Study of the operating states of intrinsic safety barriers of the electric equipment intended for use in atmospheres with explosion hazard

Article in WSEAS Transactions on Circuits and Systems · June 2010

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Abstract: - Electrical equipments destined to operate in potentially hazardous environments are externally connected through intrinsic safety barriers. Their gauging should observe th e safety standards in the field and it is made on grounds of a theoretical analysis, on which this paper focuses. The analysis of the safety barrier involves the consideration for three important regimes: the aperiodic regime, the aperiodic critical regim and the oscillatory regime. To this purpose, a theoretical analysis of the barrier was made, in which the uniformly distributed parameters were considered to be concentrated. For each of the situations mentioned above, the analytical expressions of the output voltage and of the current through the barrier were inferred. The analysis of the safety barrier is made in MATLAB environment, through numerical simulation in SIMULINK.

Key-Words: - Equipment, Explosion hazard, MATLAB, Diagram, Safety barrier

1. Introduction

Intrinsically safe equipment is defined as "equipment and wiring which is incapable of releasing sufficient electrical or thermal energy under normal or abnormal conditions to cause ignition of a specific hazardous atmospheric mixture in its most easily ignited concentration." (ISA-RP12.6)

This is achieved by limiting the amount of power available to the electrical equipment in the hazardous area to a level below that which will ignite the gases.

Electric equipments intended for use in atmospheres with hazard of explosion shall meet certain safety conditions stated in the safety standards for this specific field, i.e. their design be different from the one of equipment that operate in normal conditions.

Their external connections are made through intrinsic safety barriers that restrict the current that crosses them to values inferior to the explosive limit of the potential explosive atmosphere.

Most applications require a signal to be sent out of or into the hazardous area. The equipment mounted in the hazardous area must first be approved for use in an intrinsically safe system.

The barriers designed to protect the system must be mounted outside of the hazardous area in an area designated as non-hazardous or safe in which the hazard is not and will not be present. In Fig. 1 is presents the diagram of an intrinsically safe system.

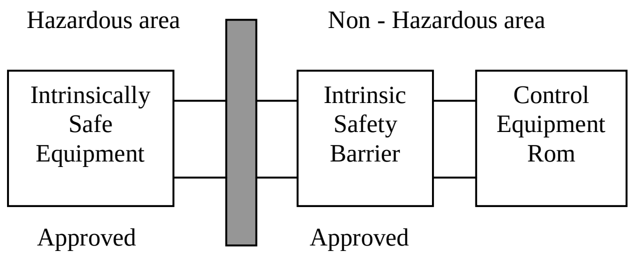

Fig.1. Diagram of an intrinsically safe system

Most of the apparatus that is mounted in the Hazardous area will have to be approved and certified for use in the Hazardous area with an approved barrier designed for use with that apparatus.

Some simple devices like thermocouples, RTDs, LEDs and contacts can be used in the hazardous area without certification as long as it is wired in conjunction with an approved barrier.

In all cases the intrinsically safe barriers and equipment must be wired per an approved drawing. Capacitance and inductance of the wiring and cables must be included in the loop evaluation.

In order to have a fire or explosion, fuel, oxygen and a source of ignition must be present. An intrinsically safe system assumes the fuel and oxygen is present in the atmosphere, but the system is designed so the electrical energy or thermal energy of a particular instrument loop can never be great enough to cause ignition.

Traditionally, protection from explosion in hazardous environments has been accomplished by either using EXPLOSION PROOF apparatus which can contain an explosion inside an enclosure, or PRESSURIZATION or purging which isolates the explosive gas from the electrical equipment. Intrinsically safe apparatus cannot replace these methods in all applications, but where possible can provide significant cost savings in installation and maintenance of the equipment in a Hazardous area. The basic design of an intrinsic safety barrier uses Zener Diodes to limit voltage, resistors to limit current and a fuse.

