Modeling of Electrical Igniters of Vehicle Occupant Restraint Systems for EMC Simulations

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***Abstract*—Electrical igniters of vehicle occupant restraint systems can be activated by electrical pulses or high frequency currents caused by electromagnetic fields. In order not to perturb unintentional ignition of the propellant charge and a releasing of the Airbags or the seat belt tightener in the vehicle, the igniters are always qualified with special ESD and RF immunity tests in the development process. Protection concepts against ESD may not affect the safe function of the restraint systems in case of a vehicle crash. Simulations make a fast examination of several test concepts possible and allow checking of parametrical influences in detail. A thermal electrical model of an igniter was developed and verified on the basis of laboratory measurements. The calculation results show a good agreement with measurements. Different configurations were examined and fundamental relations were represented.**

I. INTRODUCTION

Modern electrical igniters of occupant restraint systems have a very high protection level against ESD impulses or continuous wave currents. A deeper understanding of the effect of interfering pulses on the electrical igniters is important to specify with high confidence safety margins and to improve the test methods. The investigation of the ignite mechanism and the examination of suitable protective circuits can be accomplished in test lab and by simulation. In the past there were different studies about EMC of airbag systems [1], [2] but not with the purpose of modeling the noise immunity.

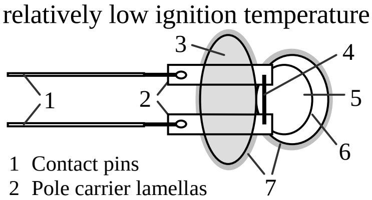
In this paper a suitable thermoelectric model of an igniter is presented. It can characterize the transient, the high frequency and the DC behavior. In order to receive the necessary ignition energy for the simulation model, first the minimum trigger levels of the igniters are determined by square-wave impulses of defined current amplitude and pulse width. Furthermore tests with ESD impulses and different discharge networks gave additional information. Finally the electrical igniters are investigated with ESD simulator models and models of RF-testing devices. The activation energy and the critical voltages at different ambient temperatures were determined with different discharge networks. The safety margin of typical RF-tests is determined.

II. MODELING OF ELECTRICAL IGNITERS FOR VEHICLE OCCUPANT RESTRAINT SYSTEMS

In the case of detection of a collision the ignition circuit of the airbag electronic control unit is activated. Therefore an electrical impulse is transferred to the integrated detonator [1], [3]. The electrical igniter consists of a pyrotechnic explosive material surrounding a resistance wire. By the current pulse the resistance wire heats up and initiates the sudden burn of the igniting mixture. The free energy activates the propellant of the gas generator [4] and the gases blows up the airbags or activates the seat belt tighteners. The currents through the resistive wire have to be considered as the source of ignition.

A. Structure of electrical igniters

The structure of an igniter is shown in Fig. 1. Between the pole carrier lamellas the resistance wire is fixed, which can consist e.g. of a nickel alloy [5]. The glow wire is surrounded by the inner explosive material. The inner explosive material detonates at a relatively low ignition temperature of 300 °C [6].



1 Contact pins
2 Pole carrier lamellas
3 Distance holder
4 Glow wire
5 Inner explosive material
6 Outer explosive material
7 Protective varnish

Fig. 1. Structure of an igniter [6]

The energy developing thereby activates the outer charge, which is mostly manufactured on the basis of sodium azide (NaN3), and finally the propellant charge of the gas generator is activated. The outer varnish protects the ignition device against humidity and mechanical shock [6].

B. Thermoelectrical basics

The resistance wire is an thermo-electrical energy converter. The temperature-dependent resistance R of the glow wire can be approximated by:

$$R = R_0(1 + \alpha \cdot \theta) \quad (1)$$

R_0 is the current-free glow wire resistance, θ the temperature change and α the resistance temperature coefficient.

