Behavioral modelling of PROFET™ devices for system-level simulation of mission profiles in automotive environment applications

Original
Behavioral modelling of PROFET™ devices for system-level simulation of mission profiles in automotive environment applications / Simonazzi, Marco; Santoro, Danilo; Bernardoni, Mirko; Delmonte, Nicola; Cova, Paolo; Menozzi, Roberto. - In: MICROELECTRONICS RELIABILITY. - ISSN 0026-2714. - 126:(2021). [10.1016/j.microrel.2021.114324]

Publisher:
Elsevier

Published
DOI:10.1016/j.microrel.2021.114324

Behavioral modeling of PROFET^{TM} devices for system-level simulation of mission profiles in automotive environment applications

Marco Simonazzi[a], Danilo Santoro[a], Mirko Bernardoni[b], Nicola Delmonte[a], Paolo Cova[a], Roberto Menozzi[a]

[a]Dipartimento di Ingegneria e Architettura, University of Parma, Italy
[b]Infineon Technologies Austria, Automotive Division, Villach, Austria

Abstract – In this work we present a system-simulation approach to model the behavior of PROFET^{TM} devices for automotive applications. Attention has been paid to the simulation speed, given the necessity to simulate long mission profiles in a short amount of time. PLECS has been chosen as a simulation tool, thanks to its system-level approach to the solution of electrical circuits and systems; the work shows how to implement the basic behavioral features described in the PROFET^{TM} datasheet, and how some typical electric features, which would normally be analyzed with a SPICE-like simulator, have been included.

1. Introduction

Robustness against different types of unexpected events such as electrical overloads and short-circuit events is a mandatory feature in power distribution systems for automotive applications. A short-circuit that is not interrupted fast enough could generate drastic overheating of cables, potentially leading to a permanent damage of harnesses and the involved electrical components, or even to a fire event in the worst-case scenario. Therefore, there is a need of using fast electronic protected switches, which can detect a hazardous condition and respond in quickly and reliably. Infineon offers products under the commercial name of PROFET^{TM} (protected FETs) that feature protections such as over-temperature and over-current, plus additional diagnostic features such as current sensing (k_{ILIS}).

These features must be accounted for in device models. System integrators need accurate models that can simulate the product's behavior, usually available as SPICE models. However, it is also necessary to investigate alternative approaches to the modelling of such products, especially when the focus is on the simulation of a mission profile, possibly with changing conditions during lifetime (e.g., ambient temperature, overload situations, etc.). Hence, a simplified modelling approach is required to keep the simulation time within reasonable bounds [1], [2].

In this work we chose PLECS [3] as a simulation tool, thanks to its simplified approach to the modelling of solid-state switches (in its simplest representation, an ideal switch); in particular, the features on which the work has focused are the implementation of the Zener clamping, a basic FSM (Finite State Machine) representing the behavior of the switch in different operating conditions, and the over-temperature/over-current protections, to capture the self-protected behavior of the product.

The presented system applications are relatively simple, but the modelling concept can be applied to more extensive and modular systems. Such a modelling approach is of particular importance during the early concept development phase of a product or a system, especially when physical prototypes are not available. Virtual prototyping is especially advantageous to evaluate new concepts for the product itself, or to check how the product would behave in more complex systems. In particular, early detection of pitfalls, block interdependences and topology optimization can be performed relying on behavioral models, even in the absence of experimental data. Behavioral modelling gives the user flexibility to replicate the relevant behavior of the system of which the considered product will be a part, while neglecting aspects that are not relevant to the problem at hand, thus making the model lean and quick to simulate. In this work, this approach is applied to a PROFET^{TM} device.

The work is structured as follows: after an introduction about the architecture of a typical PROFET^{TM}, we describe the modelling approach; finally, we demonstrate the use of this model in two applications (bulb lamp activation and short-circuit event).

2. Typical PROFET^{TM} features

A PROFET^{TM} is basically a high-side power device, consisting of an integrated power stage (or more, in case of multi-channel devices) and the logic necessary to operate it correctly. For instance, the device in [4] is a dual-channel product. Fig. 1 shows its block diagram. Since the focus is on the behavioral modelling of the product, certain features closely related to the electrical domain (e.g., Gate Control, Charge Pump) can be neglected in PLECS, where the gate is driven by a logic signal (high/low).