Equipment which has been designed for and is available for use in hazardous areas with intrinsically safe barriers includes:
- 4-20 mAdc Two Wire Transmitters
- Thermocouples
- RTDs
- Strain Gages
- Pressure, Flow, & Level Switches
- I/P Converters
- Solenoid Valves
- Proximity Switches
- Infrared Temperature Sensors
- Potentiometers
- LED Indicating Lights
- Magnetic Pickup Flowmeters

2. Theoretical study of the barrier

To analyze the variation of the current through the intrinsic safety barrier and the variation of the voltage at the outputs, there is being used an arrangement (see Fig. 2) where the uniformly distributed parameters from the inside and the outside of the barrier shall be considered as concentrated. In this figure we have:

R is the value of the resistor in the barrier,

L – the measured or estimated inductance of the line,

C – capacitance of the line from outside the barrier.

Ci - capacitance of the internal circuit and this capacitor shall become charged instantaneously when the step signal is being applied. [1], [4].

In the theoretical study the junction capacitance the diode D is neglected because this value is very low.

The paper scope is that of measure study in which is affected the intrinsic barrier character then at the external this terminal is connected an electrical cable.

Also is important to study in what step the reactive electrical parameters uniform distributed the cable affects the barrier attitude in atmospheres with explosion hazard.

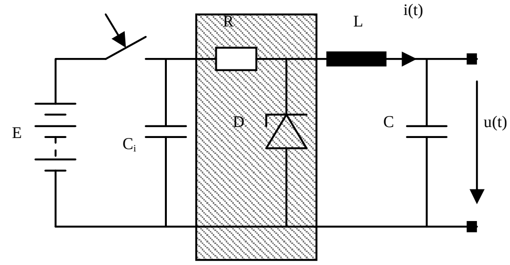

Fig. 2 – Electric model of the safety barrier at the application of the step signal

Starting under voltage thus equipment endowment by intrinsic safety barrier is equivalent by applying at the barrier input of the voltage unit signal.

The variation of the current through the barrier and the variation of the voltage at the outputs of the barrier are being studied when a step signal is applied at the end from the equipment.

The integro-differential equation of voltages at the moment of closing the circuit is:

$$Ri + L\frac{di}{dt} + \frac{1}{C}\int idt = E \qquad (1)$$

or:

$$LC\frac{d^2u}{dt^2} + RC\frac{du}{dt} + u = E \qquad (2)$$

The following notations are made:

$\delta = \dfrac{R}{2L}$ amortization of the circuit (3)

$\omega_0 = \dfrac{1}{\sqrt{LC}}$ personal pulsation of the circuit (4)

$\omega = \sqrt{\delta^2 - \omega_0^2}$ pseudo-pulsation of the circuit (5)

There shall be considered the situation when $\delta > \omega_0$ or $R < 2\sqrt{L/C}$ that is the situation checked by the resistor in the barrier.

Consequently, the solving of the differential equation gives the following solutions:

$$u(t) = E\left[1 - \frac{1}{2\sqrt{\delta^2 - \omega_0^2}}(r_1 e^{r_2 t} - r_2 e^{r_1 t})\right] \qquad (6)$$

$$i(t) = \frac{E}{2L\sqrt{\delta^2 - \omega_0^2}}\left(e^{r_1 t} - e^{r_2 t}\right) \qquad (7)$$

where r1 and r2 are the roots of the characteristic equation:

$$\begin{aligned} r_1 &= -\delta + \omega \\ r_2 &= -\delta - \omega \end{aligned} \qquad (8)$$

There shall be considered the situation when $\delta < \omega_0$ or $R < 2\sqrt{L/C}$. The following notation is being made:

$$\omega_0^2 - \delta^2 = \omega'^2 \qquad (9)$$

Consequently, the solving of the differential equation gives the following solutions:

$$u(t) = E \cdot \left[1 - \frac{\omega_0}{\omega'} \cdot e^{-\delta t} \cdot \sin(\omega' t + \beta')\right] \qquad (10)$$

$$i(t) = \frac{E}{\omega' L} e^{-\delta t} \sin \omega' t \qquad (11)$$

where:

$$\beta' = \arccos \frac{\delta}{\omega_0} \qquad (12)$$

To analyze the intrinsic safety barrier, there has been used MATLAB software with two different methods of analysis as part of it. There follows a presentation of these methods [3], [5].

