 Short-circuit detection and short-circuit protection

There are 4 tripping mechanisms (Fig. 8):

a) Temperature tripping with restart after cooling

b) Temperature tripping with latching

c) Monitoring of U_{DS}

d) Monitoring of U_{out}

Temperature protection (a or b) and current limiting are present in all PROFET types, thereby ensuring full short-circuit and overload protection across the entire operating voltage range. Some types additionally have electronic overload monitoring (c or d) which, however, only becomes effective 200µs after turn-on (U_{DS} must first fall to the operating value[2)] and because of current peaks at turn-on).

[1)] See data sheet

[2)] with switch ‘off’: $U_{DS} = V_{bb}$

a1) Tripping at temperatures >150°C with hysteresis
e.g. BTS 426 L

a2) Tripping at temperatures >135°C with hysteresis e.g. BSP 550

b) Tripping at temperatures >150°C with latch function e.g. BTS 432 F

c1) If voltage U_{DS} increases to a value > 8.6V (or 6V for the BTS 550 P), the PROFET turns off completely until it is reset.
e.g. BTS 410 E

c2) As c1) but with V_{bb}-U_{out} > 3.5V
e.g. BTS 410 H

d) If V_{out} falls below 3V the transistor turns off
e.g. BTS 412 A

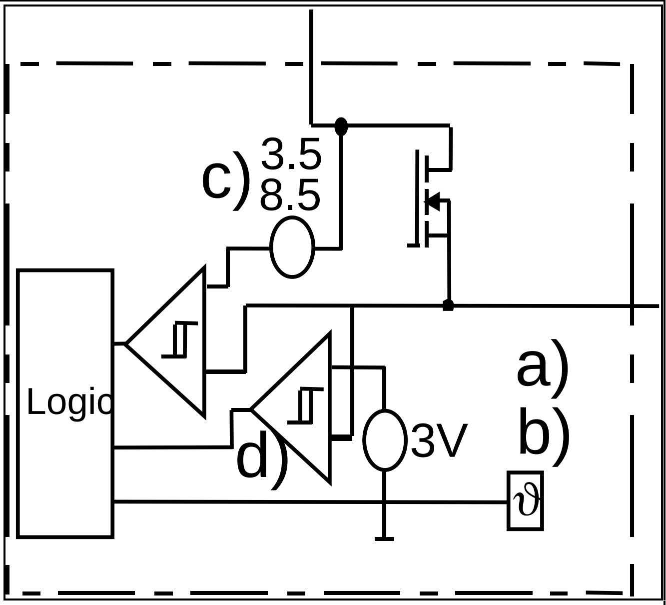


Figure 8 **Short-circuit detection methods**

2.4 The two types of short circuit

As the PROFET is also used as a switch, a distinction is drawn between two types of overloads or short circuits;

Type 1 loading: The short circuit (overload) is already present, and the switch is turned on (Fig. 9).

In the event of short circuit or very low loads (mΩ), the current never exceeds $I_{L(SCp)}$ because the protection mechanisms prevent the gate from being fully driven from the outset. The PROFET immediately assumes the current limiting mode. The current > $I_{L(SCp)}$ specified in the curve is never achieved and is also thermally ineffective.

In the event of overload, $I_{L(SCp)}$ may be exceeded under certain conditions at low U_{DS}. This case is represented by the "overload" curve. The load resistance line indicates to some extent the operating point in the linear range of the PROFET characteristic. $I_{L(SCp)}$ may be exceeded until the temperature-induced increase in R_{ON} attains the voltage threshold for current limiting.

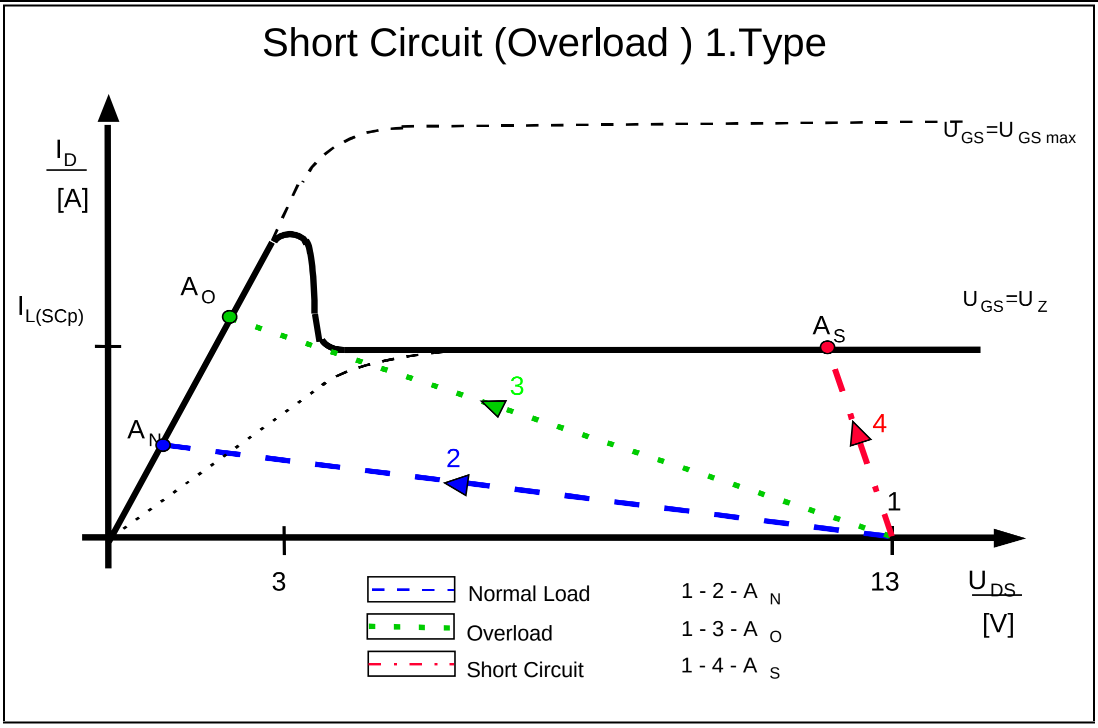


Figure 9 **Typical PROFET output characteristic with operating points of different loads (PROFET is switched to the load)**

Type 2 loading: The PROFET is ON when the fault occurs (Fig.10).

In this case, the gate is driven fully on; when faults occur the current limiting or short-circuit protection requires a certain time (a few µs) to reduce the gate voltage. The resulting maximum current is a function of the R_{ON} of the PROFET and the rest of the circuit. However, as regulation begins to operates after just a few microseconds, this current is not thermally effective and may be disregarded.

As in type 1, $I_{L(SCp)}$ may be exceeded under certain overload conditions (operating point A_O).

The thermal tripping times are different in the region of the It-characteristic in which the PROFET already starts in current limiting in the event of type 1 faults. Type 2 faults, on the other hand, still occur in the linear region of the PROFET output characteristic (Fig. 10 : load line A_O). A type 1 fault was always caused for measurements on the PROFETs.

Differences similarly occur if the silicon temperature is higher than the ambient temperature in the event of a fault due to a previous loading. Because of the smaller temperature swing required for tripping, the time taken for the protection mechanisms to operate is considerably shorter.

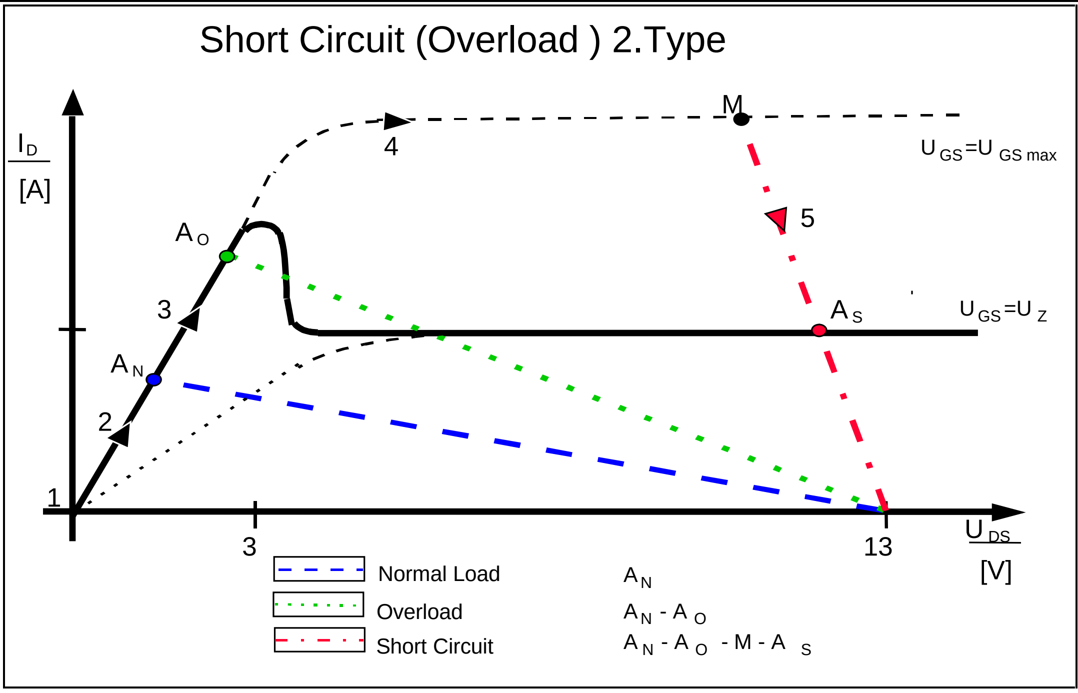


Figure 10 **Typical PROFET output characteristic with operating points of different loads (load is switched on the PROFET)**

3 THE CURRENT-TIME CHARACTERISTIC

!All observations apply for the moment to typical devices! (V_{bb}=13V and T=25°C unless otherwise noted)

The ISO load current I_{LISO} specified in the data books for the devices is not used for this PROFET application, as artificial, unrealistic ambient conditions representing the upper feasibility limit for actual use must be created (a heat sink regulated to 85°C) in order to determine this current .

3.1 Analysis of the thermal-electrical fuse behavior

The analysis is carried out based the characteristics of a BTS 640 S2 (Sense PROFET with thermal short-circuit detection), BTS 410 E2 (PROFET with electronic short-circuit detection) and BTS 550 P (high-current PROFET).

Because of the complex structure of a PROFET, as compared to a blowout fuse, the characteristic is also influenced by several factors. For a precise description of the behavior, it is advisable to subdivide it into several regions (Fig.11).

3.1.1 BTS 640 S2

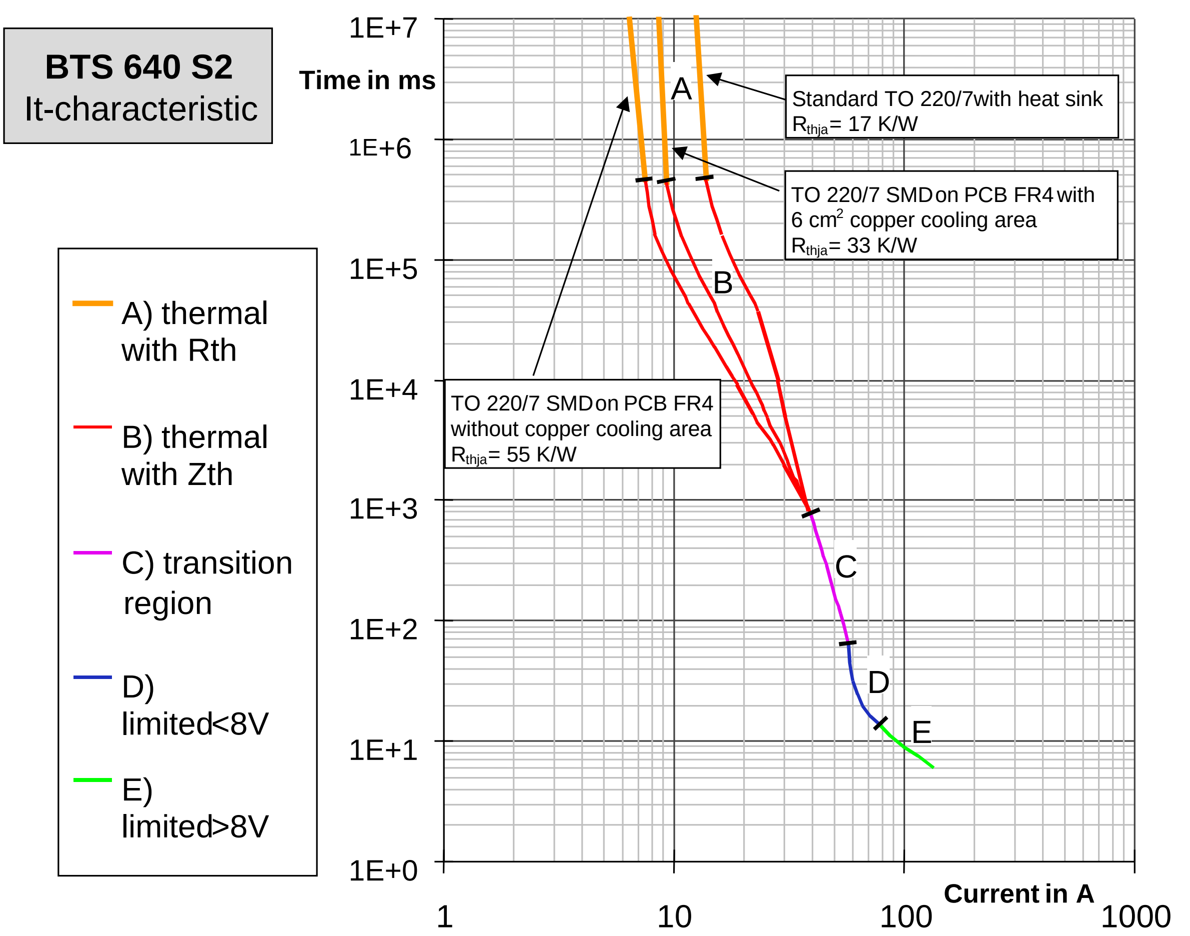


Figure 11 **shows the detailed It-characteristic of a BTS 640 S2 Sense PROFET with different cooling conditions and mounting techniques**

At low currents (region A) the PROFET exhibits purely thermal behavior, similar to a fuse. The power dissipation here is $I^2 * R_{ON}$; there is still a relatively strong interaction with the surroundings because of the long duration of effect and small R_{th} of the PROFET. For given R_{th}, the power dissipation results in a temperature rise and in some cases a temperature-induced turn-off. Heating of the semiconductor results in an increase in the R_{ON} of the FET. However, the (in comparison) very large constant load resistance R_{load} ensures a virtually constant load current. For this region a current value can be defined at which the power absorbed and the power dissipated as heat are in balance. This current corresponds to the "minimum fusing current" of a fuse and can be calculated with knowledge of some of the PROFET’s parameters

$$I_{\min.\,fuse} = \sqrt{\frac{T_{j\max} - T_A}{R_{thja} * R_{ONTj\max}}} \qquad \text{[Form.2]}$$

As in the case of the fuses, in region B the power dissipation is ever increasing, but the maximum heat that can be dissipated remains the same at constant ambient temperature. This means that the higher the current, the faster the PROFET turns off and, instead of the thermal resistance, the thermal impedance of the PROFET must be used for calculations here.

In region B, because of the high power dissipation, the semiconductor heats up so rapidly that only part of the heat energy can be dissipated away. The thermal capacities of the PROFET are here codetermined by the behavior. The power dissipation is still $I^2 *R_{ON}$. As the temperature-dependent R_{ON} of the semiconductor and R_{load} are already virtually of the same order of magnitude, the load current is no longer constant, but decreases exponentially with increasing semiconductor temperature. For known I^2t of the PROFET, a tangent can be constructed for the current-time characteristic analogously to the fuses (I^2*t=constant; PROFET like a "slow-blowing" fuse). However, this would only apply if the PROFET had no protection structures and if the time constant is so small (< 10ms) that no more energy can be dissipated to the surroundings.

Transition to current limiting region C. In this part of the characteristic, the U_{DS} exceeds the voltage threshold for current limiting after a certain time depending on the load current and the temperature of the semiconductor. Up to a certain semiconductor temperature, the FET is still in the resistive region and then changes to current limiting mode (the higher the load the sooner the changeover). Current limiting results in a step change in the power dissipation due to the increase in U_{DS}, resulting in a noticeable inflection in the characteristic. This may be seen as a change to a new "quicker-acting" characteristic. This is again only for illustration purposes, as currents greater than $I_{L(SCp)}$ are only fictitious after the onset of current limiting and never actually flow. In spite of current limiting, U_{DS} is still less than approx. 8V, and the limited current is therefore not yet completely independent of the drain-source voltage.

In region D, the drain source voltage is so high that the PROFET is in current limiting mode from the outset. The transition from region C is continuous (U_{DS} still less than approx. 8V), and here too the current is still not independent of U_{DS}. Only at higher drain-source voltages - region E - is the current influenced solely by the temperature of the PROFET. The power dissipation is now $I_{L(SCp)} *U_{DS}$,where $U_{DS} = V_{bb} - U_{load}$ and $U_{load} = R_{load} * I_{load}$. A reduction in the load until short circuit occurs does not now result in a higher load current, but only in a higher voltage drop across the PROFET (power dissipation no longer proportional to I^2 but to U_{DS}).

3.1.2 BTS 410 E2

Many PROFETS are additionally provided with short-circuit protection on a voltage monitoring basis. Their characteristic looks somewhat different and may be described with reference to the BTS 410 E2 device (Fig. 12).

The behavior in regions A-D is the same as described for the BTS 640 S2.