The radial heat flow $\dot{Q}$ of the glow wire can be approximated by the stationary heat flow of a hollow cylinder [7].

$$\dot{Q} = \lambda \cdot \frac{2\pi \cdot L}{\ln(\frac{r_2}{r_1})}(T_1 - T_2) \quad (2)$$

λ is the thermal conductivity, L is the length of the cylinder, T_1 is the inner and T_2 the outer temperature. From this equation the thermal resistance r_{th} can be derived [7].

$$r_{th} = \frac{1}{\lambda} \frac{\ln(\frac{r_2}{r_1})}{2\pi L} \quad (3)$$

The following assumptions are applied for the thermodynamic model of the glow wire:

- There are only radial heat losses, the radial temperature distribution and the axial heat losses are neglected
- The contact surfaces of the glow wire and explosive material are ideal and should have the same temperature
- The heat flow in the glow wire is approximated by equation (2)

The thermal power P_{flow} can be calculated by following equation:

$$P_{flow} = c_{th} \frac{d\theta}{dt} + \frac{1}{r_{th}} \theta \quad (4)$$

c_{th} is the thermal capacity, which is defined by $c_{th}=m \cdot c$. c is the specific thermal capacity and material dependent.

With consideration of the energy conservation the electrical and thermal power must be the same: $P_{flow} = P_{el}$. Using this relation the following equation for a thermo-electrical model of an igniter can be derived:

$$I^2 R_0(1 + \alpha\theta) = c_{th} \frac{d\theta}{dt} + \frac{1}{r_{th}} \theta \quad (5)$$

Thermal radiation has been investigated, but due to the influence of longer time constants this effect can be neglected.

C. Model parameter

The glow wire is either made of steel, copper, chromium-nickel alloy or magnesium. In TABLE I the parameters of a nickel alloy from 67% nickel and 28% copper are represented [7]:

The radius r_0 of the glow wire and the thermal capacity c_{th} can be calculated with following equations [7]:

$$r_0 = \frac{\sigma L}{\pi r^2} \quad (6)$$

$$c_{th} = m \cdot c = \rho \cdot V \cdot c = \rho \cdot \pi \cdot r^2 \cdot L \cdot c \quad (7)$$

TABLE I
PARAMETER OF A COPPER NICKEL ALLOYED GLOW WIRE

Specific resistance σ	1.18 µΩm
Resistance temperature coefficient α	0.00015 K^{-1}
Specific thermal capacity c	460 $\frac{J}{kg}K$
Thermal conductivity λ	58.5 $\frac{W}{m}K$
Density ρ	8800 $\frac{kg}{m^3}$
Melting temperature T_{melt}	1452°C

In order to calculate the tests cases defined e.g. in [8], all calculation parameters must be determined either using data sheets or by measurements. In TABLE II the verified parameters of the igniter model are shown.

TABLE II
PARAMETER OF IGNITER MODEL

Resistance of current free glow wire	2.3 Ω
Ambient temperature	20 °C
Temperature of cold glow wire	20 °C
Critical ignition temperature of glow wire	600 °C
Resistance thermal coefficient	0.00015/K
Thermal capacity	$3.088 \cdot 10^{-6}$ J/K
Thermal resistance	260 K/W

The simulation model of the igniter was implemented with the hardware description language VHDL-AMS. All simulations shown in this paper were done using a VHDL-AMS simulator.

III. EMC-TESTING OF ELECTARICAL IGNITERS BY MEASUREMENTS

A. Activation and Testing with defined square wave pulses

To characterize the behavior of electrical igniters it is necessary to investigate the activation energy that depends on the form and the width of the impulse. Therefore the igniter was connected to a computer controlled impulse generator with an impulse driving circuit, which is able to produce defined square waves with exact current amplitudes. All measurements were done with Hirtenberger igniters of type HPP 11 mm. The test setup is shown in Fig. 2.

The electrical square wave pulse energy W can be calculated with the following equation:

$$W_{el} = I^2 \cdot R \cdot \Delta t \quad (8)$$

R is the resistance of the igniter's filament and Δt the pulse width.

Typical measured ignition pulse widths and energies are shown in TABLE III.

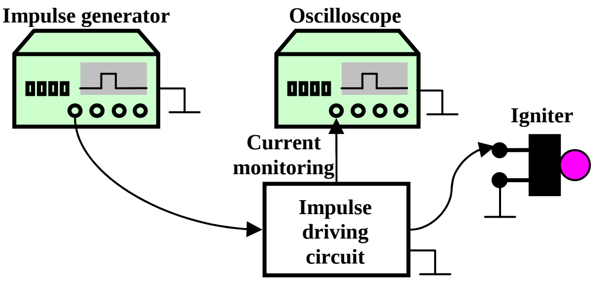


Fig. 2. Test setup for investigation of activation energy and pulse width

TABLE III
ACTIVATION ENERGY AND PULSE WIDTH AT 20 °C

Current	Pulse Width	Pulse Energy at 2.3 Ω
1 A	1600 µs	3.68 mJ
1.2 A	800 µs	2.65 mJ
1.5 A	450 µs	2.33 mJ
3.3 A	70 µs	1.75 mJ
5 A	29 µs	1.67 mJ