3. Analyzing the safety barrier by numeric simulating

The differential equation (2) can be put under the following form:

$$\frac{d^2 u}{dt} = \frac{1}{LC}\left[E - RC\frac{du}{dt} - u\right] \qquad (13)$$

SIMULINK model (Fig.3) has been conceived based on this equation.

This integrates the differential equation (2) and traces the voltage variation curves at the outputs of the barrier and of the current through the barrier for the three situations.

The simulation model in this way is conceived that is permeated voltage studying at output barrier, the current by barrier as the dissipated power on barrier resistor for different values the resistor R.

In this aim is considered three values of resistor R, value what correspond oh three important regimes:

- aperiodic regime;
- critical aperiodic regime;
- oscillating regime.

For each regime is plotted the variation diagrams of voltage at output barrier, the current of barrier and the dissipated power on resistor of barrier.

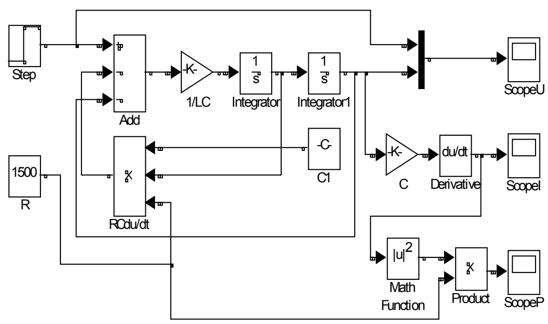

Fig. 3 – SIMULINK model of the safety barrier

If we consider:
- the value of the voltage E = 24 [V]
- the true resistance of the barrier R = 1.5 [kΩ],
- the inductance of the cable connected to the equipment L = 10^{-4} [H]
- and the uniformly distributed capacitance of the cable C = 10 [nF],

we get the following MATLAB diagrams (Fig. 4 and Fig. 5) in accord with the equations (6) and (7).

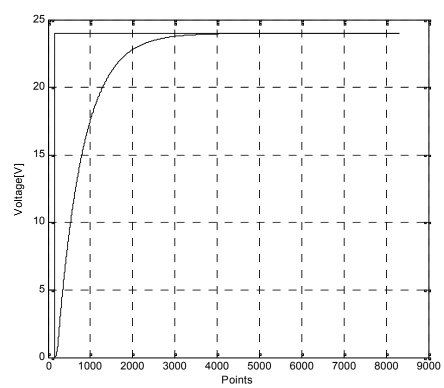

Fig. 4 – Voltage variation at the outputs of the barrier in an aperiodic working condition

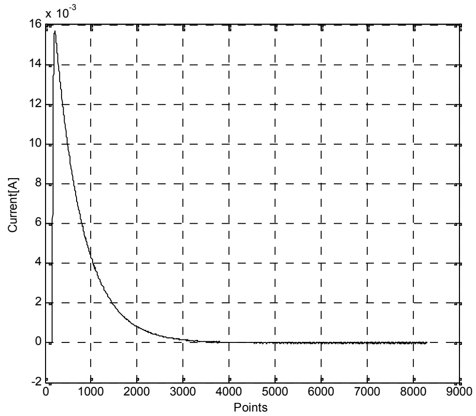

Fig. 5 – Current variation through the barrier in an aperiodic working condition

The precedents diagrams making evident a variation the aperiodical voltage at the output barrier and the current of barrier at applying the voltage unit step of 24 [V] at this input.