Differences only occur in the short-circuit protection region. If voltage U_{DS} here exceeds a

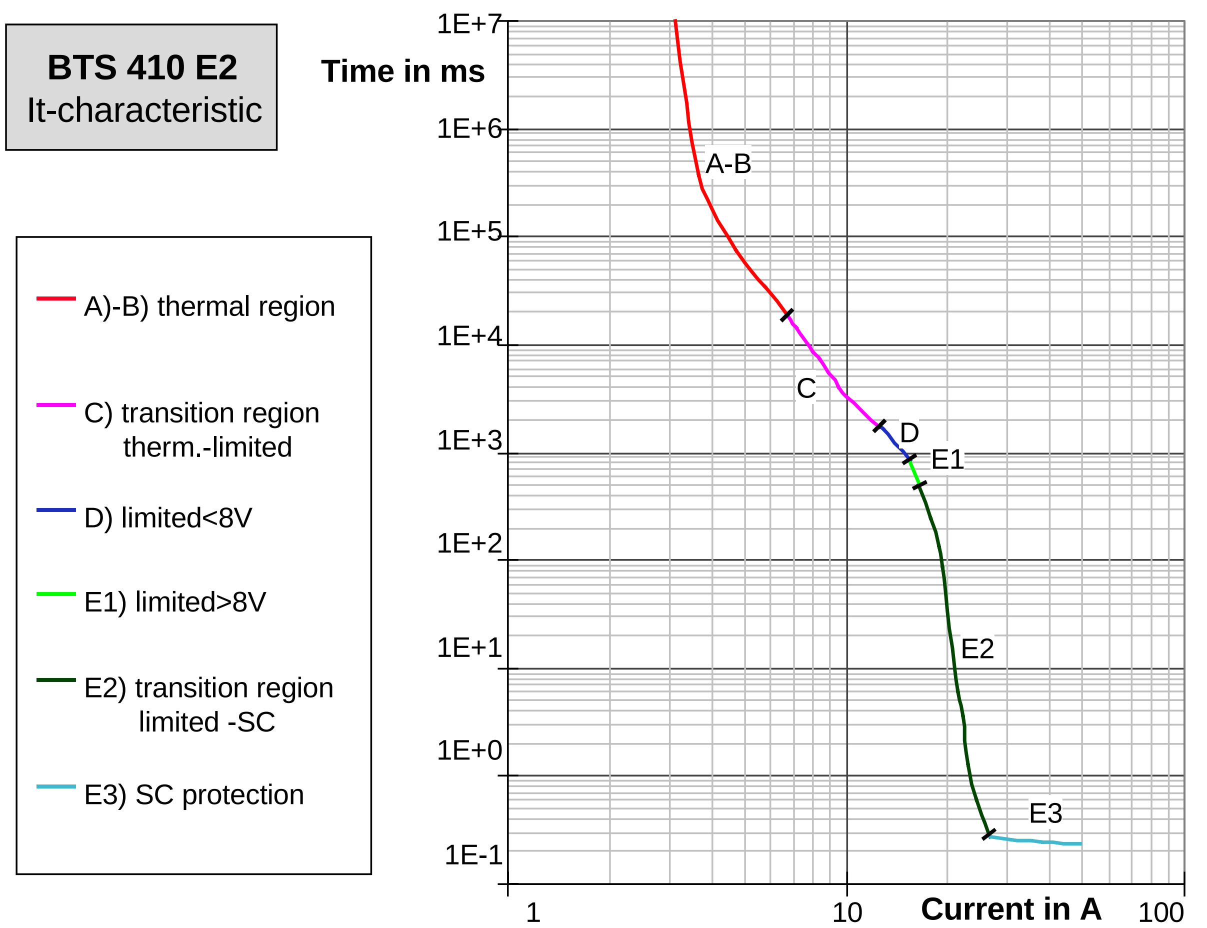


Figure 12 **Detailed It-characteristic of a BTS 410 E2 PROFET (electronic short circuit detection) with SMD case on 50mm*50mm*1,5mm epoxy PCB FR4 with 6cm² copper area**

value of approximately 8.5V, the PROFET trips and signals the fault to the status output. If one examines this in detail, another three sub-regions may be differentiated.

E1: PROFET fully limits the current, U_{DS} does not exceed 8.5V and tripping occurs due to overtemperature.

E2: Current limiting always active; because of the heating of the semiconductor U_{DS}=8.5V is exceeded and electrical short-circuit tripping occurs after a certain (load-dependent) time.

E3: U_{DS} is always greater than 8.5V, electrical short-circuit tripping occurs immediately after the turn-on delay of max. 200µs.

For PROFET types with short-circuit detection at 3.5V (e.g. BTS 410 H), electronic tripping is displaced to transition region C at lower currents.

If the protection facilities are monitoring current V_{out} (e.g. BTS 412 A), the short-circuit tripping threshold also depends on the supply voltage (short-circuit tripping at V_{out}<3V).

3.1.3 BTS 550 P

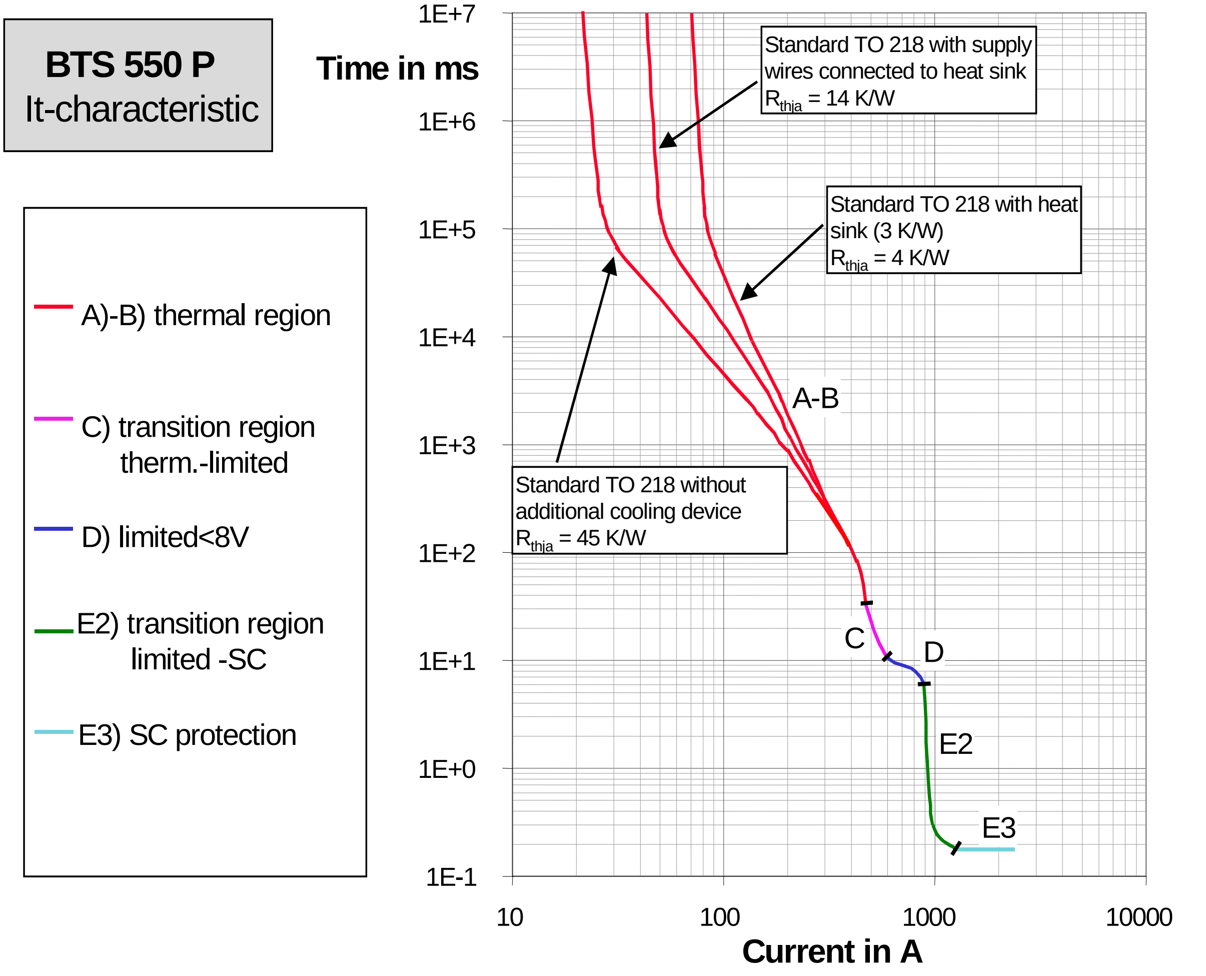


Figure 13 **Detailed It-characteristic of a BTS 550 P (high current PROFET) with different cooling conditions and mounting techniques**

The special features of high-current PROFETs are a very small R_{ON} , a high current limiting threshold (typically 5V U_{DS}) and electronic short-circuit detection at typically U_{DS} > 6V. In order to determine the behavior of the BTS 550 P in real automotive applications, a 12V 75Ah 400A car battery was used for these measurements instead of a constant voltage source (at high load the voltage falls to 6V due to the internal resistance of the battery). Operating regions A and B differ from the previously mentioned PROFETs only in terms of current magnitude. The high $I_{L(SCp)}$ in the current limiting region (C and D) and the current limiting threshold of 5V allow very large inrush currents to be switched (e.g. by starter motors). Even at U_{DS} > 6V, electronic short-circuit shutdown occurs, the region in which thermal tripping occurs with active current limiting is therefore correspondingly small (Fig.13).

3.2 Difference between type 1 and type 2 faults

The simulated characteristics of the BTS 733 L1 (Figure 14) show the turn-off times for type 1 and type 2 faults. This differentiation is only possible for switches for which $I_{L(SCp)}$ is lower than the maximum current for U_{DS} less than the voltage threshold for current limiting. For these switches (high-current switches and lamp switches) the PROFET output characteristic and the load characteristic have two possible operating points in particular cases (see Fig. 10: operating line A_O), and therefore two different power dissipations and tripping times.

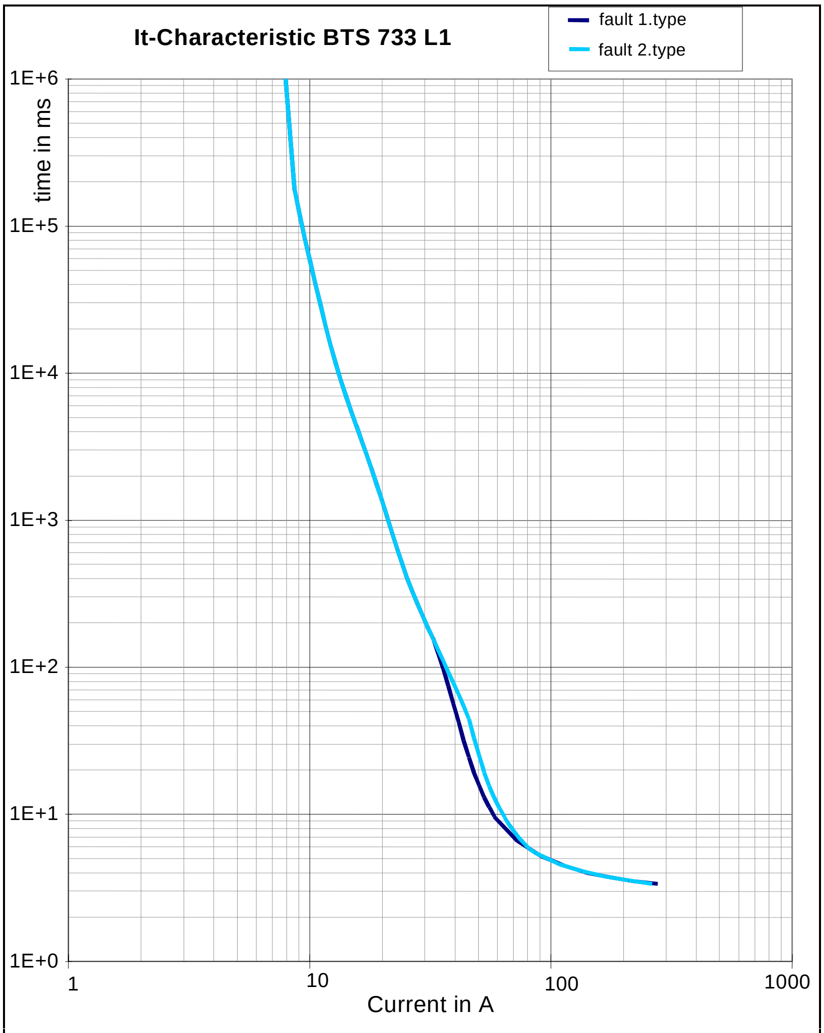


Figure 14 **Difference between type 1 and type 2 short circuit**

For all further considerations, type 1 faults will be assumed, because the characteristic with the smaller guaranteed current is critical for reliable dimensioning of applications (especially switching-on capacitive loads) (see Section.8: Hold characteristic) and because the differences are negligible.

3.3 PROFET operation:

The thermal part of the characteristic (A,B) represents the limit of the operating range of the PROFET. Currents less than the "minimum fusing current" are suitable for continuous operation, region A being the steady-state upper limit. In region B, only a transient loading of the PROFET is possible, e.g. due to the inrush current of a lamp or capacitive load. The maximum on-load time can be read off for the relevant current from the characteristic. However, it must be taken into account that the semiconductor can heat up to approximately 150° during continuous operation in the borderline region of the minimum fusing current.

Section C,D and E is designated as the protection region. Here the protection functions of the PROFET are already operative and prevent damage to the electrical circuit. The limit of the overload region is represented by regions C and D (current limiting), short-circuit protection is active in region E. Although the PROFET can be operated in its protection region, this is not recommended (see 17.2.2. Example of incorrect dimensioning).

4 USE OF PROFETS AS "ELECTRONIC FUSE"

4.1 The Sense principle taking the BTS 640 S2 as an example

An attractive alternative to fuse behavior based on thermal operation is offered by the Sense PROFET family, such as the BTS 640 S2. This highside switch additionally possesses a so-called Sense output at which a voltage signal proportional to the load current is available when an external resistance is connected to ground (Fig.15).

High-current switches BTS 550 P, BTS 555 P and BTS 650 P also have a current sense output.

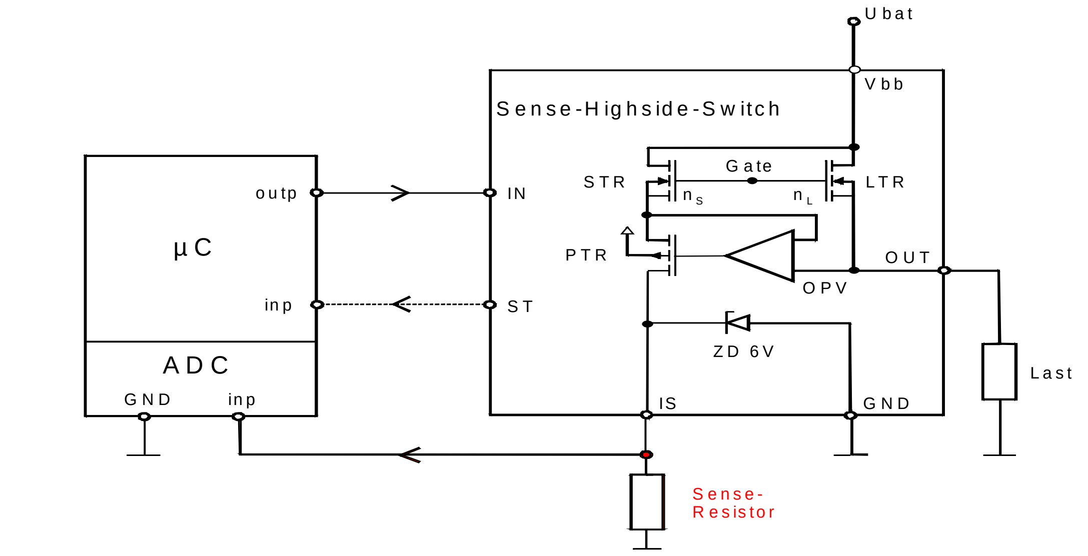


Figure 15 Circuit diagram of the Sense principle (BTS 640 S2)

In the case of the BTS 640 S2, a switch ideally suited for vehicle and industrial applications, sense transistor STR (n_S approx.10 cells) has MOS transistor cells, the actual power transistor LTR (n_L approx. 50000) cells. The STR is regulated to the same source voltage as the LTR via the current mirror formed from OPV and P-channel transistor PTR, and the sense current is mirrored via output IS at ground potential. As the current and load are virtually identical through all the MOS cells, a virtually temperature-invariant sense-to-load-current ratio n_s / n_l of approximately 1/5000 is also produced.

4.2 The advantages and possible applications of the sense current:

We shall first consider the (theoretical) temperature independence of the sense current. As the MOS cells of the load transistor and of the sense transistor are in the same cell field on the chip and have the same loading, they always have the same temperature. The ratio of load current to sense current is therefore theoretically temperature-invariant. The accuracy of the sense current as a function of the load current is approx. ±10% at I_{losd} =5A and

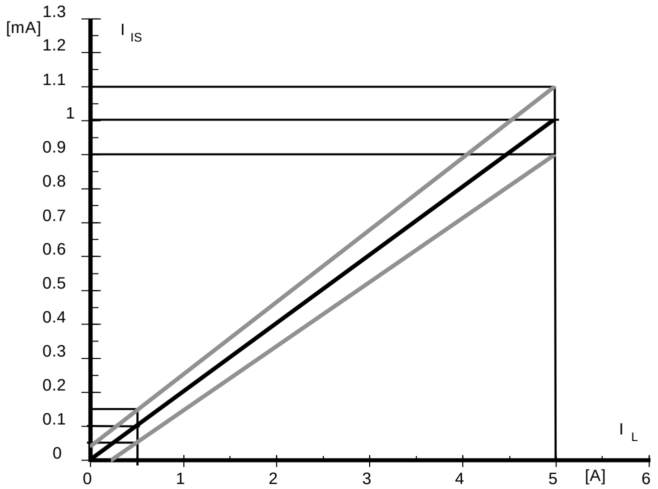


Figure 16 Sense current I_S versus load current I_L

±50% at I_{losd} =0.5A and applies to a temperature range of -40°C to 150°C and a voltage range of 6.5V to 27V (Fig.16).
The precision with which turn-off occurs in the event of overcurrent is considerably better than that of a conventional fuse or a PTC polymeric fuse. If we consider Fig.17, the heavy dependence of the conventional fuse line on the time (and naturally on the temperature, see Section 9) is immediately apparent. The rated current (likewise the minimum fusing current) of a conventional thermal fuse applies only to times $t \rightarrow \infty$. The shorter the time, the higher the maximum possible currents.

For very small times, currents of any magnitude are possible with conventional fuses. This problem never arises with the PROFET as thermal fuse because of the active current limiting, and especially not with the PROFET as electronic fuse due to the time-invariant sense current evaluation.