A comparison between the ignition energy at different ambient temperatures will be shown later in chapter V, Fig. 4, in comparison with the calculated results. At low currents the igniters need higher pulse energies. High and narrow current pulses lead to nearly adiabatic reactions. The low current reaction is determined by heat loss processes. This explains the measurement behavior. A large part of the heat energy supplied with longer pulses but lower amplitudes can leave the system by thermal conduction or radiation. Small tolerances lead to larger deviations between measurement and simulation in the low current region.

B. Activation and Testing with ESD impulses

To determinate the minimum trigger levels of the igniters by ESD, pulses with different discharge networks and discharge voltages are given directly and over a spark gap to the igniter pins. It must be noticed that it was not possible to activate the igniters with standard ESD configurations. Only untypical and not realistic resistor-capacitor configurations could cause a reaction. Some measurement results with non-standard ESD-networks are given in TABLE IV.

TABLE IV
ACTIVATION VOLTAGE OF ESD AT 20 °C FOR VERY SEVERE RC COMBINATION

Setup	Network	Activation voltage
Contact discharge directly to PIN 1 PIN 2 to GND	500 pF/100 Ω	18 kV
Contact discharge directly to PIN 1 PIN 2 to GND	500 pF/330 Ω	>30 kV
5 and 10 mm spark gap to PIN1 PIN 2 to GND	500 pF/100 Ω	19 kV

With the 330 pF/330 Ω standard network the activation voltage is always far above 30 kV, so other configurations with higher resistances and lower capacitors are disregarded.

All results shown here were done with contact mode discharges. Air discharge mode was also investigated and it could be found, that the total energy loss over a spark gap is very low. The activation voltage is in the range of one kilovolt above the contact mode discharge voltage.

IV. IMPEDANCE MODEL

To investigate the risk of unintended activation of vehicle occupant restraint systems by high frequency currents of electromagnetic disturbances an impedance model of an igniter was necessary. In [8] an immunity of igniters against sinusoidal disturbances in the frequency range of 1 - 1350 MHz with an input power of 0.5 W is required.

First simulations in the frequency range till 2.5 GHz show, that the needed power to reach the critical ignition current of 0.95 A is about 2.1 W. This is far away from the required limit of 0.5 W in [8]. If capacitive and inductive elements are integrated, the needed power at higher frequencies will increase [10]. The igniter's impedance can be determined by a S_{11} parameter measurement with a network analyzer. The impedance model is shown in Fig. 3.

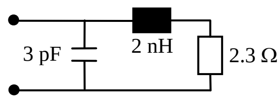


Fig. 3. Impedance model of an igniter

V. VERIFICATION OF THE SIMULATION MODEL

A. Validation with square wave pulses

In Fig. 4 an overview of the calculated and measured current dependent square wave pulse ignition energy at different ambient temperatures is shown.

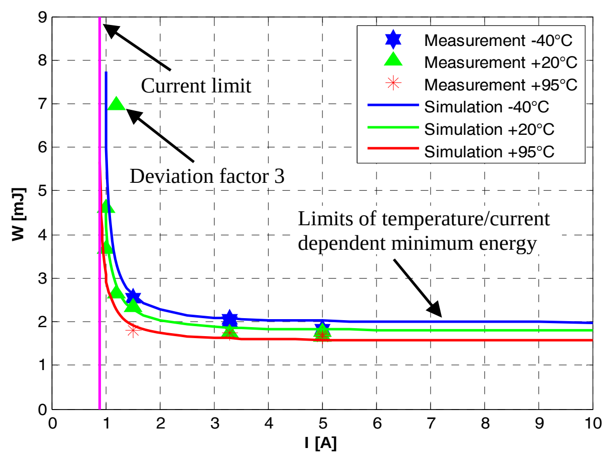


Fig. 4. Comparison of temperature and current depending ignition energy

At low currents, near the critical ignition current, the needed energy is increasing exponential. This is caused by the thermal conductivity of the model. Under 0.9 A an explosion is improbable, because the dissipated heat energy by thermal conduction is higher than the supplied electrical energy.