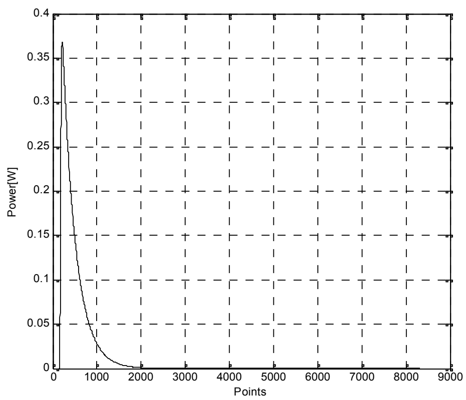

Fig.6 Power variation on resistor of the barrier in aperiodic regime

Decrease the resistance value of barrier take effect touching aperiodical critic regime.

The voltage variation diagrams at the output barrier, the current of barrier as and the power dissipated of resistor for barrier around in critic aperiodical regime are restoring in continuation and were obtained for these values the reactive parameters of cable but for a resistor value of barrier for 100 [Ω].

In diagram of Fig. 7 is cleared the voltage variation at the output barrier in around of critic aperiodical regime.

Also in Fig. 8 and Fig. 9 are plotted the current diagrams variation of barrier, respective the dissipated power of resistor in the same regime.

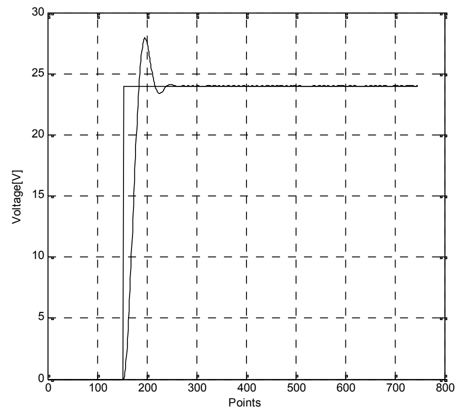

Fig. 7 Voltage variation through the barrier in the region of aperiodic critical regime

Appearance the aperiodic critical regime is confirmed of admission the voltage trend oscilation around the voltage value applied at the input barrier.

This oscillation trend is retrieval as in variation curve of current for barrier (Fig. 8) how and in variation diagram the power of resistor (Fig.9).

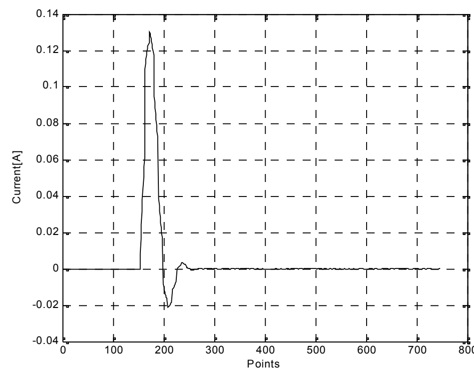

Fig.8 Current variation through the barrier in the region of aperiodic critical regime

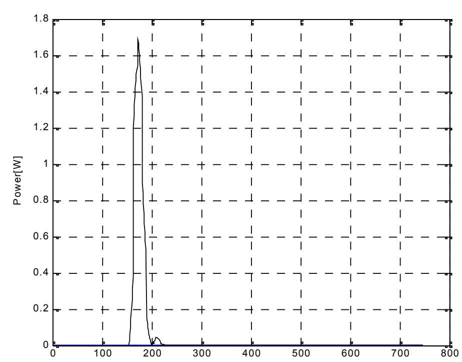

Fig.9 Power variation on resistor of the barrier in the region of aperiodic critical regime

For the group of values that correspond to the situation of oscillating charge, we have got the diagrams shown in the Fig. 10, Fig. 11 and Fig.12:

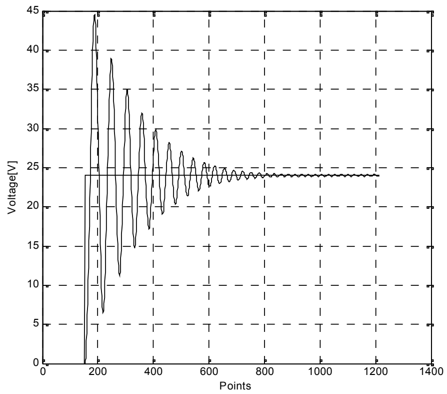

Fig. 10 – Voltage variation at the outputs of the barrier in an oscillating working condition

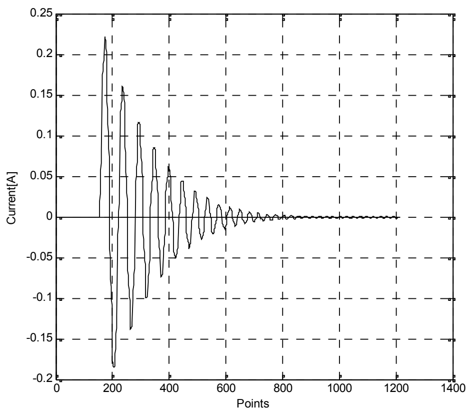

Fig. 11 – Current variation through the barrier in an oscillating working condition

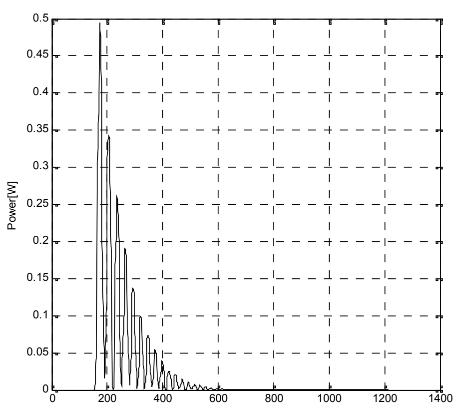

Fig.12 Power variation on resistor of the barrier in oscillating regime

The diagrams shown in Fig. 10, Fig. 11 and Fig. 12 are for the following values:
- E = 24 [V];
- L = 10^{-4} [H];
- C = 10 [nF];
- R = 10 [Ω].

4. SimPowerSystems model for the safety barrier

Matlab software provides SimPowerSystems software package that supports the simulation and analysis of electrical circuits in different working conditions.

Since the answer to the step signal or to the pulse generates a transient working condition we have used this means for the behavior of the intrinsic safety barrier to these conditions.

The benefit of this manner of simulation is that the safety barrier can be tested both at the unit step signal and impulse and it allows getting several types of diagrams specific to the circuit.

Three groups of values have been selected for this situation; these values are for the parameters of the circuit, the values that correspond to the aperiodic working conditions, aperiodic critical regim and to the oscillating working conditions [2], [9].

The SimPowerSystems of intrinsic safety barrier model with has plotted the voltage and current variation diagrams at standard signals applying at input intrinsic safety barrier, as well the frequency diagrams is given by Fig. 13.

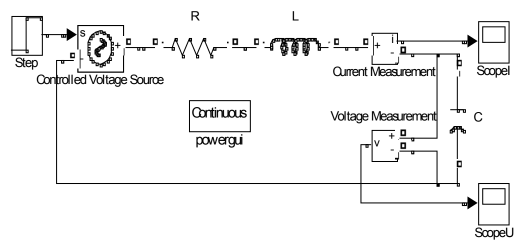

Fig.13 SimPowerSystems model of the safety barrier

The SimPowerSystems of intrinsic safety barrier admits by analysis block of POWERGUY behavior analyzation the safety barrier the applying at this input the standard signals:

- unit signal step;
- unit signal impulse.

These signals correspond in practice the particular working regimes.

4.1 Voltage at the outputs of the safety barrier

For the aperiodical charge of the capacitor we have got the diagrams that show the voltage variation at the outputs of the barrier when a unit step signal and a unit pulse are being applied to the inputs. These diagrams are shown below.