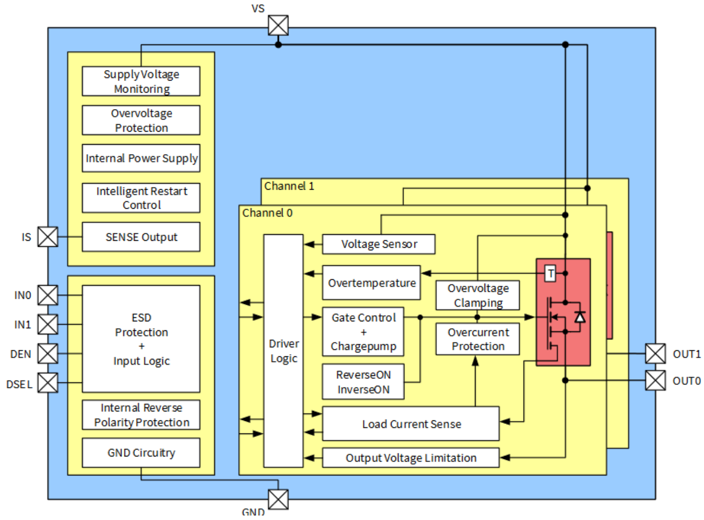

Fig. 1. Block diagram of a typical PROFET^{TM} device [4].

The mandatory features to be modeled are the following:

- Over-temperature protection, including basic thermal modelling of the thermal sensors;
- Over-current protection;
- Output voltage limitation (Zener clamping);
- Internal state diagram;
- Power Stage.

The next sections will describe in detail the simulation method used to cluster and model the above-mentioned features.

3. PROFET™ simulation model

The PROFET™ model is mainly composed by four subsystems: the input state machine (with the FSM), the power stage, the thermal model, and the fault-handling logic. The approach shown here is general, and it should be understood as an investigation of the modelling possibilities, not necessarily related to a particular product.

3.1 Input state machine model

Fig. 2 shows the input state machine with the FSM and the user input signal conditioning.

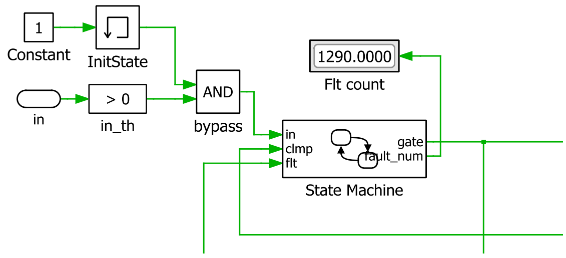

Fig. 2. PROFET™ PLECS model: input state machine subsystem.

The FSM requires three inputs: the user control signal (*in*, Fig. 2), the clamping condition signal (*clmp*, Fig. 2), and the fault condition signal (*flt*, Fig. 2). Outputs of the subsystem are the power stage gate control signal (*gate*, Fig. 2) and a fault condition counting number (*fault_num*, Fig. 2).

At the first simulation step, the FSM user input signal is kept at zero through a memory block, connected with the user control signal through an AND gate logic block. This improves convergence at the first simulation step.

Fig. 3 shows in detail the FSM, composed by four states: *Off* state, *On* state, *Fault* state and *Clamping* state.

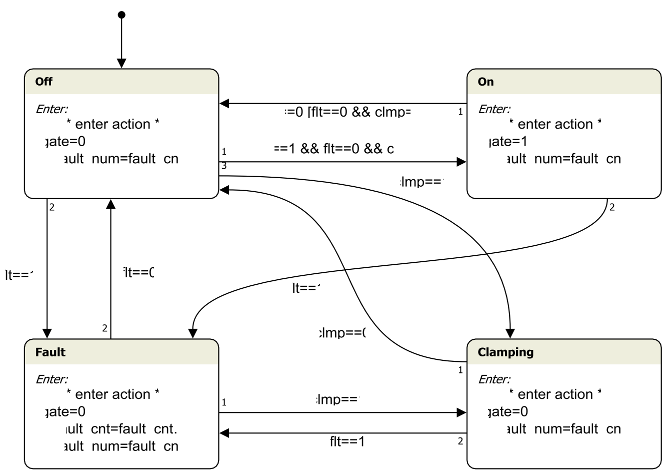

Fig. 3. PROFET™ PLECS model: FSM.