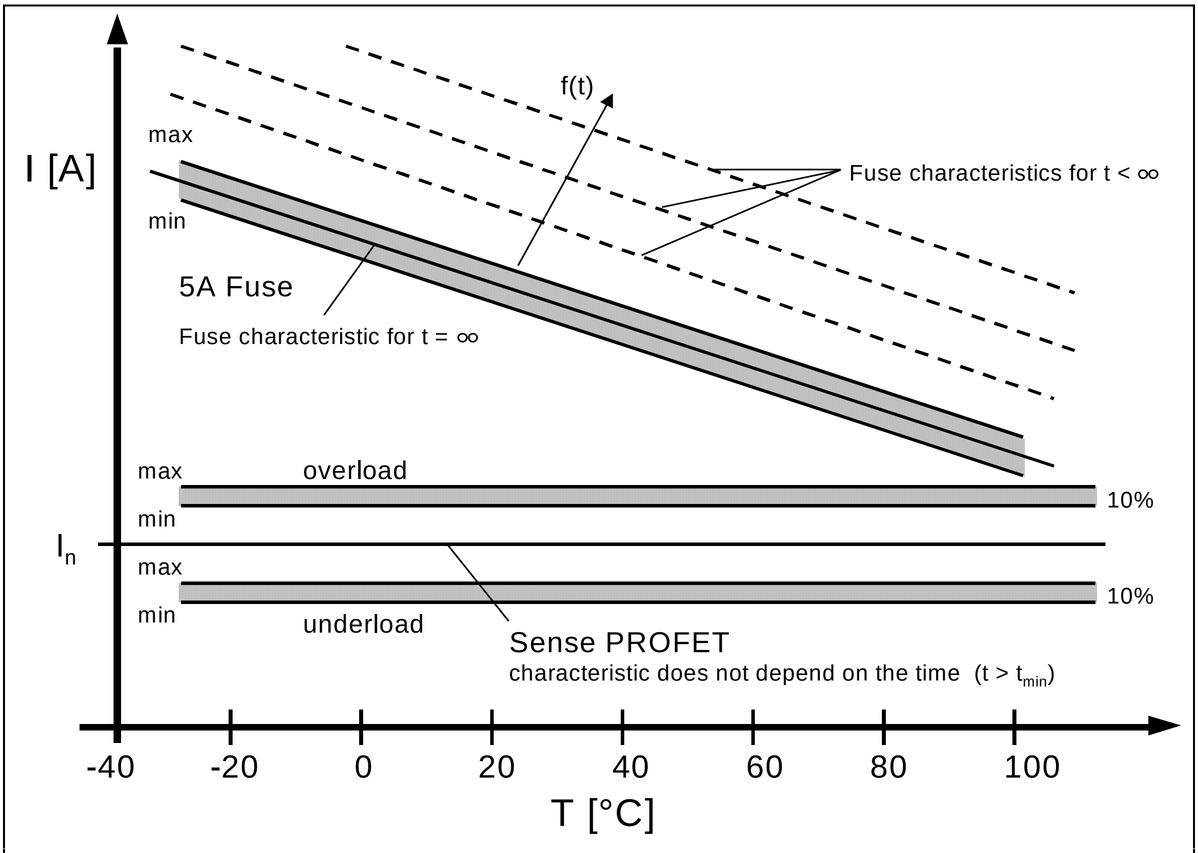


Figure 17 **Accuracy of the Sense current in comparison to the temperature and time dependant automotive fuse**

4.3 Protection and diagnostic possibilities

Using the sense signal it is possible to implement virtually any current-time characteristic. The only limitation is the It-characteristic determined by the integrated protection structures or the minimum tripping speed defined by the logic circuitry.

The simplest implementation of an electronic fuse is an overcurrent detection arrangement that takes no account of the duration of the occurrence. If the current threshold set (voltage at sense pin) is exceeded, the PROFET trips within less than 100µs (cable or overload protection).

For applications in which the time dependence of the load current is significant (inrush current of a lamp), the sense signal can be evaluated using an analog network or µcontroller. Because of the accuracy and temperature-independence of the sense signal, it is now possible to tailor the fuse to a particular application (Fig. 18).

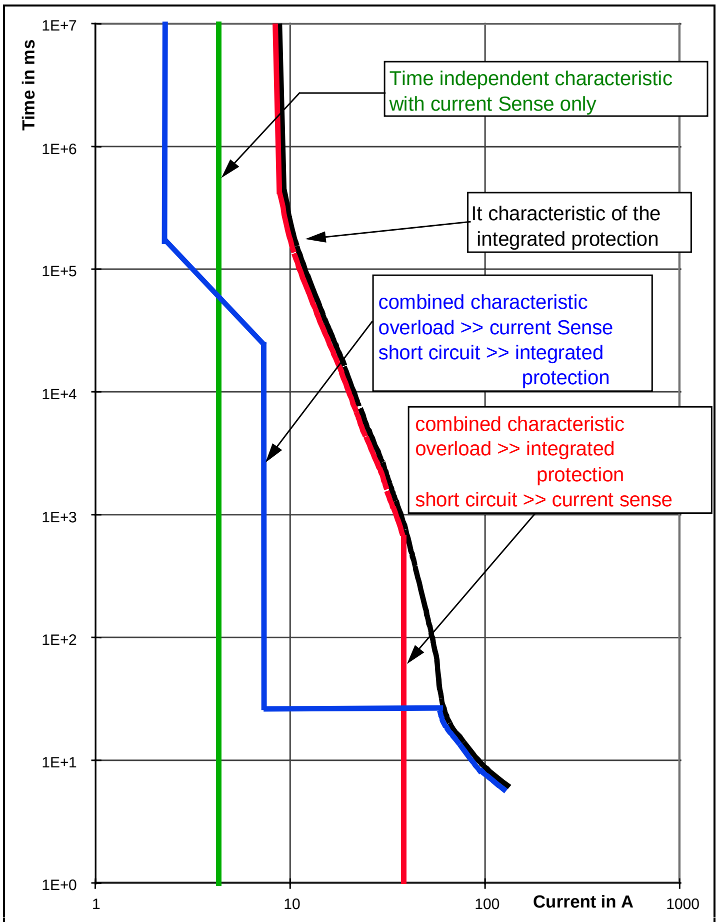


Figure 18 **Examples for possible It-characteristics with the Sense PROFET**

Additional options become available for fault diagnostics. Via the sense PROFET it is not only possible to determine whether e.g. a lamp is connected, but also whether it is the correct one. In addition, in the event of a fault, the cause of a problem can be determined relatively accurately, as the output current is determined quantitatively.

4.4 Monitoring of dynamic events

After a defined settling time, the sense signal is present and follows the response of the load current. With appropriate evaluation of the sense current it is now even possible to implement dynamic monitoring of the load current. For example, the current can be cut off if a maximum dI/dt is exceeded. This method can be employed as short-circuit protection. In the case of slow current rises, the temperature-induced tripping of the PROFET provides adequate protection. If a short circuit is present, there is a very rapid current rise which will be detected and can result in electronic tripping of the PROFET.

5 THE EFFECT OF COOLING, PACKAGE AND SILICON ON THE CHARACTERISTIC

Unlike the fuses, the PROFET allows several different materials to be used for fabrication. The different thermal conductance and capacitance values (of e.g. silicon, gold, aluminum or molding compound) result in a complex thermal impedance Z_{th} (Fig. 19).

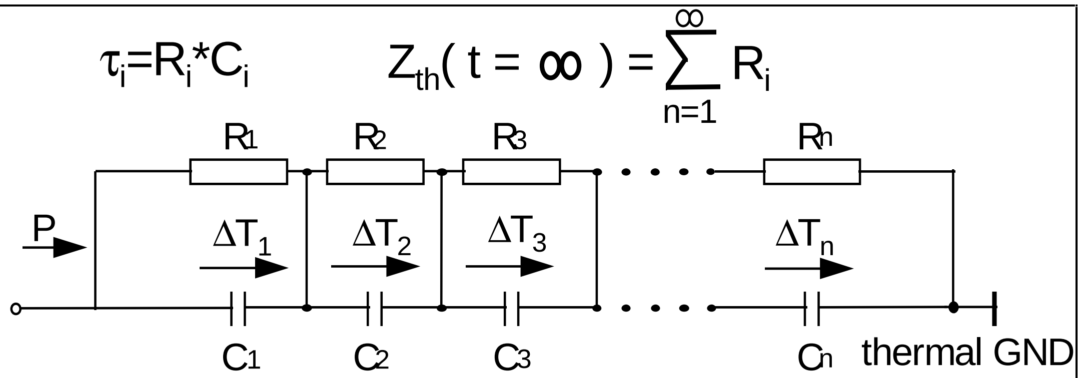


Figure 19 Thermal equivalent network ($Z_{th\ ja}$)of the PROFET

As a result of this Z_{th}, the surrounding have a considerable effect on the current-time characteristic. Here it is interesting to consider the characteristic in the time domain. For very short loading times (approx. 10ms and less), there is virtually no external influence. Although I^2t = constant here, this region is never reached due to the usually prior onset of current limiting. For longer times, effects due to the internal chip structure are only noticeable later (from approx. 10ms), and due to package and heat sink from approx. 100ms. The time constant τ and associated R_{th} of the thermal impedance reflect this behavior $\Rightarrow$ with package selection and mounting the characteristic can be subsequently manipulated in the operating region. In the steady-state region, the maximum current depends virtually exclusively on the heat sink, resulting in a "minimum fusing current" of the PROFET that can be set by the user within certain limits.
For further details see PROFET simulator section

6 Effect of temperature on characteristic and R_{ON}

A marked temperature dependence is caused solely by the semiconductor material itself. Taking R_{ON} as an example, it may be seen that the curve has a parabolic form (Fig. 20).

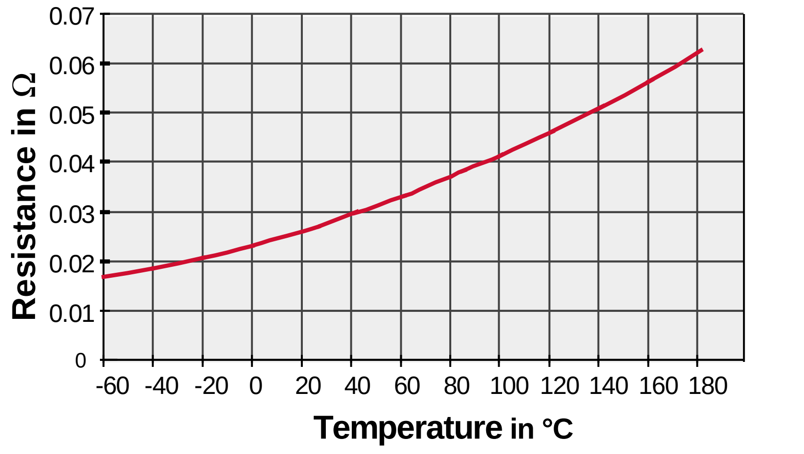


Figure 20 Temperature dependence of the semiconductor ON-resistance

With two known resistance points of this curve and the temperature at the base of the parabola, it is possible to calculate the resistance value for every semiconductor temperature (see Form. 4). The temperature dependence becomes particularly noticeable in the current limiting region. Here the ON-resistance of the FET is critically important for the current in the circuit. In the case of highly resistive loads, on the other hand, the variable R_{ON} has little effect on the size of the current.

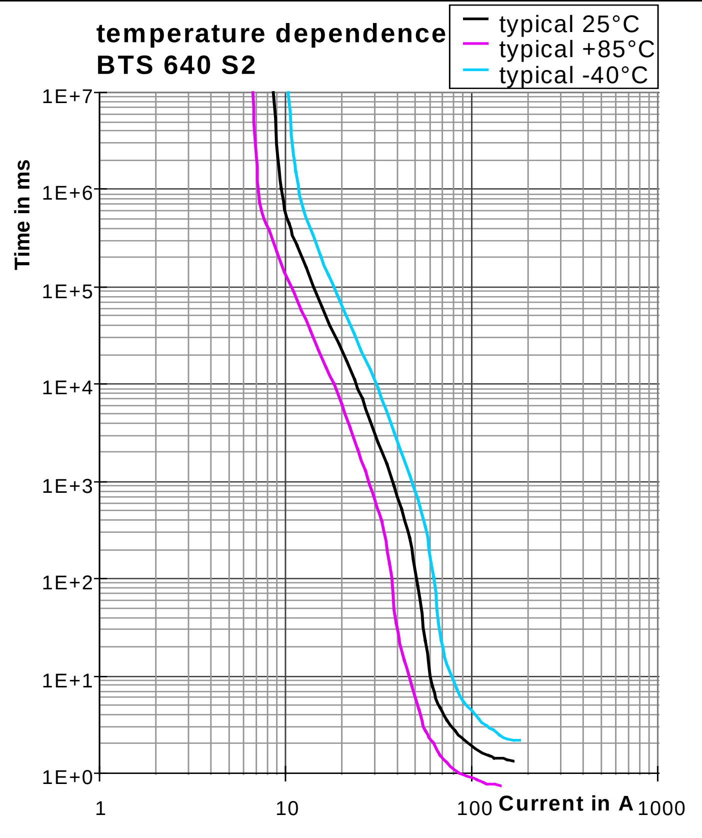


Figure 21 Typical current-time characteristic for different ambient temperatures

In the steady-state region, temperature dependence is likewise present. As already mentioned (see Form. 2), the "minimum fusing current" is also dependent on the ambient temperature. The difference between $T_{ambient}$ and $T_{junction}$ here as the root term affects the maximum current .

Finally mention should also be made of the temperature dependence which can also be observed in the fuses and which is critical for the "time to trip", especially for small time values. Due to the changed ambient temperature, the temperature swing required to reach the tripping temperature is different. Consequently, a different amount of energy and therefore a different time for a given power dissipation is required in order to reach the tripping temperature. Combining the temperature dependencies, we obtain the family of curves shown in Fig. 21. As may be seen, an increase in the ambient temperature results in a displacement of the entire characteristic to the left and the "minimum fusing current" is reduced.

7 EFFECT OF THE SUPPLY VOLTAGE ON THE FUSE CHARACTERISTIC

In the operating range of the PROFET, in which only the current and R_{ON} govern the tripping time, the operating voltage has virtually no effect on the current-time characteristic. Variations only occur in the current limiting region (Fig. 22). Here the load resistance and ON-resistance of the limiting PROFET form a voltage divider for the supply voltage. The higher the supply voltage, the higher the drain-source voltage drop for the same load resistance. If the load resistance is zero - in the case of a short circuit - the voltage dependence has the most marked effect on the tripping time. As a result of current limiting, the load current is largely independent of the operating voltage, and therefore a higher supply voltage results in a linear increase in the power dissipation in the PROFET in the current-limiting region, and therefore a shorter tripping time. If the supply voltage overshoots e.g. by 20%, the tripping time is reduced by a factor of 1.2 in the event of a short circuit.

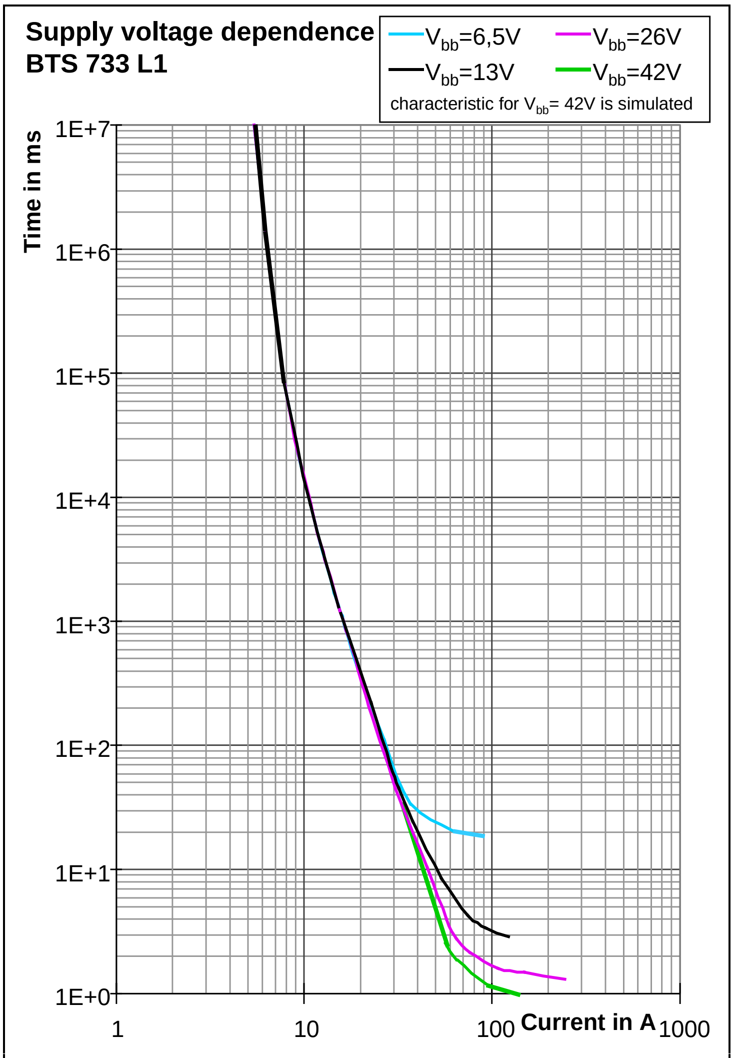


Figure 22 **Supply voltage influence on the It-characteristic**

At high supply voltages (in the region above the maximum permissible V_{bb}) the power dissipation caused by the $I_{L(SCp)}$ and voltage drop U_{DS} is no longer in the so-called "safe operating area" in the event of a hard short circuit, i.e. thermal destruction of the PROFET is possible in this case. In order to avoid this, $I_{L(SCp)}$ will in future be reduced with increasing drain-source voltage (either incrementally or continuously). As a result, even at impermissibly high voltages the PROFET will not be destroyed in the event of a fault. In terms of fuse behavior, regulation of this kind results in the current-time characteristic being less dependent on the supply voltage

8 Worst Case Scenario for Device Variability

When designing an application, it is necessary to use the limit values guaranteed by the manufacturer rather than the typical parameters of a device. In this way a delimited area (area of typical devices) is obtained in which each typical device must lie. The two characteristics enclosing this area represent worst case conditions (Fig. 23). For the protection aspect, the upper characteristic is of interest - trip characteristic -, as all the overloads with values greater than this characteristic are guaranteed to result in operation of the protection function (switch off area). The lower characteristic - hold characteristic - is important for operation, because loads in the area below than this characteristic (operating area) are guaranteed not to cause tripping of the fuse. Only by making measurements on the device is it possible to determine where a specific individual device is within this area. Detailed considerations will be discussed below.