The simulation show, that the ALL-FIRE-LIMIT demanded in [8] at 1.2 A is fulfilled in every temperature dependent case.

At short pulses with high currents the ignition energy is about 1.5 mJ at 95 °C.

B. Validation with ESD impulses

TABLE V shows a comparison between calculated and measured activation voltages by ESD. The matching of the results is good. With lower capacitors and higher resistances in the discharge network an ignition can't be initiated.

TABLE V
VERIFICATION OF ACTIVATION VOLTAGE OF ESD AT 20 °C

Network	Setup	Measured activation voltage	Calculated activation voltage
500 pF/100 Ω	Contact discharge directly to PIN 1 PIN 2 to GND	18 kV	18 kV
500 pF/330 Ω	Contact discharge directly to PIN 1 PIN 2 to GND	>30 kV	31 kV

C. ESD investigations by simulations

With the developed simulation model investigations of protection concepts can be carried out. Limits in existing test standards can be evaluated. Fig. 5 shows the ignition voltage of typical discharge networks depending on the capacity of the discharge network. In [8], [9] an ESD network of 150 Ω/150 pF is required. The calculated ignition voltage of 35 kV for high temperatures is far above the limits in the specifications.

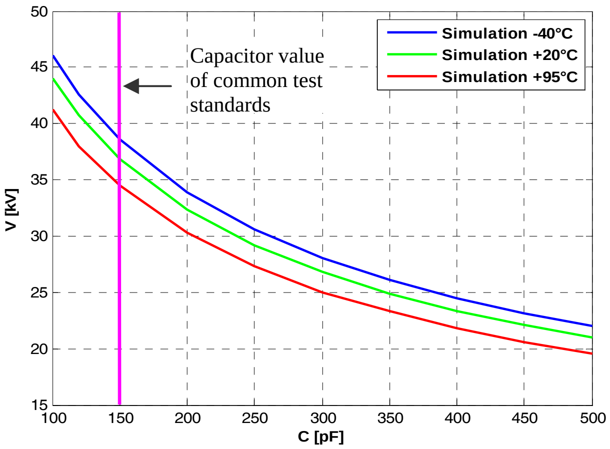


Fig. 5. Capacity dependent ESD ignition voltages with R=150 Ω

D. Ignition currents at very low and very high frequencies

The critical effective RF ignition current above 100 kHz and the DC ignition current are the same ($I_{RF} = I_{DC}$), as long as influence of wire inductance is low. At very low frequencies this dependence is no longer valid. A sinusoidal current with the frequency of 1 Hz and an effective current of 0.67 A can initiate an ignition, because the time the amplitude is exceeding the critical DC current of 0.95 A at 20 °C is sufficient. In Fig. 6 the frequency dependent effective current is given. It can be seen, that for low frequencies below 100 kHz a correction factor of $\sqrt{2}$ is required.

For very high frequencies the effective ignition current will increase because of the igniter's inductivity of about 2 nH. The needed ignition power is always over the limits demanded in [8].

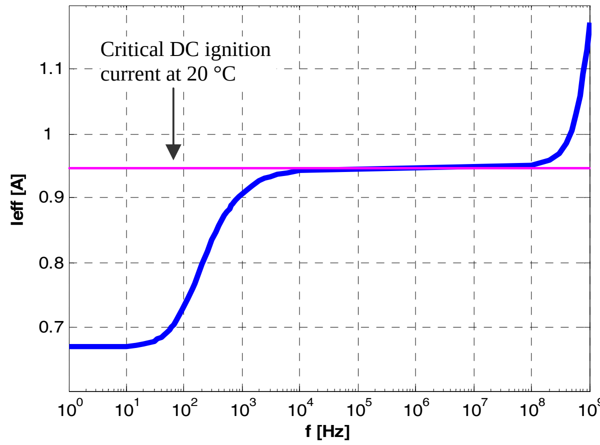


Fig. 6. Effective ignition current

VI. CONCLUSION

An accurate thermal-electrical model for igniters for automotive EMC applications was developed. Due to the usage of VHDL-AMS as modeling language the model can be interfaced easily with other circuit models. Complex simulations are possible. It could be shown that the existing test standards for automotive igniters ensure a very high ESD protection level. Some of the typical tests might be redundant. Provided results can help to save testing time by removing tests that give no additional information.

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