Starting from the *Off* state, when the user input "in" goes to 1 with no fault and no clamping signal condition, the FSM moves to the *On* state, setting the output "gate" to 1. In this state, two possible signal transitions can happen: the input could change from 1 to 0, still with no fault and no clamping conditions, therefore the FSM moves to the *Off* state. Otherwise, a fault signal transition from 0 to 1 could move the FSM to the fault state. In both cases, the gate output signal is 0. In both *Off* state and *Fault* state, when the clamping signal becomes 1 the FSM moves to the *Clamping* state.

To turn on the power stage, the FSM necessarily moves through the *Off* state. Therefore, latch or automatic restart behavior in case of fault can be modeled by changing the verification of the user input, which can be done through either transition detection or a condition verification. In Figure 3, the "in" signal is written between square brackets, meaning that the device will restart automatically as long as the signal is kept high. Therefore, the restart is defined by the external fault signal. After a fault condition vanishes, the fault signal can be kept high for a determined amount of time. This allows to restart the PROFET™ with a different rate in relation to the detected fault. Instead, if the "in" signal is checked outside the brackets, the input has to be lowered and then raised back to 1 for the *Off* to *On* transition, obtaining a latch behavior of the PROFET™.

3.2 Power stage model

Fig. 4 shows the power stage model. The model consists of an ideal switch (FET1) and an antiparallel Zener diode. This model considers the PROFET™ on-resistance, the body diode, and the clamping behavior. If the FET1 is turned off, the Zener diode allows the current discharge and fixes V_{DS} at the clamping voltage. When $I_{D1} > 0$, the clamping condition is verified by a comparator block and used as input signal for the FSM control.

The voltage between drain and ground is sensed as well to check for the undervoltage fault condition.

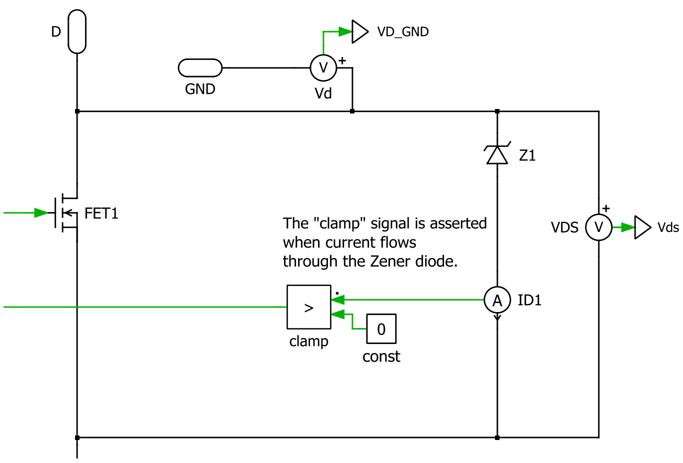

Fig. 4. PROFET™ PLECS model: power stage.

3.3 Thermal model

Fig. 5 shows the thermal networks and protections subsystem. The thermal networks block models three RC Forster thermal networks for the DMOS junction temperature estimation, the DMOS temperature sensor and the reference sensor over the whole PROFET™ package. Input of the thermal block is the instant power dissipation on the DMOS, given by $V_{DS} \cdot I_D$. The DMOS temperature sensor model output is connected to a relay block (Schmitt trigger) with thresholds of 150 °C and 180 °C (*Relay1*, Fig. 5), which generates an *OT* fault signal. Furthermore, the difference between the sense temperature and the reference temperature of the PROFET™ is checked with a hysteresis from 40 °C to 80 °C, generating a *dT* fault signal (*Relay2*, Fig. 5).

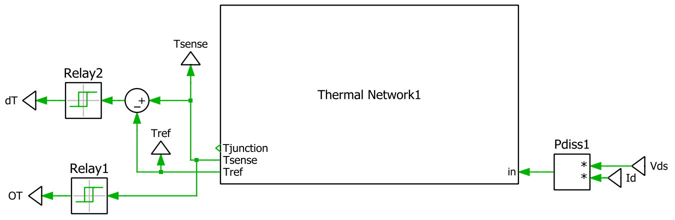

Fig. 5. PROFET™ PLECS model: thermal networks and protections.

3.4 Fault logic model

The temperature fault signals together with I_D and $V_{D\text{-}GND}$ are sent to the fault logic subsystem, as shown in Figure 6.