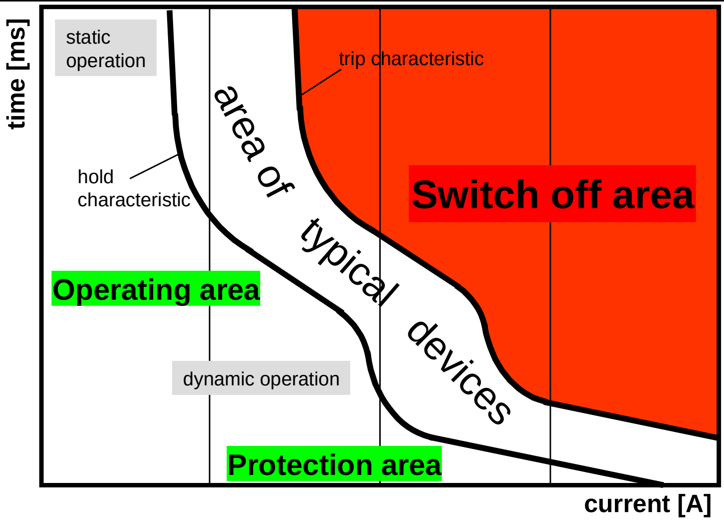


Figure 23 **Sketch of the hold- and trip- characteristic**

8.1 Effect of the type variability of R_{ON}

A variation in the ON-resistance results, for a given current, in a linear change in the power dissipation in the operating region (linear portion of the PROFET output characteristic). If a high R_{ON} is therefore present, the power dissipation is higher and the switch-off temperature is reached more rapidly. With increasing R_{ON}, the "minimum fusing current" is shifted in the direction of smaller currents. The onset of current limiting also occurs earlier at high R_{ON}, because the voltage threshold is reached at lower currents ($U_{DS} = I_{load} * R_{ON}$) (Fig.24). Beyond loads at which the PROFET immediately goes into current limiting mode, there is no longer any time when the linear portion of the output characteristic obtains. The influence of R_{ON} is no longer effective. As we shall see, R_{ON} together with the ambient temperature is the most powerful influencing factor of the It-characteristic in the operating range. However, as the forward resistance can be extremely well controlled during manufacturing, the deviation from the typical characteristic of the PROFET remains within acceptable limits.

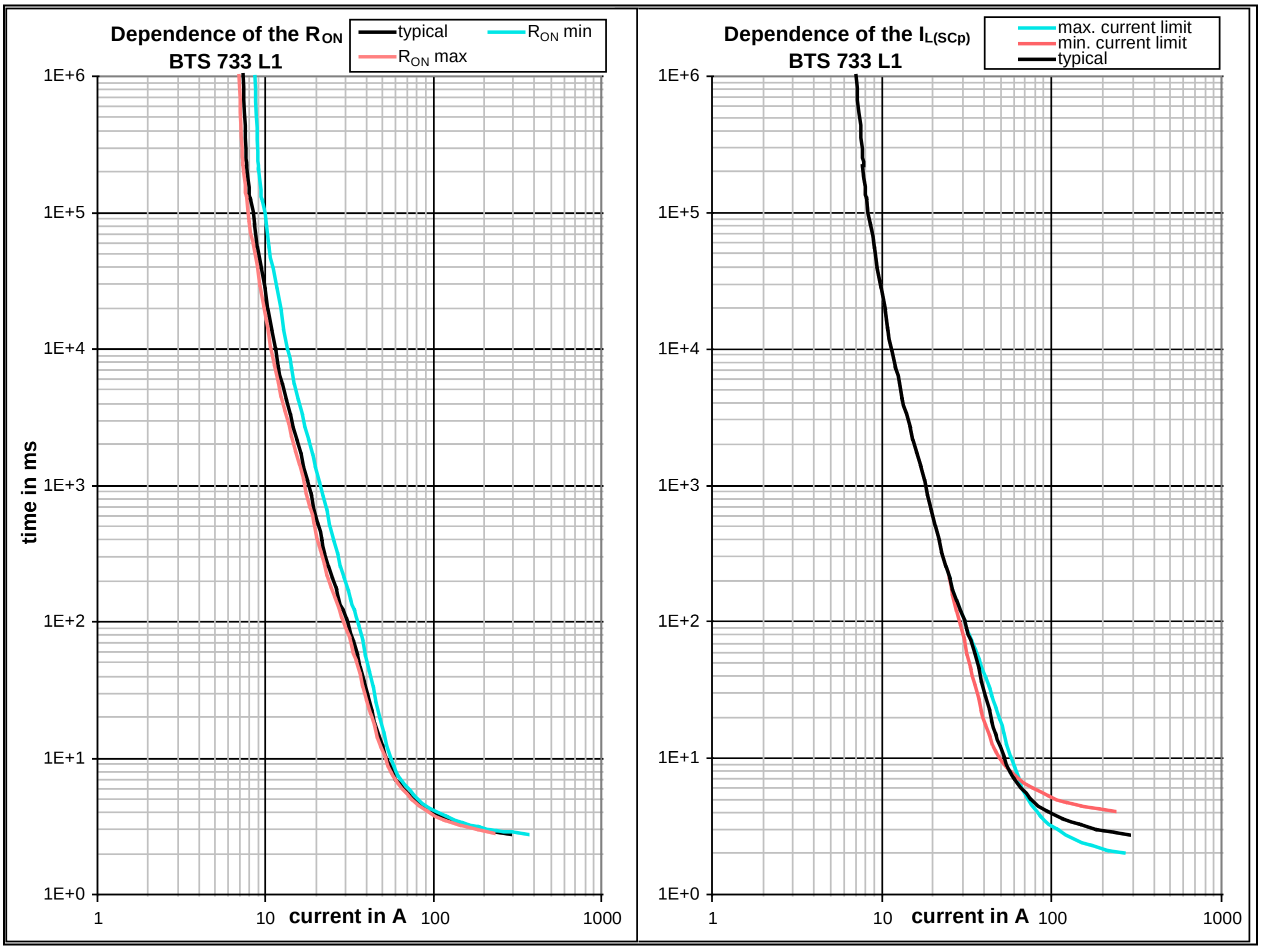


Figure 24 **dependence of the R_{ON} on the It-characteristic BTS 733L1** **dependence of the $I_{L(SCp)}$ on the It-characteristic BTS 733L1**

8.2 Effect of the $I_{L(SCp)}$ value

$I_{L(SC)}$ is dependent on the semiconductor temperature and the gate voltage U_{GS} of the power FET in the current limiting region. In the same way as the R_{ON} discussed above, the gate voltage and the threshold voltage are also subject to type variation within certain limits, as is therefore the short-circuit limiting current. The magnitude of $I_{L(SCp)}$ affects the It-characteristic in two ways. It firstly determines the transition from the operating region to the protection region - onset of current limiting and knee in the characteristic (to be observed for dimensioning) - , and secondly governs the power dissipation in the current limiting region and the tripping time in the event of short circuit (Fig. 24). A smaller $I_{L(SCp)}$ means early onset of current limiting, smaller switchable inrush currents and slower tripping in the event of a short circuit.

8.3 Effect of tripping temperature $T_{j\,max}$

A higher (lower) tripping temperature means that a higher (lower) amount of energy is necessary for the PROFET to heat up sufficiently strongly for it to trip. Similarly to the temperature dependency, there is a shift in the characteristic ⇒ less energy necessary, faster switch-off. In the data sheets a maximum semiconductor temperature of 150°C is guaranteed, and with the majority of PROFETs it is typically 175°C. Even this fault is so slight that it may be disregarded for the majority of requirements. The fanning out of the characteristics in the current limiting region again depends on the fictitious load current and the power dissipation which increases linearly with the drain-source voltage[3)] .

8.4 Characteristic evaluation

For the majority of applications, precise simulation or measurement on the fuse is not necessary. A "rerating" of the typical 25° characteristic to match the conditions currently obtaining is generally adequate. For fuses, the "thermal derating curves" for the ambient temperature (at $t = \infty$) or the minimum and maximum "opening times" for individual points on the current-time characteristic are specified. An estimation of this kind can likewise be performed using the PROFET datasheet information. Using the formula for the "minimum fusing current" (Formula 2), the ambient temperature can be taken into account for the steady-state case (very large times). As in the case of the temperature dependence described above, a different temperature in the operating area only results in a displacement of the characteristic. Another influence to be taken into account is the device variability of the ON-resistance. This can likewise be estimated via the "minimum fusing current" formula (Formula 2) and like the ambient temperature in the operating area only results in a displacement of the characteristic. For the estimation, these effects are no longer taken into account in the current limiting region, as the constant current through the PROFET means that only fictitious current valuesare used for the characteristic which are unable to be used for dimensioning.

[3)] see temperature dependence

The variations in the maximum short-circuit current, on the other hand, affect the transition from the operating to the protection region and shift the characteristic along the log. time axis in the limiting region. For the short circuit, this effect can be taken into account with a simple observation. If the energy required for heating is constant, the time is reduced by a factor of $(1.2)^2$ for a $I_{L(SCp)}$ higher by a factor of 1.2 (square relationship, Formula 3). With this information the hold characteristic and the trip characteristic can be determined using the "minimum fusing current" formula (Formula 2) for the operating temperature range.

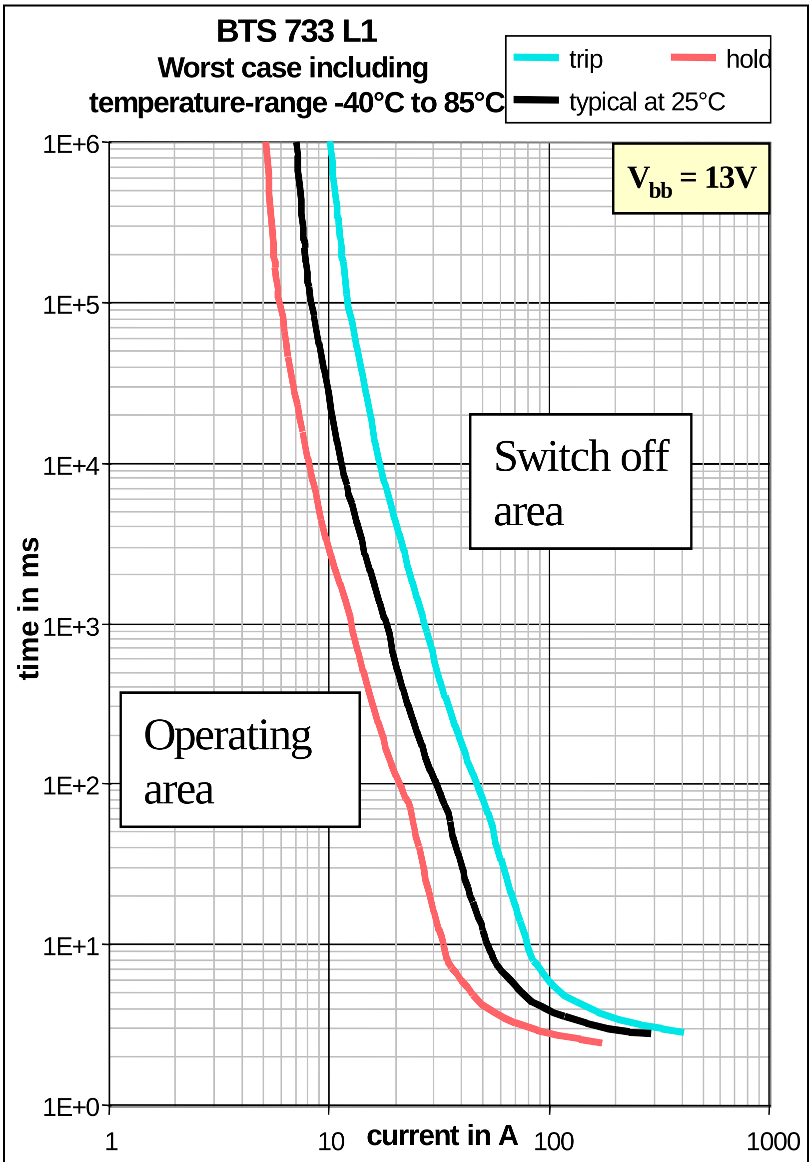


Figure 25 Combined worst case and temperature dependence of the BTS 733 L1

$$I_{\min.fuse} = \sqrt{\frac{T_{j\max} - T_A}{R_{thja} * R_{ONTj\max}}} \qquad \text{[Form.2]}$$

$$t_{\min;25°} = \frac{t_{typisch,25°} \cdot \left(I_{L(SCp),typisch,25°}\right)^2}{\left(I_{L(SCp),\max,25°}\right)^2} \qquad \text{[Form.3]}$$

Upper limit for operation is the hold characteristic at 85°C :

T_A= 85°C; T_{jmax}= 150°C; $R_{ONTjmax}$= $R_{ON\ max}$ at 150°
and minimum $I_{L(SCp)}$ at 150°⇒ I_{Hold} at 85°

Shift the typical characteristic along the log. current axis to this value

Variations in the current limiting region are still, as the current values here are only fictitious and operation in this region should be avoided in any case.

Fig.25 shows the combined influencing factors. If a sufficiently precise simulation is available, these curves can also be calculated.

9 BEHAVIOR OF CONVENTIONAL FUSES AT VARIOUS TEMPERATURES

For fuses and PROFETs, the ambient temperature has an effect on the tripping times. For small times (no power dissipation to the surroundings possible) the changed temperature swing to achieve the tripping temperature is the critical factor.

The amount of energy required to trip the fuse (I^2*R*t= energy), decreases with increasing ambient temperature (e.g. half the amount of heat energy means half the time for the same power).

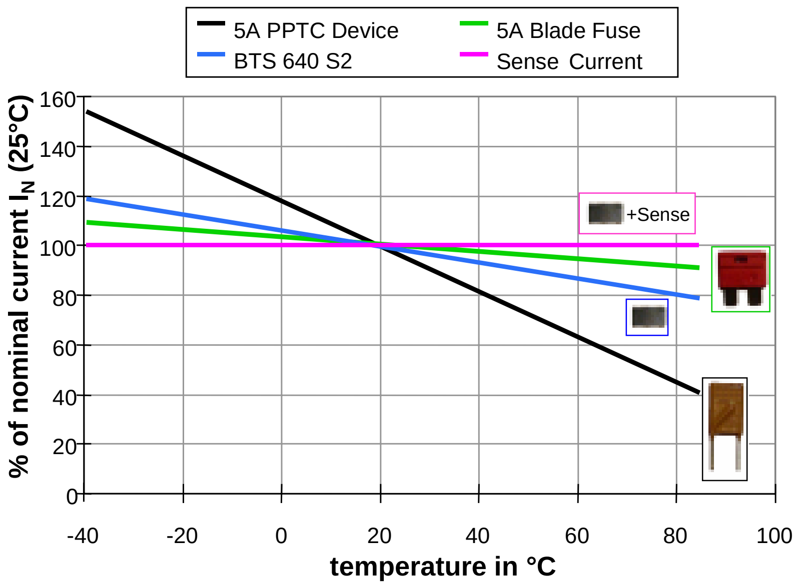


Figure 26 Static thermal derating curves

The large temperature swing of the blade fuse (>500°) means that for small times a change in the ambient temperature is less important than for the PROFET or the PTC polymeric fuses. A different way of looking at it is necessary for the steady-state region. Here the temperature difference between fuse and ambient, as well as the thermal resistance R_{th}, are important.

In general it may be said that a higher fuse operate temperature reduces the effect of the ambient temperature. Because of the low tripping temperature of 120°C, the hold current of the PTC polymeric fuse is heavily dependent on temperature. In the fuse datasheets, a "% of rated current" value is given for various temperature values. This allows the current values referred to 25°C to be recalculated for any ambient temperature (Fig.26).

Information of this kind can be obtained for the various PROFET types both for the case of thermal tripping and for electronic protection using the sense current. In the latter case the temperature effect is theoretically zero. (The nominal current I_{LNOM} guaranteed in the datasheets is already referred to an ambient temperature of 85°).

10 DIRECT COMPARISON OF THE THREE FUSE TYPES

This section provides a direct comparison of PROFET, PPTC fuse and blowout fuse. The following were used for the test:

- PROFET BTS 734 L1 (I_{LNOM} = 4.7A) in single channel mode
- 5A blade fuse and
- 5A PPTC device.

A 12 V car battery (400A 47Ah) was used as power supply.
The It-characteristics in Fig. 27 immediately indicate the main characteristics and differences.

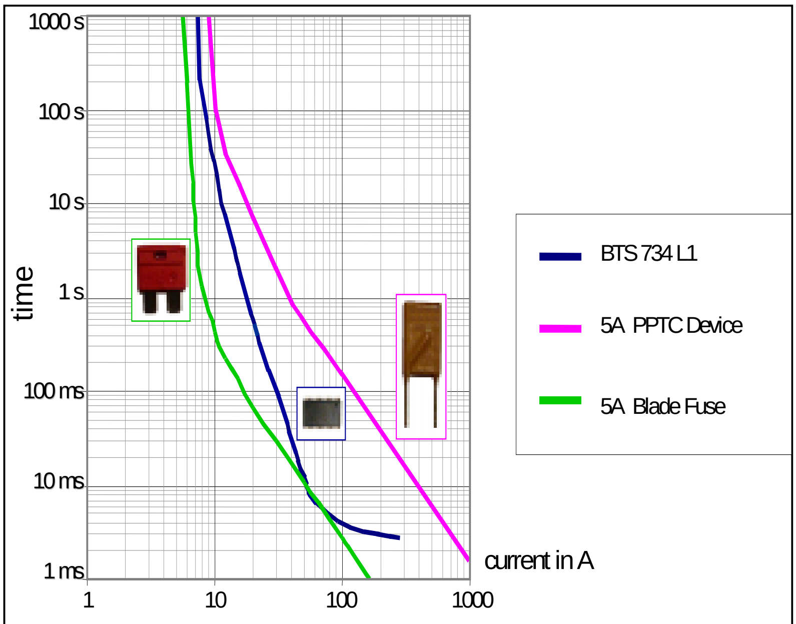


Figure 27 **comparison of three different types of 5A fuses**

The blade fuse is the fastest acting because of its low thermal capacitance in the operating region and has the shortest tripping time in the event of short circuit. The switching of loads with high inrush currents is therefore highly problematical, i.e. the fuse must normally be over-dimensioned. Other disadvantages are that the protection function can only be used once and the short-circuit current which can be very large due to the low resistance of the fuse (see Fig. 28 and Fig. 29).