There shall be considered the following values of the electric parameters:

a) For the aperiodic working condition:
- E = 24 [V], voltage at the outputs of the barrier;
- R = 1.5 [kΩ], true resistance in the barrier;
- L = 10^{-4} [H], inductance of the cable connected to the equipment;
- C = 10 [nF], uniformly distributed capacitance of the cable

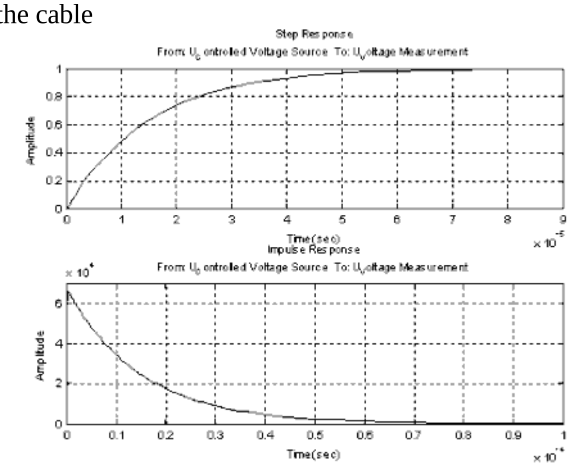

Fig. 14 - Voltage variation at the output of barrier when step signal and pulse are being applied in an aperiodic working condition

b) In case of aperiodic critical regime the powerguy block analysis generates the diagrams shown in Fig.15 which corresponds for output intrinsic safety barrier at apply the signal unit step respective, the signal unit impulse.
This diagram given in Fig. 15 was obtained of following values the electrical parameters:
- E = 24 [V];
- R = 100 [Ω];
- L = 10^{-4} [H];
- C = 10 [nF]

The aperiodic critical regime setoff an oscillation tendency at output barrier voltage.

This oscilation tendency is so much the pronounced the resistor value from intrinsic safety barrier is less.

Decreasing the value of R below this value generates an oscillatory regime by all effects regime which will study here below.

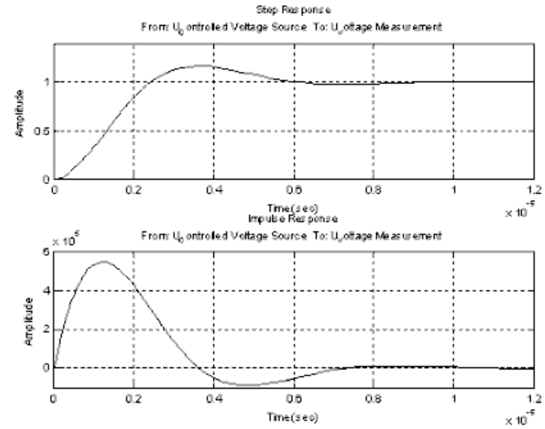

Fig. 15 Voltage variation at the output of barrier in aperiodic critical regime

c) For the oscillating working condition:
- E = 24 [V];
- R = 10 [Ω];
- L = 10^{-4} [H];
- C = 10 [nF],

POWERGUY analysis block allows getting the following Matlab diagram with the help of the first values.

When the group of values related to the parameters of the circuit corresponds to the oscillating working condition, the simulation model together with POWERGUY analysis block form the diagrams shown in Fig.16.

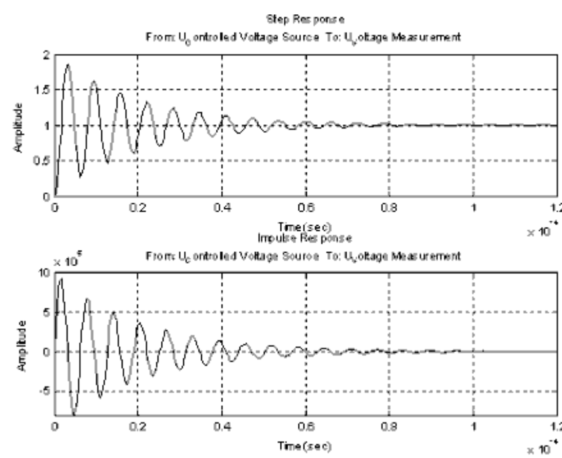

Fig. 16 - Voltage variation at the output of barrier when step signal and pulse are being applied in an oscillating working condition

POWERGUY analysis block also allows tracing the frequency characteristics of voltage at the outputs of the barrier; the frequency in logarithmic coordinates (BODE diagram) is on the horizontal axis. (Fig. 17).