The fault logic subsystem considers all the different fault signals from the power stage and the thermal subsystem. The output of the OR logic gate is sent to the FSM (*flt*, Fig 2). I_D is compared with the ITRIP value and an overcurrent fault signal is generated if I_D > ITRIP. When the undervoltage fault is enabled, the $V_{D\text{-}GND}$ voltage is connected to a hysteresis block, and a fault signal is sent to the FSM when the voltage decreases under 3.1 V. For the overcurrent and undervoltage faults, a *monoflop* block of PLECS is used to maintain the fault condition for a certain amount of time after the condition is terminated.

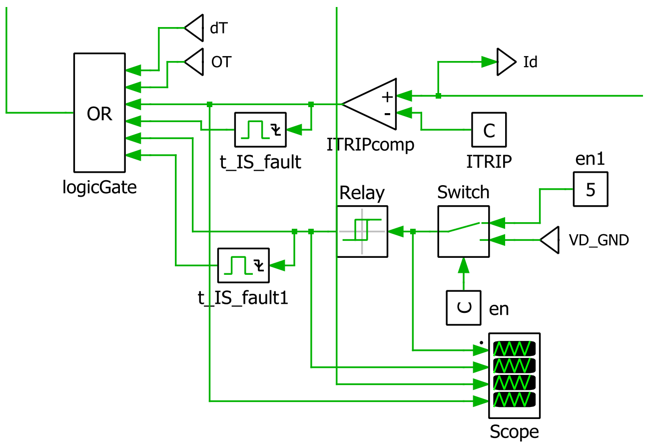

Fig. 6. PROFET™ PLECS model: fault logic subsystem.

4. DC wire and bulb lamp models

In order to test the device model, additional component models have been developed in the PLECS environment, namely, the behavior of DC distribution cables and, as a typical load, a heated filament bulb lamp.

4.1 DC automotive wire modelling

We considered a simple modeling approach for both the electrical and thermal behavior of a DC cable [5]. The cable contribution to the global system robustness cannot be neglected for many reasons, especially when fault events are taken into account. From the electrical and operating point-of-view, potentially dangerous behaviors are induced by voltage drops. Cable resistive and inductive effects are responsible for these drops. Furthermore, from a safety point-of-view, cable heating must be modeled. Overheating issues can be checked, and the cable resistance per-unit-length (*pul*) can be changed in relation to the chosen cable. Fig. 7 shows a possible PLECS implementation.

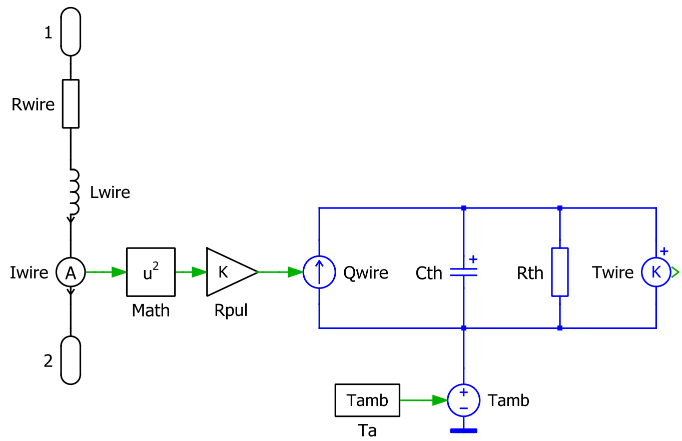

Fig. 7. PLECS implementation of a DC cable.

The electrical part of the model consists of an elementary R-L series circuit featuring *pul* values for the specific type of cable; *pul* values are multiplied by the particular cable length. The thermal behavior of the cable is modelled by a single stage RC Foster thermal network. The heat flow in W/m Q_{wire} is computed starting from the value of the current flowing in the cable according to equation (1):

$$Q_{wire} = R_{pul} * I_{wire}^2 \qquad (1)$$

4.2 Heated filament bulb lamp modelling

Legacy electromechanical components, such as relays and passive protections like fuses, can be replaced by PROFET™ devices for driving loads turn-on and turn-off. A typical load is represented by heated filament lamps [6]. This kind of light sources are characterized by a strong dependence between the electrical and the thermal behavior. In particular, the filament equivalent resistance is related to its temperature by a positive coefficient.