Contrast this with the "resettable" PPTC fuse. The advantage of reusability is obtained at the expense of a high thermal capacitance (inertia). Inrush currents certainly present no problem for this fuse, but this is at the expense of long tripping times and a large amount of short-circuit energy. The greatest weakness is certainly that the circuit is not broken when the tripping temperature is reached (the polymeric PTC fuse is in fact basically a heat-dependent resistor). According to the "time to trip" specified, only a marked reduction in short-circuit current (max 40A!) initially occurs. With the RUE 500 used here, it takes approximately another 200ms for the current to exceed the rated current of 5A. This can hardly be described as a reliable way of interrupting the defective circuit. As long as the fault is present, a hold current flows to maintain the high resistance state. After the circuit has been interrupted, the PPTC fuse cools down and assumes a low-resistance state again, but requires considerably longer than a PROFET to do so (the PTC fuse cannot be reactivated until at least >10s, depending on the ambient temperature). The original low-value resistance is in some circumstances not achieved at all.
The PROFET combines the advantages of both protection concepts. Inertia in the operating region for **reliable switching of inrush currents plus short tripping times** and a reliable, complete breaking of the circuit in the event of a fault. In addition, the current is also actively limited even under full short-circuit conditions. The PROFET can be reset only a few ms after the occurrence or removal of the fault.

Fig. 28 shows a type 2 short-circuit test after loading with rated current and Fig. 29 a type 1 short-circuit test.

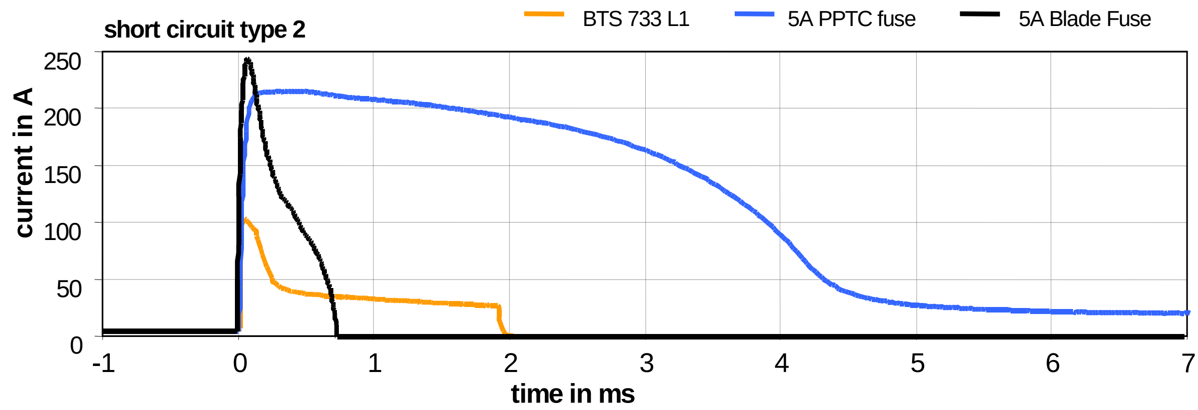


Figure 28

Type 2 short circuit		**BTS733L1**	**PPTC 5A**	**5A Blade Fuse**
Loading	I_L [A]	4.38	4.38	4.38
	U_{DS} [mV]	246	100	82
	R_{ON} [mΩ]	56	23	18
Short circuit	$I_{SC\ pulse}$ [A]	105	215	243
	t_{pulse} [ms]	0.22	4.5	0.7
	$I_{L(SCr)}$ [A]	28	latch function	latch function
	t_{trip} [ms]	**1.9**	**4.5**	**0.7**
Time until current falls below nominal	t_{Inom} [ms]	1.9	200	0.7
Continuous current short circuit	I_{SC} [A]	0	0.27	0
Restart time after short circuit	t_{rep} [ms]	< 50	latch function	latch function
Short circuit energy	E_{trip} [J]	0.82	5.6	0.81

In the case of the PROFET, the difference between type 1 and type 2 short circuits is the current spike. This is due to the fact that the switch is in the linear region of the output characteristic at the start of the short circuit (gate is fully driven). In the event of a fault the operating point moves along the characteristic until the voltage across the device has reached the voltage threshold for current limiting. It now takes some time until the gate of the field effect transistor is discharged to a lower voltage U_{GS} and the current is limited to values less than $I_{L(SCp)}$. However, the energy of this current spike is so low that it has no detrimental effect on PROFET and circuit. It is generally true of both tests that, because of active current limiting, the short-circuit power of the PROFET is considerably lower than that of the two other types of fuse. Current source and cabling are therefore protected much more effectively.

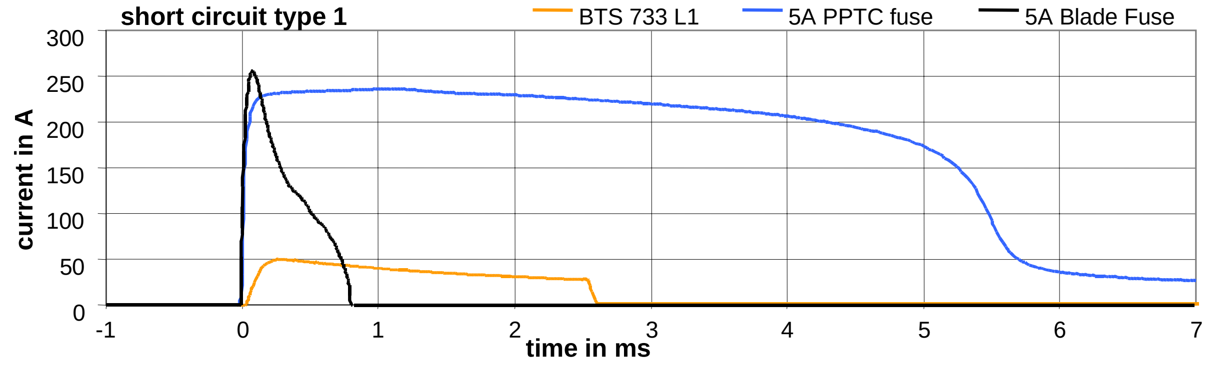


Figure 29

Type 1 short circuit		BTS 733	PPTC 5A	5A Blade Fuse
Short circuit	$I_{SCpulse}$ [A]	50	236	255
	t_{pulse} [ms]	-	5.5	0.7
	$I_{L(SCr)}$ [A]	28	latch function	latch function
	t_{trip} [ms]	**2.6**	**5.9**	**0.8**
Time until current falls below nominal	t_{Inom} [ms]	2.6	200	0.8
Continuous current short circuit	I_{SCh} [A]	0	0.27	0
Time to first auto-restart	t_{r1} [ms]	1.5	latch function	latch function
Restart time fault removal	t_{rrep} [ms]	40	>100ms	latch function

In the case of the type 1 short circuit shown in Fig. 29, there is no loading prior to the fault and therefore no heating of the fuses. The larger temperature swing necessary for tripping results in longer tripping times (than for type 2 short circuit). For this type of fault there is no current overshoot in the case of the PROFET.

11 CABLES

Particularly in automotive or industrial applications, the so-called wire harness occupies an important position among the network components to be protected. The great variety and in some cases considerable length and packing density of the cables used makes then particularly susceptible to persistent overloads (overheating). The maximum current carrying capacity of a cable depends on its resistance, type of insulation, material and ambient temperature[4)]. A cable including insulation generally consists of at least two materials with different thermal capacitance and thermal resistance.

The cable mass (and therefore also the thermal capacitance) and the surface (important for R_{th}) are much higher than those of the protecting blade fuse and the maximum cable temperature of approximately 150°C (determined by the plastic insulation) is very close to the operating temperature of the PROFET switch. The temperature response will therefore be more similar to that of the PROFET than that of the blowout fuse.

[4)] for precise formulae, see applications, cable protection

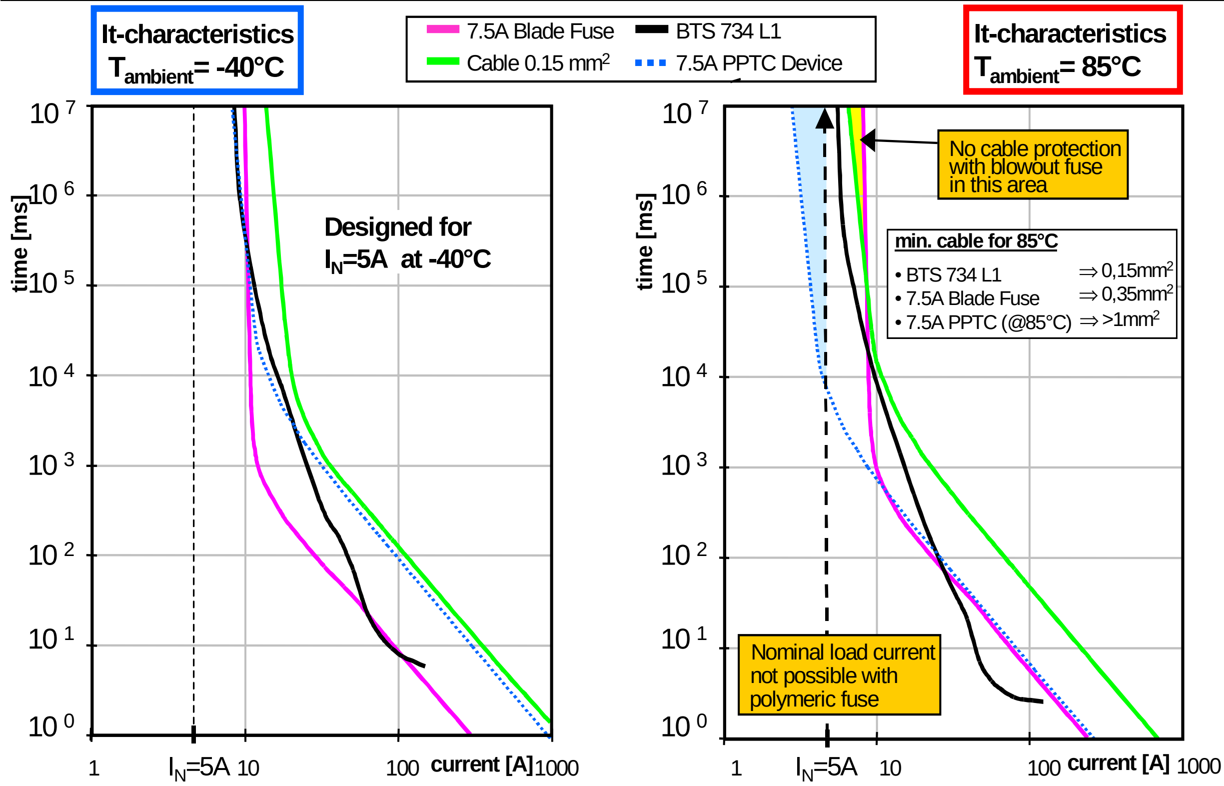


Figure 30 **Cable protection** **Comparison of different typical characteristics for different ambient temperatures**

If a polymeric PTC fuse is used, the high dependence of the fuse on the ambient temperature (±50% in the automotive temperature range) causes a number of dimensioning problems. Under normal conditions (cable "generously" dimensioned), adequate cable protection is always provided with a blowout (non-resettable) or PPTC fuse. In borderline cases, if the current-time characteristic of fuse, cable and the nominal application current are close together, there may be an overlap of the characteristics at certain ambient temperatures (fuse characteristic and cable characteristic are shifted by differing amounts). The cables, switches and fuses in Fig. 30 have been selected such that a 5A automotive application can just be operated. For purposes of illustration, no safety margin was provided. Because of its temperature dependence, the conventional blowout fuse is incapable of reliably protecting the $0.15mm^2$ cable against overload at high temperatures. In the case of PPTC fuses with their marked ambient temperature dependence, cable protection is provided but the application can no longer be operated at 85° (fuse trips even before the rated current is reached). In order to allow operation at 85°C, a 12A PPTC device (not available) would have to be used. This would in turn require a cable of at least 1mm^2 diameter, because a polymeric PTC fuse of this size would be very slow-blowing in the event of a short circuit (particularly at –40°C). The PROFET characteristic, on the other hand, is displaced approximately the same amount as the cable characteristic, so that no overlap occurs in the entire operating temperature range and protection is therefore effective (Fig.30). It is therefore apparent that even a 40mΩ switch with a current limiting threshold $I_{L(SCp)}$ ≈50A is capable of protecting a very thin cable (∅ =0.15mm^2).

12 FORMULAE FOR CALCULATING THE MAIN PARAMETERS

12.1 „Minimum fusing current“

$$\boxed{I_{\min.\,fuse} = \sqrt{\frac{T_{j\max} - T_A}{R_{thja} * R_{ONTj\max}}}}$$

[Form.2]

$T_{j\ max}$ Semiconductor temperature at which the PROFET trips
T_A Ambient temperature
$R_{th\ ja}$ Thermal resistance of junction-ambient of PROFET+ cooling conditions
$R_{ON\ Tjmax}$ Resistance of semiconductor at the tripping temperature

Using this formula it is also possible to calculate the semiconductor temperature for each steady-state current value.

12.2 ON-resistance of PROFET

The figures for $R_{ON,25°C}$ and $R_{ON,150°C}$ may be obtained from the data books

$$\boxed{R_{ON}(T) = \frac{1}{59375} \cdot \left((y_2 - y_1) \cdot T^2 + 300 \cdot (y_2 - y_1) \cdot T + 67500 \cdot y_1 - 8125 \cdot y_2 \right)}$$

[Form.4]

y1 ..R_{ON} at 25°C
y2 ..R_{ON} at 150°C
T Semiconductor temperature in °C

12.3 Limited current $I_{L(SC)}$

The $I_{L(SCp)}$ figures apply to drain-source voltages greater than $U_{DS} \approx 8V$. For simplification, the current is assumed to be independent of U_{DS} from the onset of current limiting onwards. The temperature dependence of $I_{L(SCp)}$ is linearly approximated to the values for 25°C and 150°C.

$$\boxed{I_{L(SCp)}(T) = k \cdot T + d} \text{ [Form.6]}$$

$$k = \frac{\Delta I_{L(SCp)}}{\Delta T} = \frac{I_{L(SCp)150°} - I_{L(SCp)25°}}{150° - 25°}$$

$$d = I_{L(SCp)25°} - \frac{25 \cdot \left(I_{L(SCp)150°} - I_{L(SCp)25°}\right)}{150° - 25°}$$

$I_{L(SCp)25°}$	Short-circuit pulse current at 25°C
$I_{L(SCp)150°}$	Short-circuit pulse current at 150°C
T	Semiconductor temperature in °C

The figures for $I_{L(SCp)}$ may also be obtained from the datasheet.

12.4 Power dissipation in the PROFET:

without current limiting $\boxed{P = I_L(T)^2 \cdot R_{ON}(T)}$ [Form.6]

with current limiting $\boxed{P = I_{L(SCp)}(T) \cdot \left(V_{bb} - R_{load} \cdot I_{L(SCp)}(T)\right)}$ [Form.7]

13 ADVANTAGES OF USING PROFET SWITCHES

As a result of the characteristics described above, there is much to recommend using the PROFET as a fuse.

• **Highside application**	Complete fault protection by direct installation at the positive voltage terminal
• **Resettable Fuse**	Fuse resets itself automatically or in response to an electronic signal
• **Active current limiting**	Avoidance of high pulse or short-circuit currents
• **Possibility of high inrush currents**	For lamps with full protection against both overload and short circuit
• **High quality and reliability**	
• **Integrated diagnostic functions**	Evaluation of cause of fault via status and sense signal
• **Controllability of the It-characteristic**	Using package type and R_{th}
• **Any current-time characteristic**	Implementation with Sense PROFET and µC
• **Temperature independence**	By means of electronic fuse unit with sense current
• **Dynamic protection**	By monitoring the rate of rise of current (dI/dt)
• **Adaptable to applications**	By selecting short circuit detection method (e.g. for lamps or ind. loads)
• **Cable protection**	Improved by similar temperature dependence over entire operating range
• **Mechanical superiority**	◊ Insensitive to mechanical stress ◊ Does not need to be accessibly installed ◊ No particular mounting position necessary ◊ Direct mounting without connector or ◊ Terminal contacts on PCB
• **Advantages compared with PTC polymeric fuses**	◊ Lower temperature dependence ◊ Greater temperature handling capability ◊ No hold current ◊ Quicker blowing on short circuit ◊ Switchable ◊ More rapidly resettable ◊ Current limiting

The full capability of the PROFET is obtained when it is used as a combined fuse and semiconductor power switch. The following advantages are obtained in addition to the above:

• **Cost and material saving**	Replacement of switch and fuse by the PROFET
• **Low error probability**	Use of a single device
• **Lower voltage drop in operation**	Shorter cables No additional switching relay No mechanical holders
• **Low drive power**	Through integrated logic
• **TTL and CMOS compatibility**	
• **Possibility of pulse width modulation**	

13 POSSIBLE FAULTS AND HAZARDS

In order to be able to compare the hazard sources when using blowout fuses, polymeric PTC fuses and smart power switches (PROFETs), Fig. 31 shows five different fault scenarios which are summarized in the following table.

Fault 1: A hard short circuit is present at the fuse. Each fuse can handle this event, the blowout fuse must be replaced.
A short circuit does not result in destruction of a smart power switch. A protection risk could only arise with the semiconductor solution if the PROFET were destroyed in the event of a short circuit occurring. However, short circuit is a specified and tested operating state and does not result in destruction of the semiconductor. Only operation outside the specified values, such as overvoltage (see fault 5) and excessively high inductive quenching energies (see fault 3) will result in destruction, and this can be eliminated by correct application.

Fault 2: An overload is present; this case is to be treated in the same way as fault 1, the tripping times being somewhat longer due to the lower currents.