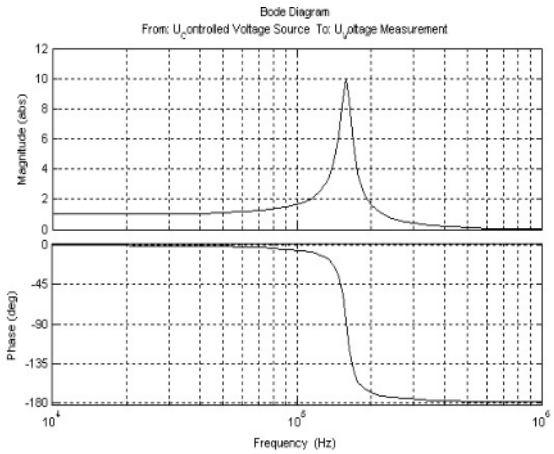

Fig.17 Frequency diagrams of the oscillating voltage at the outputs of the barrier

The anterior diagram accentuating a maxim the output barrier voltage by approximate 10 [V] in terms of in which at the input intrinsic safety barrier applied the signal unit step (1[V]).

4.2. Current variation through the safety barrier

For the values that correspond to the aperiodic working condition, we get the following diagrams (Fig. 18), [6], [7].

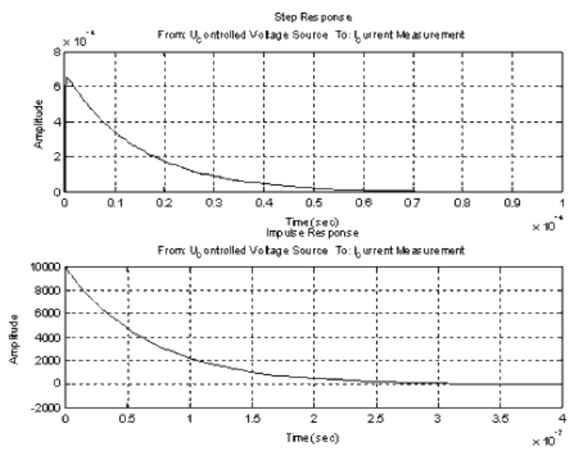

Fig. 18 - Current variation through the barrier when step signal and pulse are being applied in an aperiodic working condition

In case of aperiodic critical regime the powerguy block analysis generates the diagrams of Fig. 19 which corresponds the barrier current in case applying the unit signal step and the unit impulse signal.

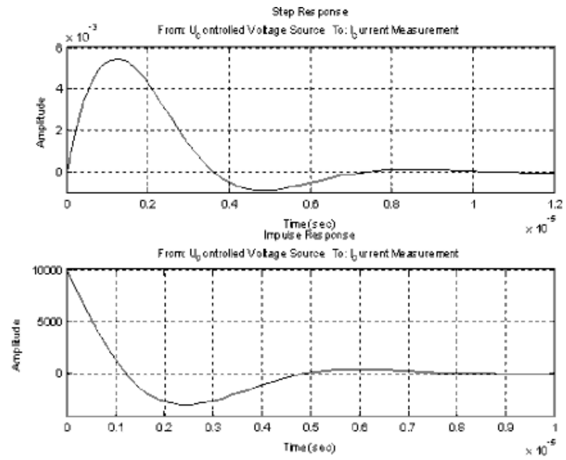

Fig.19 Current variation through the barrier for aperiodic critical regime

The critical aperiodic regime setoff an oscillation tendency of intrinsic safety barrier current.