The resulting behavior consists in high inrush currents at cold temperature (at turn-on), decreasing to the nominal rated value as the filament reaches the typical operating temperature of a few thousand Kelvin. The model presented in [7] has been chosen for the PLECS implementation. It consists of a thermal network with two thermal capacitances, as shown in Figure 8.

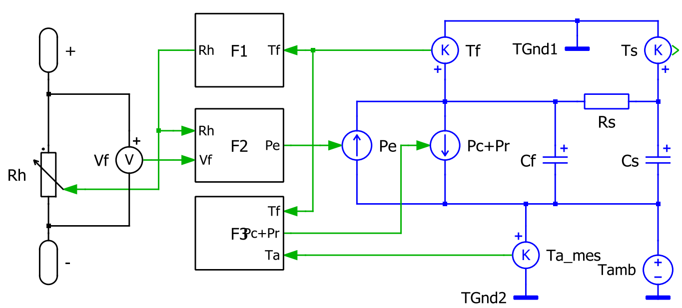

Fig. 8. Heated filament bulb lamp model implementation.

C_f represents the thermal capacitance of the filament, while C_s is the lamp support thermal capacitance. T_f and T_s represent the filament and lamp support absolute temperatures, respectively. There are three power contributions: the joule effect electric power contribution P_e, the convection (P_c) and radiation (P_r) power contributions. The joule effect power P_e is computed by the subsystem *F2* according to equation (2).

F2:
$$P_e = \frac{V_{in}^2}{R_h} \tag{2}$$

Convection and radiation are packed as a single negative source and computed through the empirical expression related to Fourier and Stefan-Boltzmann laws of equation (3).

F3:
$$P_c + P_r = a(T_f - T_a) + b\,T_f^4 \tag{3}$$

The coefficients, a and b, have been empirically extracted in [7] for an H4 automotive lamp.

A comprehensive expression for the thermal model is given by the system of equations (4).

$$\begin{cases} \frac{dT_f}{dT} = \frac{1}{C_f}\left[P_e - (P_c + P_r) - \frac{T_f - T_s}{R_s}\right] \\ \frac{dT_s}{dT} = \frac{T_f - T_s}{R_s C_s} \end{cases} \tag{4}$$

Finally, the electrical behavior is modelled by a variable resistor, the value of which is obtained by implementing equation (5) in subsystem *F1*:

F1:
$$R_h = R_c\left(\frac{T_f}{T_c}\right)^{1.2285} \tag{5}$$

R_h and T_f are the estimated resistance and temperature of the filament, while R_c is a resistance reference value measured at cold conditions, at the temperature T_c.

5. Simulation results and discussion

In this section we show simulation results involving the PROFET™ device behavioral model. The simulations are focused on typical application scenarios at both normal and fault operating conditions.

Fig. 9 shows the first simulation scenario. It consists of a PROFET™ driving a bulb lamp. Realistic conditions are modeled introducing two distribution cables: a 2-meter-long supply-side wire (20 mΩ, 2 µH) and a 10-meter-long load-side wire (100 mΩ, 10 µH).

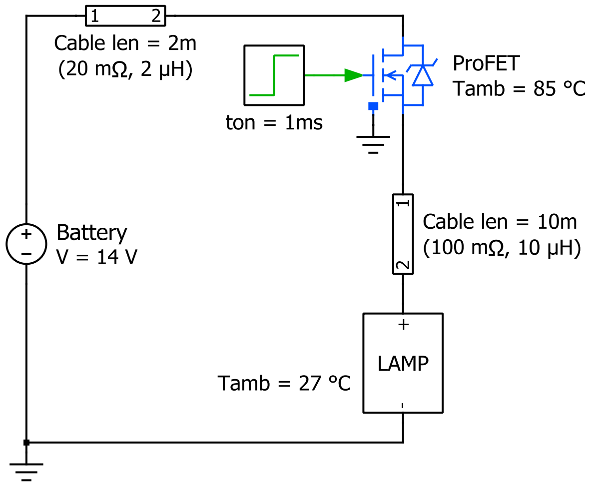

Fig. 9. First simulation scenario: a typical load driving application.