Fault 3: The switch is defective with low resistance or short-circuited. In both cases the load is connected (the rated current flows) and cannot be controlled, the fuse is inoperative. The blowout fuse would still be intact for blowing out (compare case 5)

Fault 4a: The fuse is destroyed with high resistance. As the switch and fuse are combined in a single element in the case of the power semiconductor, this failure does not arise with the semiconductor fuse and would already be taken into account in a possible ‘high-resistance switch’ fault. The semiconductor fuse has one fewer failure possibility here.

Fault 4b: The fuse is destroyed with low resistance or short-circuited. This fault should be treated in the same way as fault 4a

Fault 5: A double fault is present, short circuit of the fuse and simultaneous overvoltage. In the event of overvoltages greater than the active Zener voltage, the semiconductor switch may be destroyed and there is a risk of fire. The same applies to the blowout fuse. If the specified dielectric strength of e.g. 32V is exceeded, there is also a risk of fire here. This dual fault is

not generally taken into account because of its low probability.
If the overvoltage does not occur during short circuit but under rated load conditions, the semiconductor switch is not destroyed for some time (e.g. specified load dump resistance). If this time is exceeded, the switch may be destroyed either at high or low resistance. The high-resistance case is trivial, the low-resistance case is then equivalent to fault 3.

Fault 6: Replacement of a fuse under load or short circuit conditions (not shown graphically). This fault only exists for the blowout fuse. There is a risk of contact melting or fire due to arcing particularly at higher supply voltages of e.g. 42V.

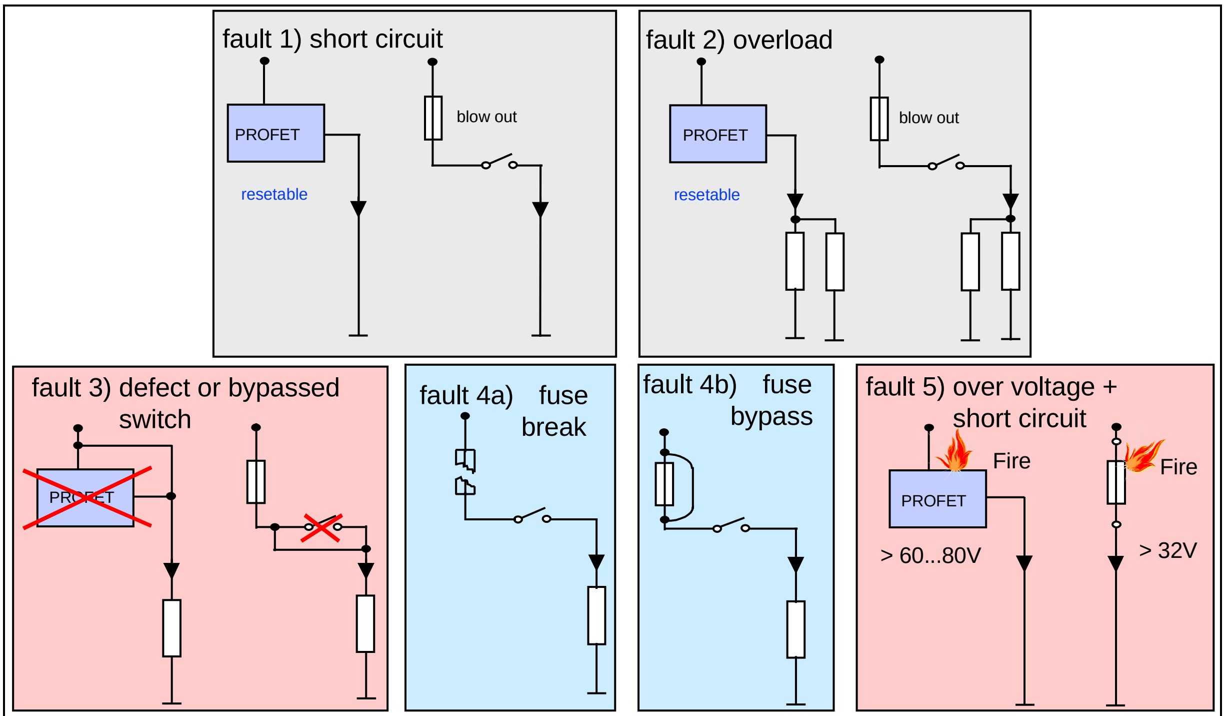
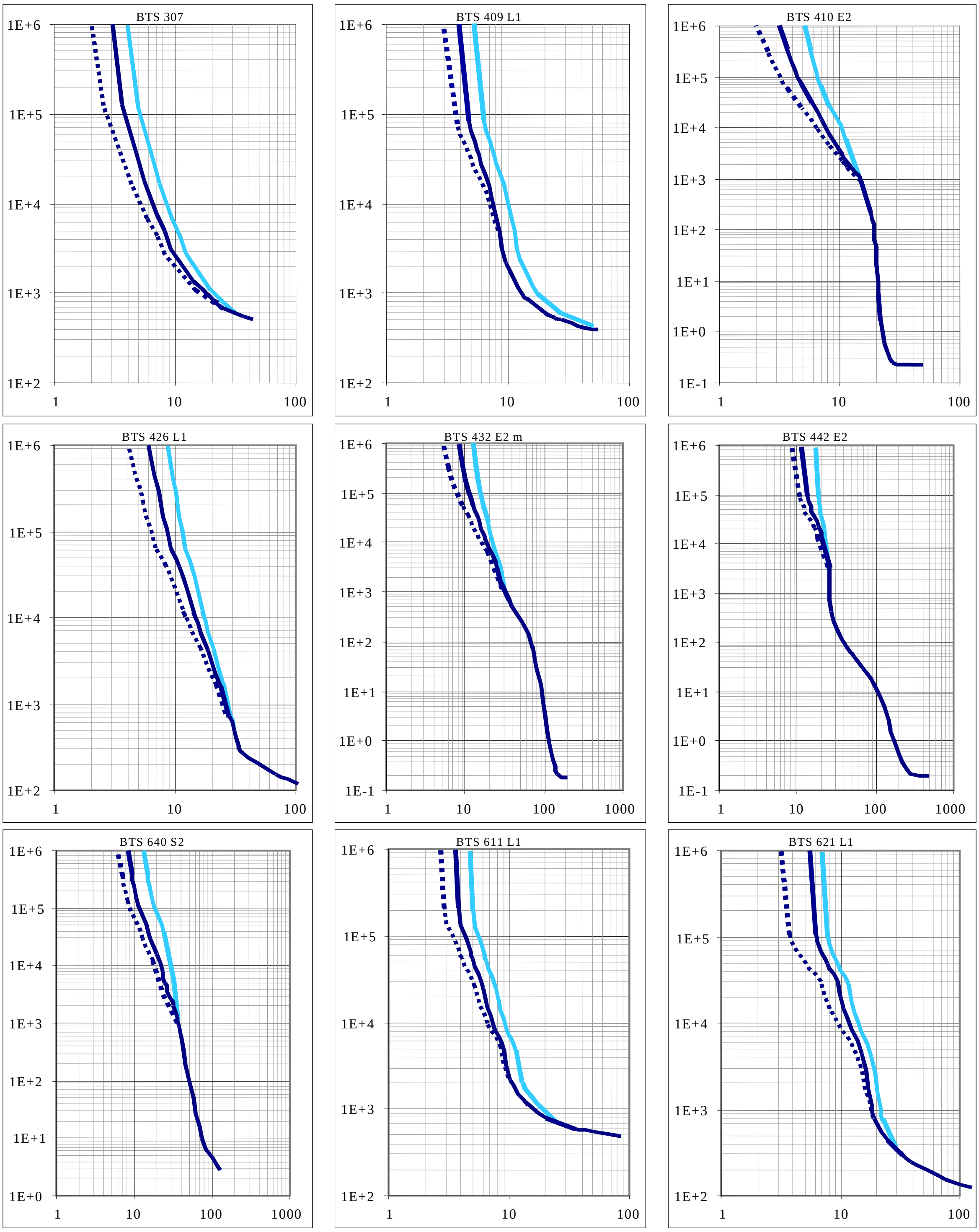


Figure 31 **Possible faults and hazards in automotive circuits**

	Fault scenario	Blowout fuse +switch	PPTC fuse +switch	PROFET
1	Short circuit	Fuse blows **Replacement necessary**	Fuse trips **No replacement necessary**	PROFET trips **No replacement necessary**
2	Overload	Fuse blows **Replacement necessary**	Fuse trips **No replacement necessary**	PROFET trips **No replacement necessary**
3	Defective short-circuited or bypassed switch	Protection function not initiated, Load permanent on	Protection function not initiated, Load permanent on	Protection function **not able to be initiated**, Load permanent on
4	Defective fuse			
	a) Break	No danger, Replacement necessary	No danger, Replacement necessary	**No fault source** because single device
	b) Bypass	No protection, **Danger**	No protection, **Danger**	**No fault source** because single device
5	Double fault: overvoltage and short circuit	Operation up to e.g. 32V, above this destruction and risk of fire	Specified up to 15V, 30V or 60V, response at higher voltages unknown	Operation up to active Zener clamping, above this **destruction and risk of fire**
6	Fuse replacement at active load or short-circuit	At high voltages (42V) **contact melting and arcing** possible	Not applicable	Not applicable

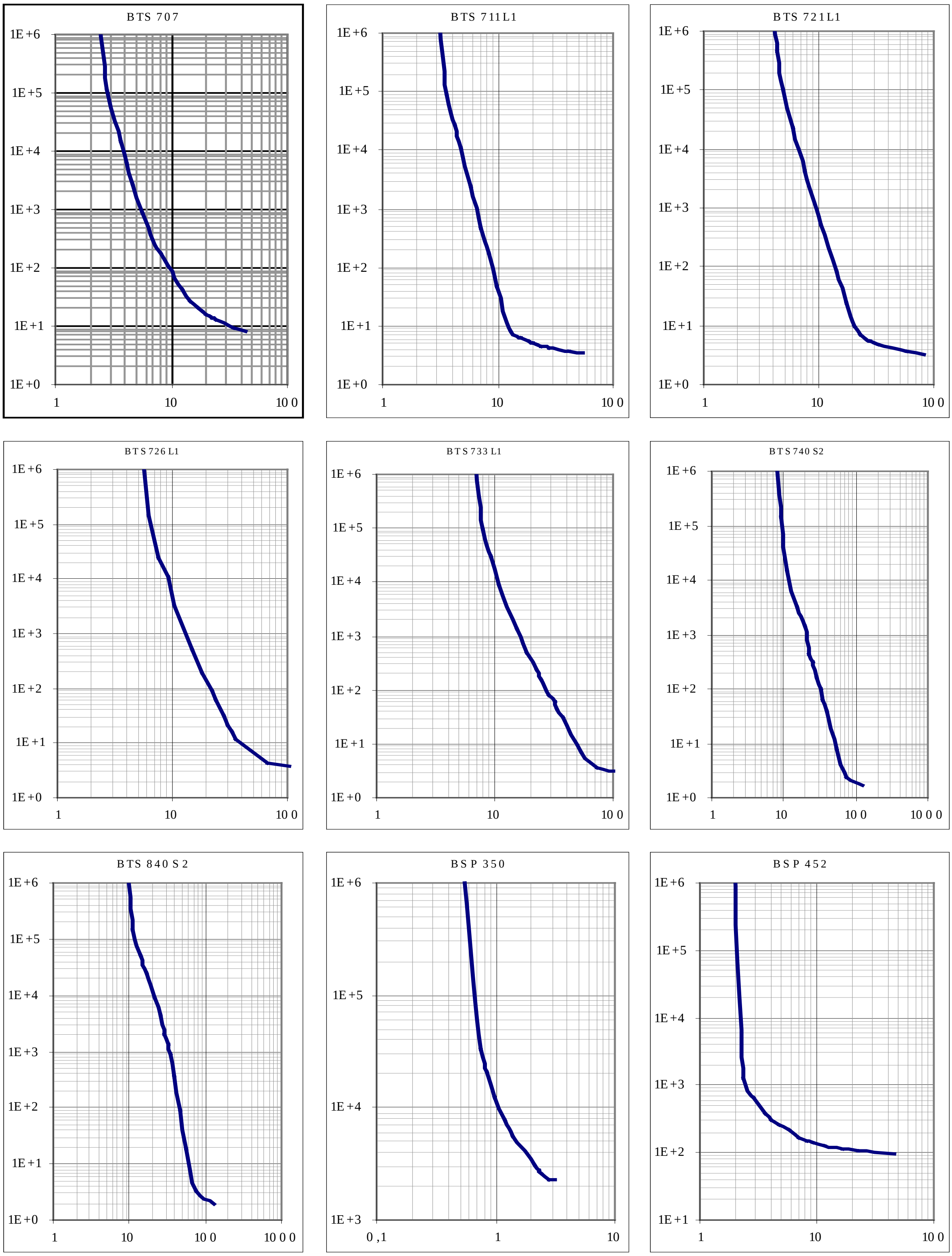
15 OVERVIEW OF It-CHARACTERISTICS OF SOME PROFET TYPES

X axes: Current in A **Y-axes: Time in ms**



dotted line:	TO220 SMD mounted on 50mm*50mm*1.5mm epoxy PCB FR4 without copper cooling area and blown air
dark line:	TO220 SMD mounted on 50mm*50mm*1.5mm epoxy PCB FR4 with 6 cm^2 copper cooling area without blown air
light line:	TO220 standard with 7.5 K/W heat sink without blown air

X axes: current in A **Y axes: Time in ms**



Mounting method: **P-DSO-20** mounted on 50mm*50mm*1.5mm epoxy PCB FR4 with 6 cm^2 copper cooling area without blown air
SOT 223 mounted on epoxy PCB 40mm*40mm*1.5mm with 6cm^2 copper cooling area without blown air

16 NOMINAL CURRENT AND FIELD OF APPLICATION OF VARIOUS PROFETs

All R_{th} specifications apply only to the following mounting techniques

A) SOT-223 Device on epoxy PCB 40mm*40mm*1.5mm with 6cm2 copper area without blown air

B) P-DSO-20 Device on 50mm*50mm*1.5mm epoxy PCB FR4 with 6 cm2 copper area(70µm thick) without blown air

C) TO 218 or TO 220 with heatsink (4.5 K/W)

D) TO 220 SMD Device on 50mm*50mm*1.5mm epoxy PCB FR4 with 6 cm2 copper area (70µm thick) without blown air

$T_{ambient}$ = 85°C and $T_{junction}$ < 150°C

Protection behavior:	thermal	Tripping initiated by temperature sensor
	sense	Sense current provides customized electronic tripping
	eSC	Internal electronic short-circuit protection

Name	Package	Test condition	Operation	R_{th} [K/W]	Nominal current $I_{L(NOM)}$	Fuse characteristic
Mini PROFET						
BSP 350	SOT-223	A		72	0.07 A	thermal
BSP 452	SOT-223	A		70	0.7 A	thermal
Sense PROFET						
BTS 640 S2	TO 220/7 SMD	D		33	5.7 A	thermal+sense
BTS 740 S2	P-DSO-20	B	1 channel	40	5.2 A	thermal+sense
			2 channel	33	1x 8,1A or 2x 4.1A	
1 channel PROFET						
BTS 307	TO 220/5 SMD	D		39	1.8 A	thermal
BTS 409 L1	TO 220/5 SMD	D		39	2.0 A	thermal
BTS 410 E2	TO 220/5 SMD	D		35	2.1 A	thermal+ eSC
BTS 426 L1	TO 220/5 SMD	D		34	4.0 A	thermal
BTS 432 E2	TO 220/5 SMD	D		33	5.3 A	thermal+ eSC
BTS 442 E2	TO 220/5 SMD	D		33	7.5 A	thermal+ eSC

2 channel PROFET						
BTS 611 L1	TO 220/7 SMD	D	1 channel	37	2.1 A	thermal
BTS 621 L1	TO 220/7 SMD	D	1 channel	35	3.0 A	thermal
BTS 707	P-DSO-20	B	1 channel	45	1.9 A	thermal
			2 channel	37	1x 2.8A or 2x 1.4A	
BTS 726 L1	P-DSO-20	B	1 channel	41	4.0 A	thermal
			2 channel	34	1x 6A or 2x 3A	
BTS 733 L1	P-DSO-20	B	1 channel	40	4.8 A	thermal
			2 channel	33	1x 7.3A or 2x 3.65A	
4 channel PROFET						
BTS 711 L1	P-DSO-20	B	1 channel	44	1.9 A	thermal
			2 channel	41	1x 2.8A or 2x 1.4A	
			4 channel	35	1x 4.4A or 4x 1.1A	
BTS 721 L1	P-DSO-20	B	1 channel	43	2.9 A	thermal
			2 channel	41	1x 4.0A or 2x 2.0A	
			4 channel	34	1x 6.3A or 4x 1.55A	
High current PROFET						
BTS 550 P	TO 218	C		5	1x 38.0 A	thermal+ sense
BTS 555 P	TO 218	C		5	1x 44.7 A	thermal+ sense
BTS 650 P	TO 220	C		5,5	1x 28.1 A	thermal+ sense

17 APPLICATIONS

17.1 Cable protection

In automotive applications, the wire harness constitutes a significant portion of the electrical system. It is therefore necessary to include the cables in the dimensioning considerations. In order to analyze cable protection, a current-time characteristic must be prepared for each cable used. This is generally in the form of a typical curve, but can be approximately calculated using a formula (Fig. 32). As already mentioned in the section "11 Cables", the specific resistance of the conductor material and the type of insulation are important for calculating the cable diameter. The biggest problem for the cables is not high transient currents (thermal capacitance of the cables generally large enough), but long-duration overloads resulting in gradual thermal destruction of the cable. The formulae given allow an approximate calculation of the It-characteristic of a cable.