Fig. 10 shows simulation results of the turn-on behavior with a lamp load. Initially, the current quickly increases up to 45 A and the temperature T_{sense} on the PROFET™ device

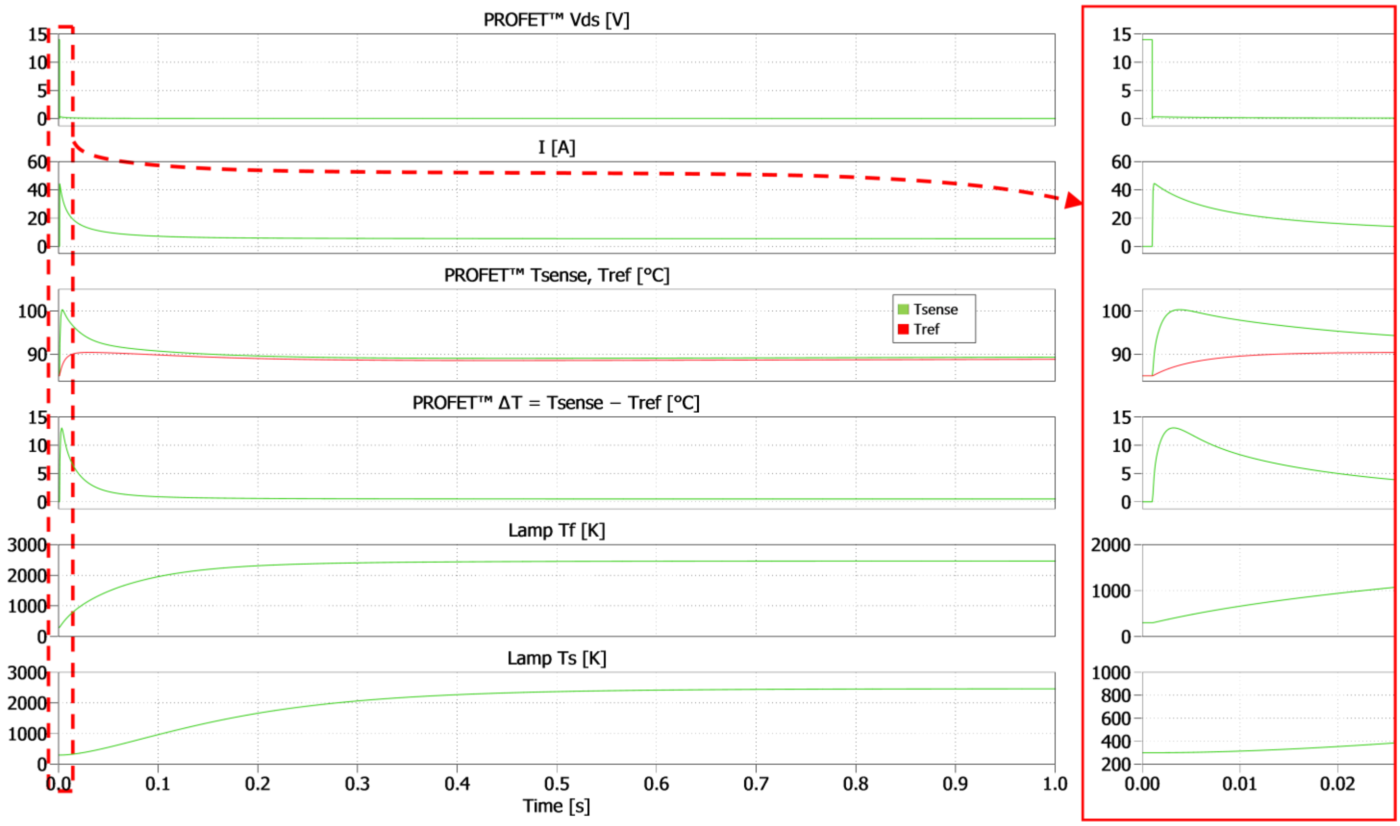

Fig. 10. Simulation results of a typical load application scenario.

increases due to the current inrush; T_{ref} increases, too, but with a slower time constant. Then, in about 200 ms, the current approaches its nominal value corresponding with the lamp filament steady-state temperature. In this scenario no faults are triggered.

The second scenario, shown in Fig. 11, consists of a short circuit event with the device automatic restart configuration.

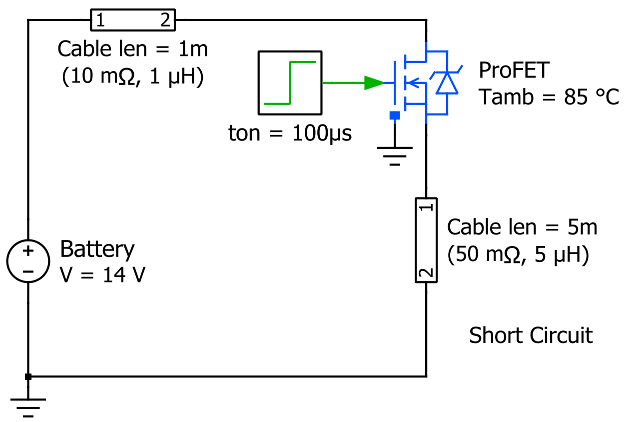

Fig. 11. Second simulation scenario: short circuit fault.

Simulation results are summarized in Fig. 12. Because of the short circuit, when the device is switched on, the current starts increasing and it quickly reaches the ITRIP threshold of 80 A (red line in Fig. 12). In this case the ITRIP protection signal is sent to the FSM, which forces the DMOS to switch off. The overvoltage due to the stray inductances of wires is handled by the PROFET^{TM} via Zener clamping. The self-heating induced by such fault event is higher than in normal operation, and the protections are designed to keep the device within its SOA. The device is then allowed to restart when the protections are internally released, since the faulty condition has disappeared. Due to the persistence of the short-circuit, at each restart the temperature T_{ref}, as well as T_{sense} peak value, keeps increasing until reaching a periodic behavior. This results in a progressive increase of the delay in restart time. In fact, the average temperature reached by the device is closer to the lower threshold, so the OT requires more time to exit from its fault condition.

The experimental validation can be performed by operating the system under different conditions (for instance over different ambient temperatures, power supply voltages, different loads, different cables), recording the waveforms of interest (in particular load current and voltage drops across the components in the system), and comparing them against the simulated ones. Due to the complexity of the system and the large number of parameters involved, least-square optimization will have to be used to tune some component models whenever parameter values are not known a priori or cannot be determined experimentally.

6. Conclusions

In this work we presented a system simulation approach for a PROFET^{TM} device developed in the PLECS environment. The device behavioral model implementation has been examined with specific attention to the main integrated