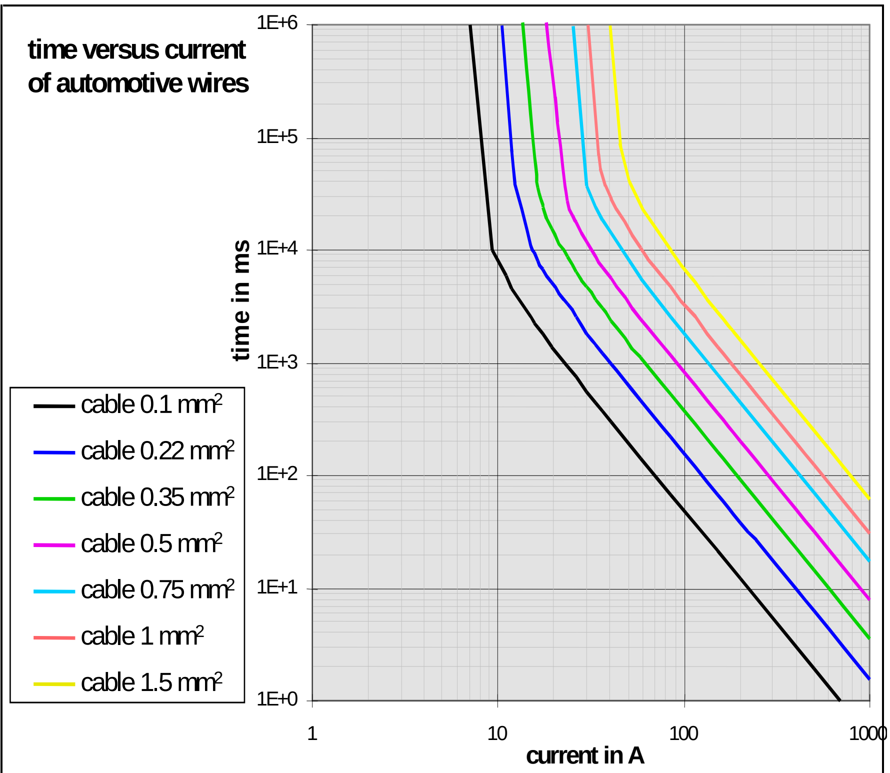


Figure 32 It-characteristics of cables with different cross sections

Cable core temperature =	T_c	$$A = \frac{\left(R_c \cdot \left(1 + 0.00393 \cdot \left(T_A - 20\right)\right)\right)^{1.275}}{354.8}$$ [Form. 8]
Ambient temp.=	T_a	
Current =	I	
Time =	t	
Time constant of cable =	τ	$$\tau = \frac{194.98}{R_c^{0.645}}$$
Cold resistance of cable = per meter at 20°C	R_c	
Temp. dep. cable resistance =	R_h	$$R_h = R_c \cdot \left(1 + 0.00393 \cdot \left(T_a - 20\right)\right)$$ [Form. 9]

$$T_c = T_a + (A\cdot I^2\cdot(1-e^{\frac{-t}{\tau}})) = T_a + \left[\frac{(R_c\cdot(1+0.0039\cdot(T_A-20)))^{1.275}}{354..8}\cdot I^2\cdot\left(1-e^{\frac{-t}{\tau}}\right)\right]$$

$$I(t) = \sqrt{\left[\frac{T_{insul.max}-T_A}{A*(1-e^{\frac{-t}{\tau}})}\right]}$$ [Form. 10]

To provide cable protection it is necessary that the characteristic of the cable does not intersect the trip characteristic of the fuse over the entire ambient temperature range specified. Here it is assumed that the ambient temperature is the same for cable and fuse. If cable and fuse are in areas of markedly differing temperature, the cable characteristic must be compared with the trip characteristic of the fuse at the lowest specified temperature. In this case the nominal current of the fuse and that of the cable are farther apart, because both have a relatively high temperature dependence. Fig. 33 shows the trip characteristics of a BTS 733 L1 (at -40°C and at 85°C) and two cables with different diameters at 85°C. This illustrates the large extent to which the "inverse ambient temperature assumption" influences the dimensioning of the PROFET or cable. It is advisable to consider whether this extreme case can occur at all and whether this assumption is necessary.

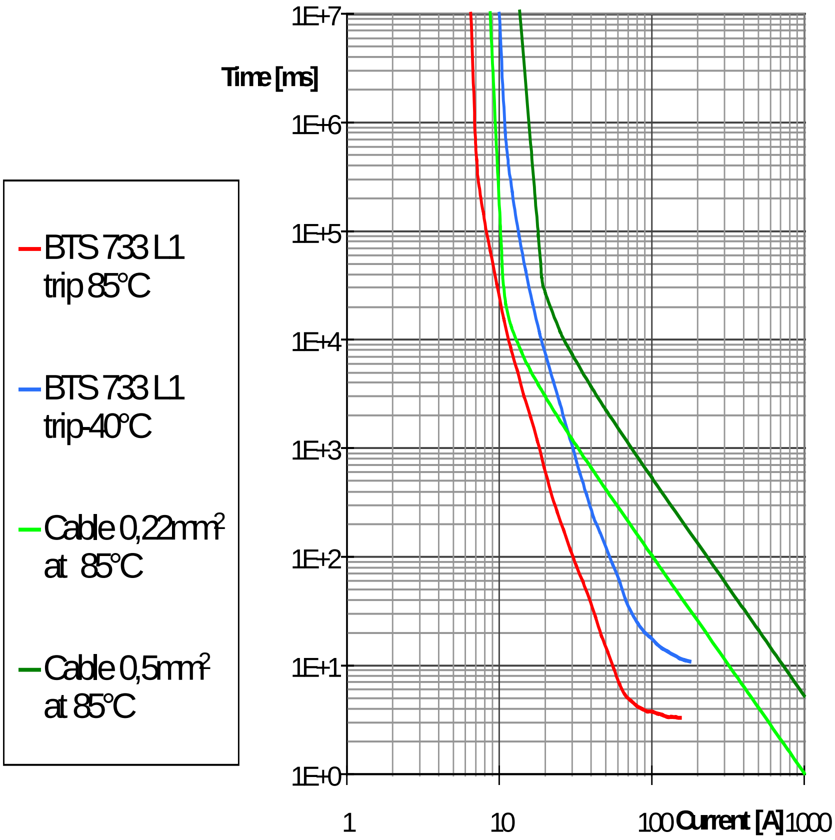


Figure 33 **Cable protection with two different ambient temperature assumptions BTS 733 L1**

Even in the event of a fault during operation (PROFET and cable are warmer than the surroundings due to the nominal load) cable protection is still provided. In the case of a conventional "blow out" fuse, this is not necessarily always the case.

17.2 Halogen lamp switches, e.g. dipped headlights

The PROFET is very widely used as a lamp switch. If it were possible to provide a protection function using the same PROFET, this would have a number of positive effects. With the PROFET, for example, selective protection is automatically implemented and the supply cable need no longer pass via the "fuse box" (thinning of the wire harness). With a Sense PROFET, fault detection is even possible when several lamps are switched using a single channel.

The main problem in this application is the positive temperature coefficient of the filament material of halogen lamps. In the cold state, the halogen lamp presents low resistance and causes a very high inrush current to flow. The current heats up the filament and its resistance increases exponentially with time to its nominal value (Fig.34). When dimensioning the PROFET as a fuse care must be taken to ensure that the inrush current of the halogen lamp does not yet result in activation of the protection function. As in the case of cable protection

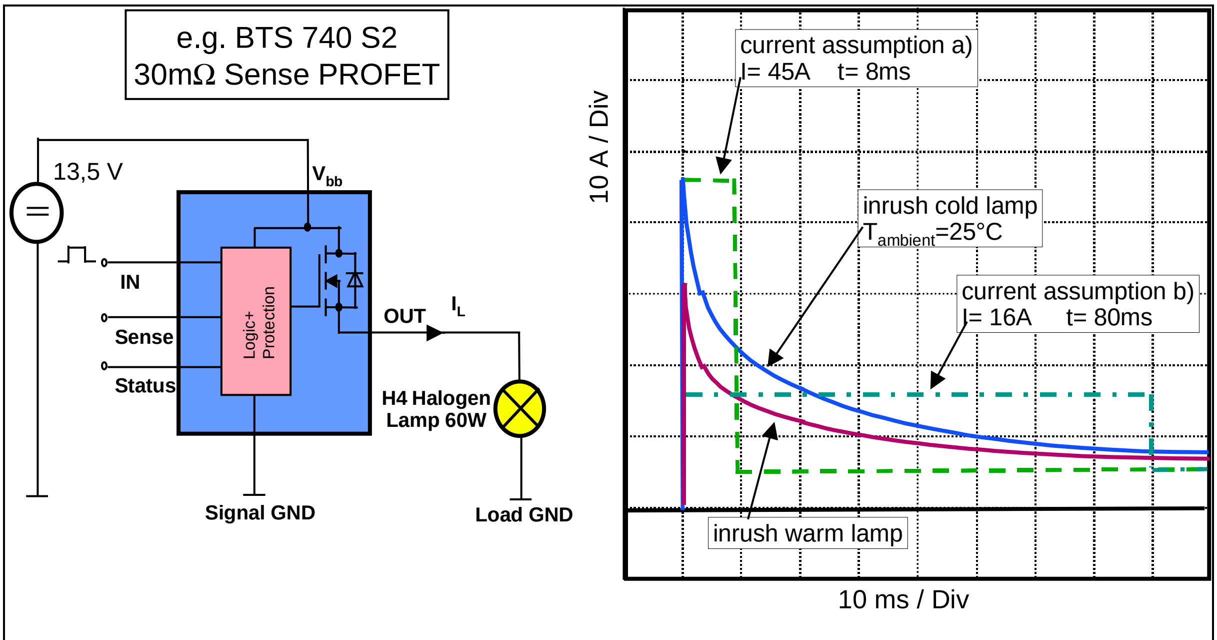


Figure 34 Application block diagram and H4 inrush characteristic

(Section 17.1) an assumption regarding the ambient temperature must again be made. In the worst case scenario the lamp is at -40°C (maximum inrush) and the PROFET at 85°C, an assumption which can only occur in real applications with physical separation of switch fuse and lamp (e.g. switch in hot engine compartment and lamp in cold housing).

17.2.1 Correct dimensioning of the switch (PROFET)

For this application, the same ambient temperature is specified for all components (T_{amb}=25°C). However, the complex current response at switch-on cannot be compared directly with the It-characteristic of a PROFET (or a fuse). One possibility would be a precise simulation (PROFET Simulator section), the second variant is a simplification of the inrush current response. Two simplifications will be considered:

a) The current is assumed to be constant, its magnitude corresponding to the maximum current value on the inrush current curve at 25°C. The duration of the pulse is calculated via the energy which is converted until the inrush current falls to 150% of the nominal current (standard value for heating).

b) Current constant, its magnitude being the root mean square of the inrush current until reduction to 150% of the nominal current, the pulse duration corresponding to the time until reduction to 150% of the nominal current. For this approach it is also necessary to check whether the maximum inrush current value initiates current limiting.

Specifications for dimensioning

12V H4 halogen lamp with 60W
V_{bb} = 13.5V $I_{duration}$= 5.6A
$T_{ambient}$ =25°C $I_{max\ 25°}$ =45A

a) $$E_{150\% I_N} = R_{ON} \int_0^{t(150\% I_N)} I^2 dt$$

E ≈15*R_{ON} [J]
t_{Imax} ≈ 8ms

b) I_{mean} = 16A;
t_{mean} = 80ms

These simplifications produce a point (current and time) in the double logarithmic It-representation (Fig.35). If this point is in the operating region, the PROFET is correctly dimensioned. Of course it is also necessary to check whether the PROFET will withstand continuous loading (5.6A). Repeated switch-on results in no problems as the lamp filament is still hot and the inrush current significantly smaller.

We can see that, for example, the BTS 740 L1 with 30mΩ in an SO package and without heat sink is capable of switching on an H4 lamp. The dimensioning of this application is, however, very tight, with the result that the PROFET has a large power dissipation even at nominal loading with I_{nom} = 5.6A and becomes correspondingly hot (device ΔT=70°C hotter than ambient). At the maximum ambient temperature of 85°C permissible in the automotive field, this is already close to the limit for the tripping temperature. For this application as halogen lamp switch a BTS 640 S2 SMD with 30mΩ, for example, is more suitable because of its smaller thermal resistance (ΔT is approx. 60°C at nominal current). Despite the heat sink, the protection behavior in the event of a fault is not significantly worse than for the BTS 740 S2.

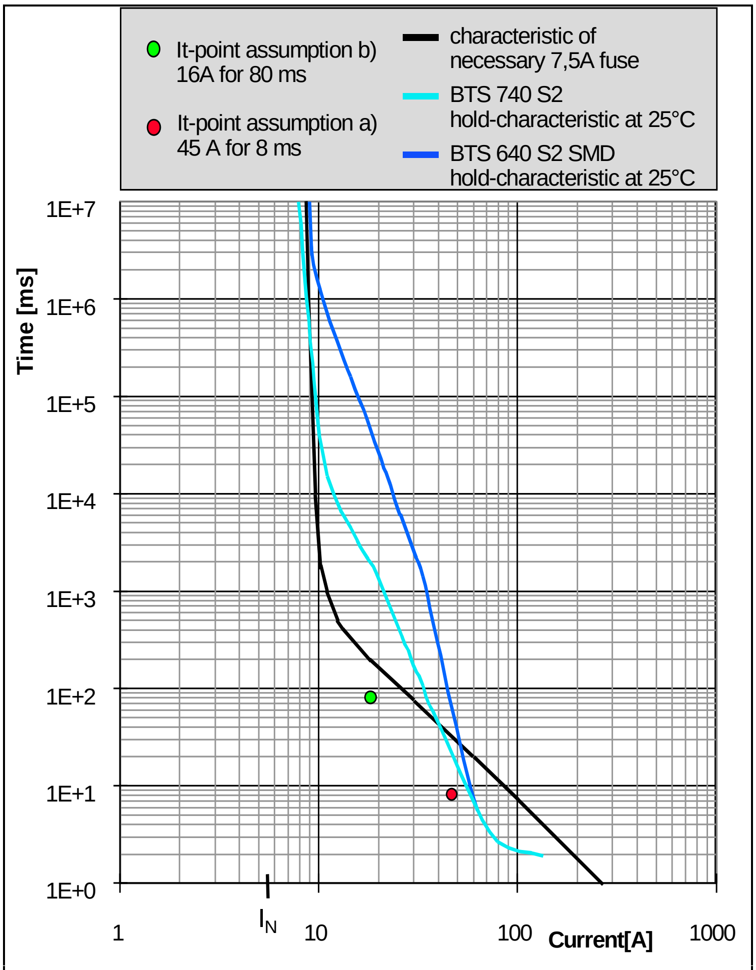


Figure 35 **comparison between BTS 733 L1 at 25°C and 7,5A blade fuse to turn on a 60W H4 Lamp**

If the application is not time-critical, the PROFET can also start up briefly in the current limiting region, provided it does not heat up to the point of tripping. However, it is preferable that switch-on occurs without the semiconductor going into current limiting, in order to avoid a significant thermal load (temperature change). If a soft start is required, this can be implemented with much less stress on the device using pulse width modulation of the PROFET.

17.2.2 Incorrect dimensioning of the PROFET

The same initial conditions apply as in Section 18.2.1.

If the dimensioning of an electronic switch only takes the nominal current into account and not the inrush currents of a lamp (or resistive-capacitive load generally), the following case occurs. Although the PROFET can handle the nominal current of the lamp with no problem, the low lamp resistance at switch-on causes active current limiting to occur. This results in two effects which are very detrimental to switching behavior:

a) More power dissipation occurs in the switch during current limiting
b) The current through the lamp is less and the filament needs longer to reach its operating temperature; the low-resistance load for the PROFET lasts considerably longer than with correct dimensioning.

As shown in Figs. 36 and 37, the PROFET starts in current limiting and heats up until the tripping temperature is reached. In the case of latching PROFET types or if the status signal is evaluated via a µC, tripping would now occur because of overload. The BTS 725L1 used here has an auto restart function in the event of cooling by a specific temperature value. The filament is now further heated with current pulses - only operates because the PROFET cools down quicker than the lamp, until its internal resistance has become so great that the PROFET is turned fully on (point 2) and the "normal" operating state can be achieved.

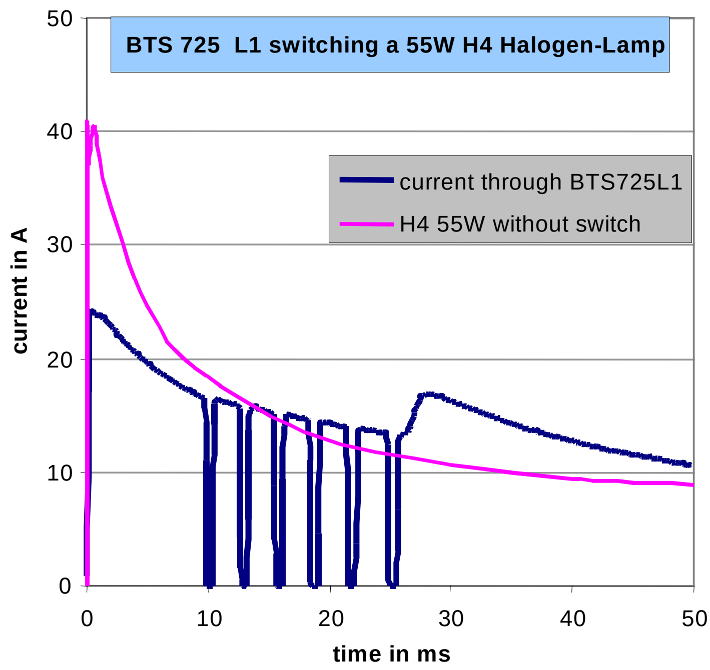


Figure 36 current limitation by the PROFET

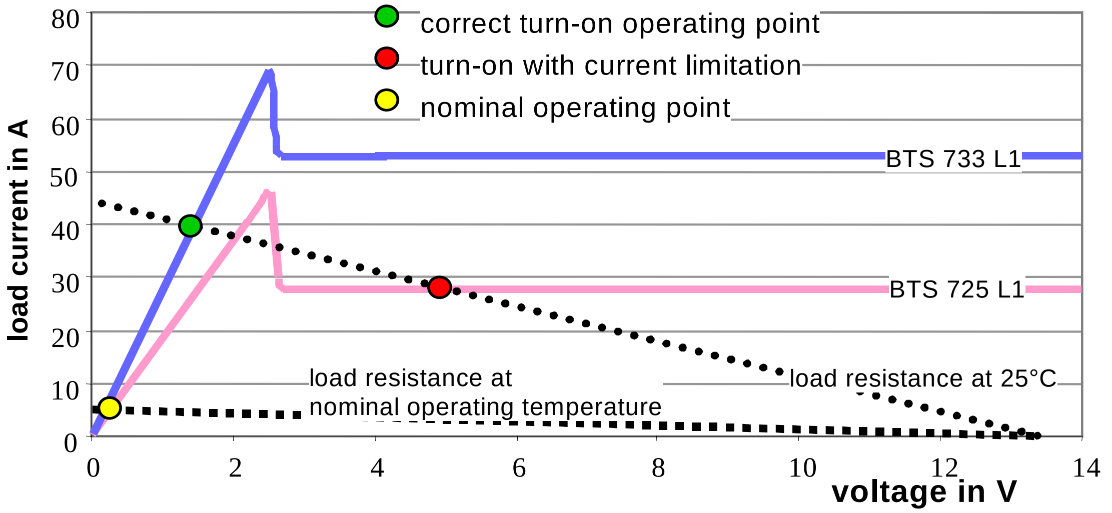


Figure 37 PROFET output and load characteristics

Inadequate dimensioning results in delayed lighting of the lamp (critical e.g. for brake lights) and greater thermal stress for the switch. Soft starting of the lamp can be better achieved via pulse width modulation.

Fig.37 shows why the BTS 725 L1 starts in current limiting. For optimum dimensioning, the minimum $I_{L(SCp)}$ of the PROFET switch must be greater than the maximum inrush current of the lamp (resistive-capacitive load).

17.3 Power converter for xenon lamps

A new innovative lamp is currently gaining ground in the automobile industry. The light is generated by an arc in an extremely small quartz glass cylinder instead of using an incandescent filament as in conventional lamps. It is therefore no longer possible to connect these lamps directly to the 12V supply. The power converter required generates not only the 20kV necessary for igniting the lamp but also the variable operating voltage of 67V - 112V (Fig.38) and provides various protection functions during operation. This special power converter now dictates the parameters for using PROFETs as switches and fuses.

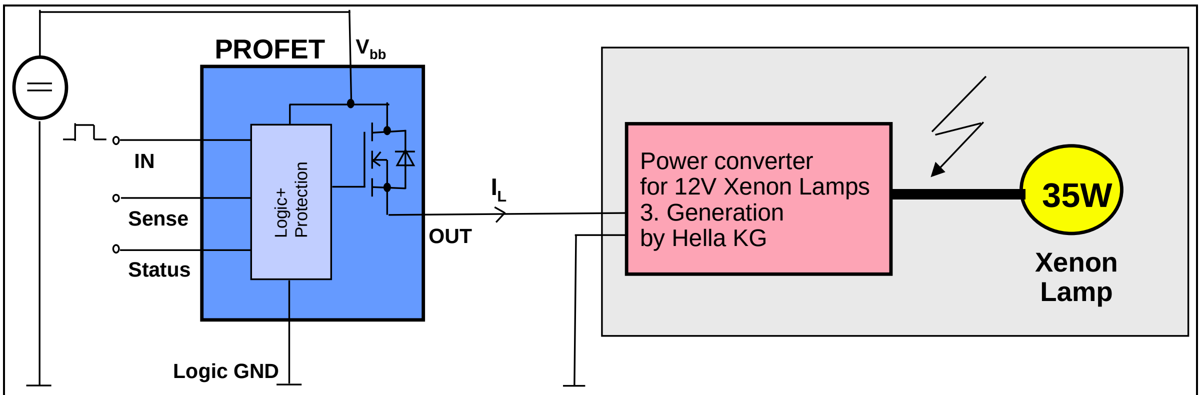


Figure 38 **Block diagram of the application**

Specifications from the power converter data sheet:

Nominal voltage:	13.2V
Lower turn-on:	9V
Operating voltage range:	9V to 16V
Electrical power consumption:	approx. 42W
Peak inrush current:	20A
Starting current:	≤ 17A for max. 10sec
Nominal current:	3.18A
Proposed fuse:	15A (16A)
Power dissipation	35W ± 1W at T_G=25°
No-load ignition voltage:	approx. 20kV max. 23kV
Lamp voltage range:	67V to 112V
Housing temperature range:	-40°C to 105°C

Because of the high starting current, a PROFET must be found which can both withstand the high inrush and also trip quickly enough in the event of a fault. With conventional fuses, this presents the dilemma of having to design the fuse for 15A, even though the nominal current is only 3.18 A. In the event of a fault with 100A, tripping does not occur until after 50ms, with the BTS 640 S2 by comparison after only 10 ms plus current limiting to currents <65A. In this application a BTS 733 L1 PROFET (already in use in the automobile industry) with 2 channels connected in parallel can be used. This chip is in a **P-DSO-20 package and requires no heat sink or heat slug**. !Silicon instead of heat sink! This means that an SMD device without heat sink is capable of supplying a starting current of approx. 15A over a comparatively long period.

For correct selection of the PROFET, the operating voltage range of 9V to 16V and the current data are relevant. To operate the power converter it is necessary that the PROFET never trips or begins to switch under the operating conditions specified.

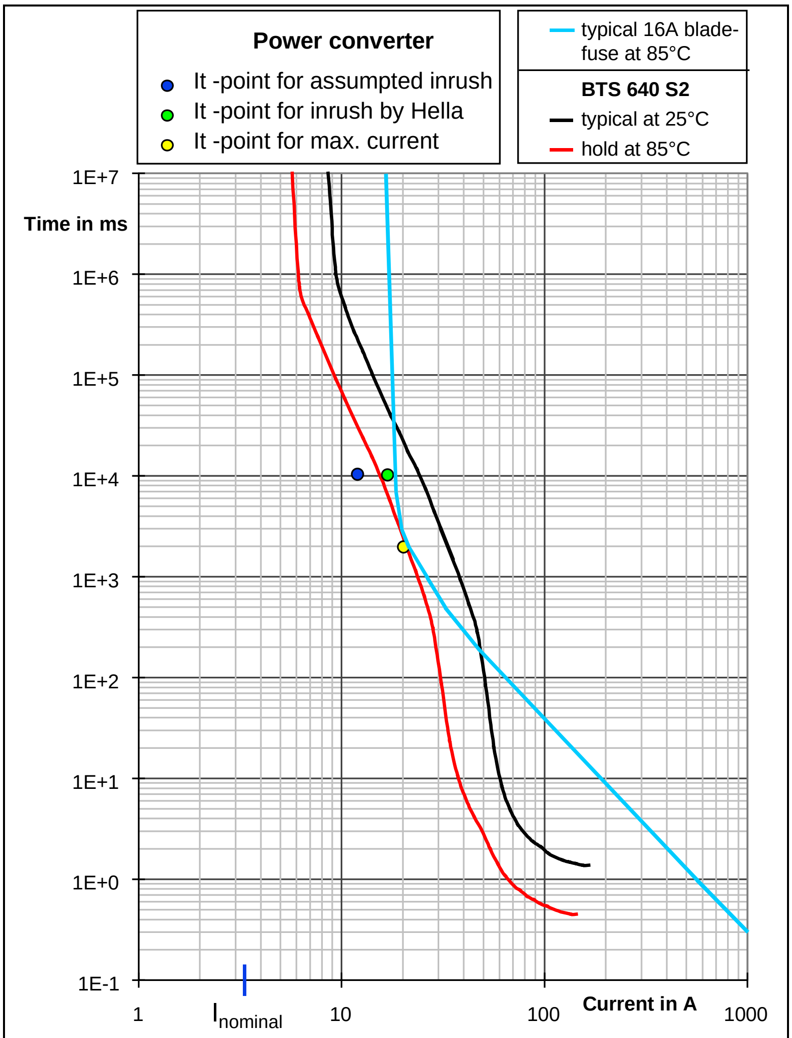


Figure 39 BTS 640 S2 hold-characteristic and characteristic of recommendet 16A blowout fuse at 85°C

Approach adopted:

1) Determining the hold characteristic of the PROFET for the maximum operating temperature (+85°)
2) If certain current-time values must not be exceeded, also determine the trip characteristic for the minimum operating temperature (-40°)
3) Does the nominal current of the power converter exceed the minimum fusing current?
4) How long may the peak current be present?
5) How long can the PROFET carry the maximum starting current? (Fig.39)

If we now consider the hold characteristic (+85°) e.g. of the BTS 640 S2, we can see that item 3) is easily fulfilled. The 3.18A nominal current of the power converter can be carried by the PROFET for any length of time. The peak inrush current (item 4) of 20A only causes tripping after 2 seconds and likewise presents no problem for the PROFET in question. The starting current (item 5) of the power converter is specified by the manufacturer at max. 17A for 10s. Under this assumption, the PROFET is incapable of switching on the Xenon light. However, if one considers the actual starting current of the power converter (at 25°C) it can be seen that it does not have the assumed rectangular waveform with 17A (Fig. 40). The curve has its maximum in the starting region at approx. 11A and then falls (exponentially) after 20s to a value of approx. 4A. After only 12s the current has fallen below 5A and is therefore already below the worst-case minimum fusing current of the PROFET for 85°C ambient temperature. Test measurements on the power converter have shown that the temperature dependence of the inrush current may be disregarded. In the case of repeated switch-on events, the inrush current is considerably lower and never results in tripping of the PROFET.

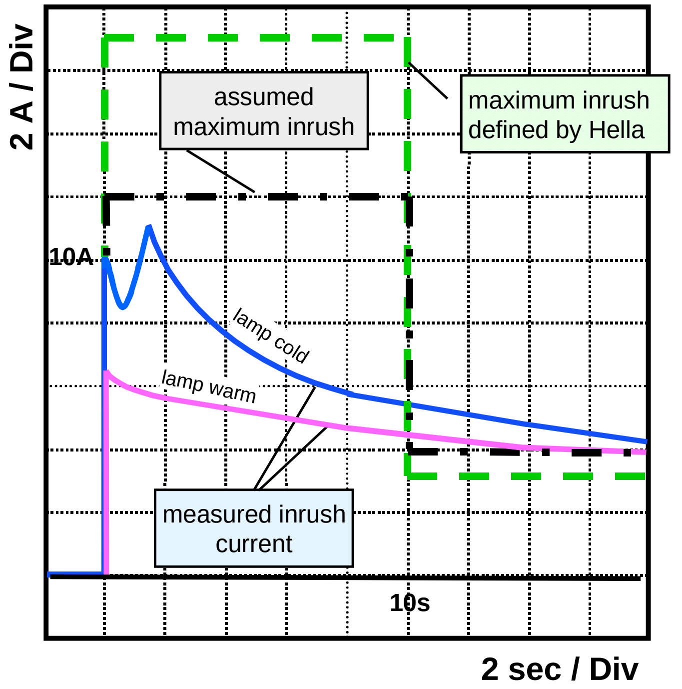


Figure 40 **Inrush current of the power converter**

A PROFET can be dimensioned much smaller, for this application; than a blowout fuse, without any resultant loss in reliability.

17.4 Switching of DC motors

Although actually an inductive load, DC motors have inrush currents similar to those of lamps (Fig. 41). At the switch-on instant, the self-induced voltage in the motor is zero and the current required for the starting torque is only limited by the resistance and inductance of the primary winding. As the speed increases, a voltage is induced inside the motor which counteracts the supply voltage applied and the current falls to a load-dependent nominal value. With load torques greater than the maximum load torque, the motor stalls and the current is again limited only by the winding resistance (stalled motor). After the motor is switched off, the energy stored in rotation and in the magnetic field of the windings must somehow be discharged. This can be effected either via a free-wheeling diode or the switch itself.

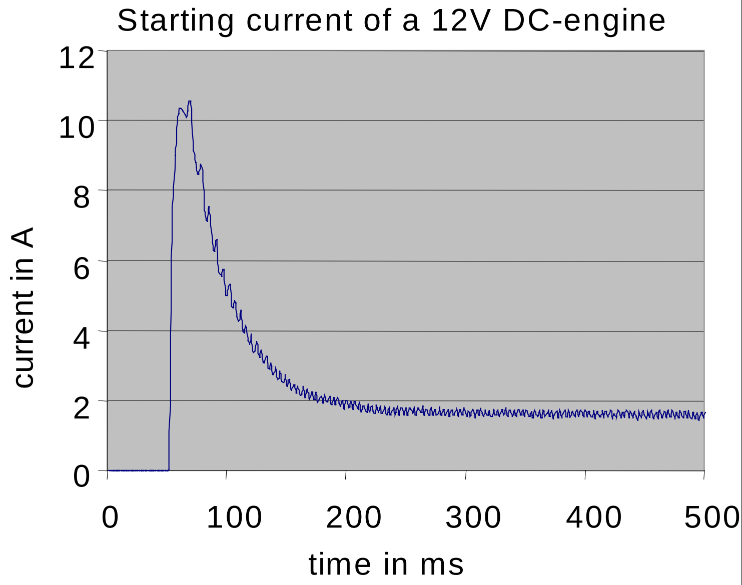


Figure 41

Type: 12V DC geared motor

Application: Sunroof actuator

Nominal current:	I_{Nmax}=4A
Torque:	6 - 8.5Nm
Operating voltage:	12V
Inductance:	710µH
Max. current drain:	I_{SC}=30A

(only with very cold motor)

The PROFET as a fuse must provide all the operating states and nevertheless offer adequate protection.

1. The starting currents must not result in active current limiting or thermal tripping
2. The nominal current must supportable for a defined period
3. If the motor has no over temperature protection of its own, the PROFET must trip in the event of overloads or stalling before damage is caused to the motor
4. The magnetic energy converted during tripping (also in the event of a fault) must not result in destruction of the PROFET

When using a BTS 726 L1 in single-channel mode, the following occurs (Fig.42):

Item 1: $I_{L(SCp)150°}$ of >12A is sufficient to reliably switch on the motor under all conditions ($I_{start}< I_{L(SCp)}$)

Item 2: Even at 85°C ambient temperature, the switch can still carry the maximum load current I_{Nmax}=4A for a further 2 minutes at least. In each case enough to open e.g. a sunroof.

Item 3: No more than 5ms after a low-resistance fault (I_{SC}) the PROFET trips (+ current limiting). If the motor stalls (I_{start}), the PROFET takes no more than one second to trip. In these short periods no damage will be caused to the copper windings due to overheating.

Item 4: The maximum possible current at tripping in the event of a fault is 24A ($I_{L(SCp)\ max.\ 150°C}$); with the motor inductance of 711 µH, this gives a maximum dissipation energy of 205 mJ. No problem for the BTS 725 L1 (500 mJ in single-channel mode).

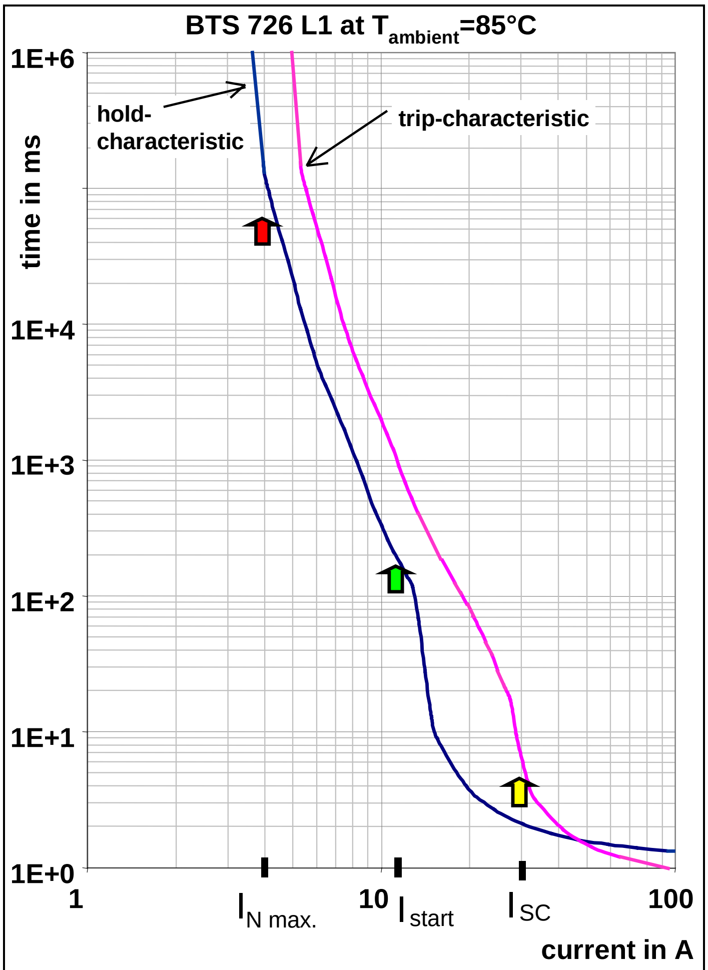


Figure 42 **hold and trip It-characteristic of the BTS 725 L1 at 85°C ambient temperature**

General comment:

The information describes the type of components and shall not be considered as assured characteristics.

[1] Littelfuse V.B.: Fuses for Automotive Applications, Utrecht The Netherlands, First published 1996.

[2] Raychem Corporation: Circuit Protection Databook, PolySwitch™ Resettable Fuses, February 1997 http://www.raychem.com

[3] OSRAM: Program of lights 97/98

[4] HELLA KG Hueck & Co: Technical information, 12V Xenon Power Converter 3. Generation, Lippstadt, July 1997

[5] SIEMENS AG: Smart Power Switches, Data Sheets 04.97
http://www.siemens.de/Semiconductor/products/36/363.htm

[6] Tietze, U.; Schenk, Ch.: Halbleiterschaltungstechnik, 10.Auflage, Springer-Verlag 1993

[7] Dr.Graf, A.; Koroncai, A.; Sommer P.; Dr.Tihanyi, J.; Dr.Blessing, A.: Sense Highside Switch in Smart Power Technology takes over Fuse Function, International Conference Vehicle Electronics, Baden-Baden, 12./13. September 1996,
http://www.siemens.de/Semiconductor/products/36/pdf/baba96a.pdf

[8] Dr.Xu, C.; Dr.März, M.; Sander, R.; Dr.Graf, A.: 4mΩ Smart-Power Highside Switch with Current Sense, 17. Conference 'Vehicle Electronics', Munich, 3.-4.June 1997,
http://www.siemens.de/Semiconductor/products/36/pdf/hdt_550a.pdf

[9] Dr. Graf, A.; Vogel, D.; Gantioler, J.; Dr.Klotz, F.: Intelligent Power Semiconductors for Future Automotive Electrical Systems, 17. Conference 'Vehicle Electronics', Munich, 3.-4.June 1997
http://www.siemens.de/Semiconductor/products/36/pdf/hdt972e.pdf