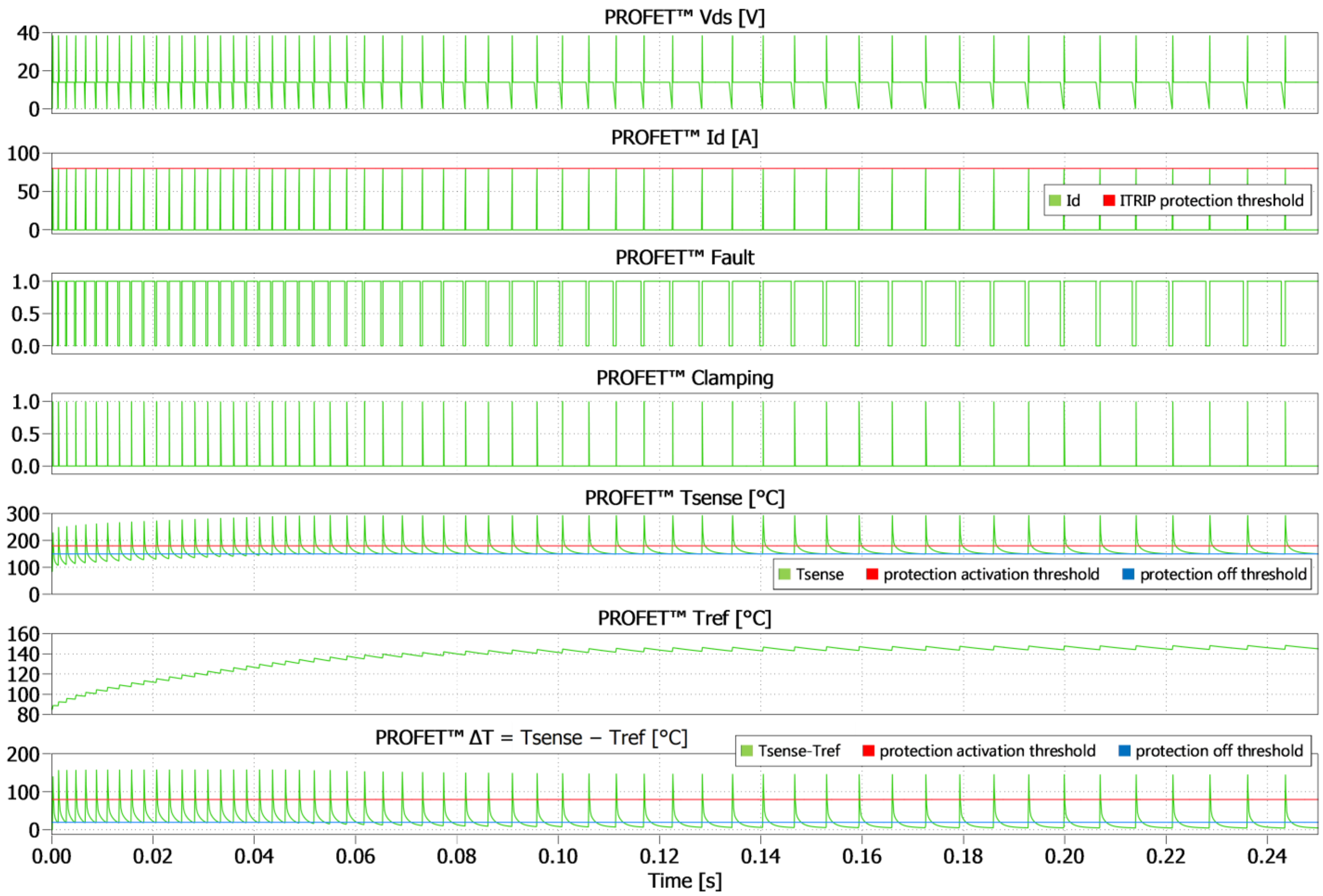

Fig. 12. Simulation results of a short circuit fault scenario with the applied protection thresholds.

protection systems: overcurrent (ITRIP), overtemperature (OT, dT), undervoltage. A finite-state machine-based approach is used to model the integrated logic operation. We also included thermal networks, which are necessary for overtemperature protections.

The model also features additional components to simulate the device behavior under realistic operating scenarios: in particular, DC cables and a heated filament bulb lamp. The thermal network of the DC cables is required for proper sizing of the cables themselves. The heated filament bulb lamp thermal network allows the determination of the internal bulb resistance, coupling thermal and electrical characteristics.

Our system level simulation results demonstrate that the developed modeling approach provides insightful understanding of the different interdependences between the power supply, the switching device and the load. In particular, the advantage of the approach lies in the fact that it simultaneously captures the main system dynamics (load driving, thermal response of the product and its logic behaviour, electrical interconnections), offering valuable inputs to improve understanding of the system’s behavior well before its physical prototyping. In this context, lack of experimental data is not uncommon, and it is often compensated by performing plausibility checks on the models themselves (e.g., the device switching off for currents above its threshold, the switch-on transient of the bulb being in the correct time range of ms – tens of ms, and so on), which will eventually result in typical operating patterns for the device. Consistency of the model with datasheet parameters is also a reality check that vouches for its use in the simulation of more complex systems and as a preliminary investigation tool during a concept development phase, where the benefits of such a compact, multi-physical behavioral model are great even in a situation of little or no supporting experimental data.

References

[1] C. Dolea and A. Mocanu, "Behavior Modelling Application for Automotive Industry", *Proc. ISC 2007*, p. 455.

[2] J. Schönberger "An Overview of Simulation Tools". In: F. Vasca, L. Iannelli "Dynamics and Control of Switched Electronic Systems. Advances in Industrial Control", Springer, London.

[3] J.H. Alimeling and W.P. Hammer, "PLECS-piece-wise linear electrical circuit simulation for Simulink", *Proc. PEDS'99* (**1**) 355.

[4] BTS7008-2EPA datasheet, *available online*.

[5] V. Balakrishnan, T. Dinh, H. Phan, D. V. Dao, and N. Nguyen, "A Generalized Analytical Model for Joule Heating of Segmented Wires." *ASME. J. Heat Transfer*. *July 2018*; 140 (7): 072001.

[6] S. Fraissé, "Smart High-Side Switches", Application Note, Infineon Technologies, 2010, *available online*

[7] S. Ben-Yaakov, et al., "A SPICE compatible behavioral electrical model of a heated tungsten filament", *Proc. APEC 2005* (**2**), 1079.