For the values that correspond to the oscillating working condition, we get the diagrams in Fig. 20.

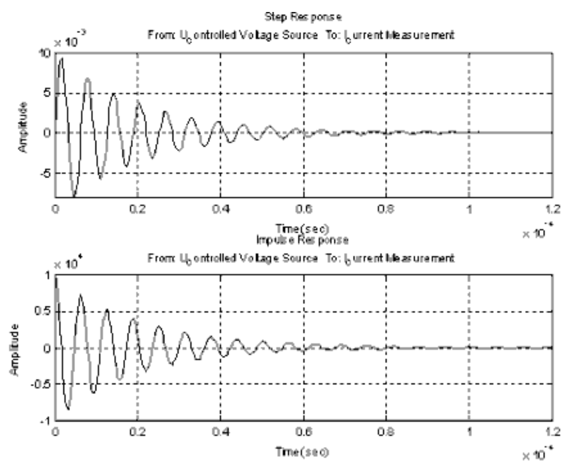

Fig. 20 - Current variation through the barrier when step signal and pulse are being applied in an oscillating working condition

POWERGUY analysis block also, allows getting the frequency diagram for the oscillating current through the barrier (Fig.21).

The diagrams which is shown in Fig. 21 setoff a maxim by intrinsic safety barrier current of 0,1 [A], that is a value of 100 more than by barrier intensity current in normal conditions of working (equations 17).

This phenomena has chair because in intrinsic safety circuit barrier produced a voltage resonance which has value of $1{,}59 \cdot 10^5\ [Hz]$ (equation 17).

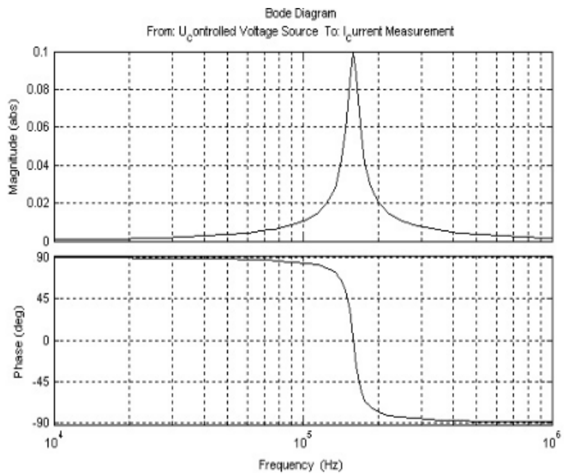

Fig. 21 - Frequency diagrams of the oscillating current through the barrier

The connecting to the supply network of the equipment is equivalent with appearance the unit step signal to the input of intrinsic safety barrier.

The appearance of transitory overvoltages with great amplitude in the supply network of equipment is approximate equivalent with application of signal impulse to the input of intrinsic safety barrier.

The following ideas can be underlined for the diagrams that show the voltage frequency at the outputs of the barrier and the current that crosses the barrier:

- Voltage at the outputs of the barrier is maxim at a value of the frequency that is inferior to the resonant frequency of the circuit f_0:

$$f_c = f_0 \cdot \sqrt{\frac{2-d^2}{2}} \cong 1{,}58 \cdot 10^5\ [Hz] \qquad (14)$$

where:

$$d = R\sqrt{\frac{C}{L}} = 0{,}1 \qquad (15)$$

is the amortization factor of the circuit.

$$U_{C\max} = \frac{U}{d\sqrt{1-\frac{d^2}{4}}} = 10{,}01[V] \qquad (16)$$

i.e. approximately ten times bigger than the input voltage (unit step).

- Current intensity through the barrier is maxim at a value of the frequency that is equal to the resonant frequency of the circuit:

$$f_0 = \frac{1}{2\pi\sqrt{LC}} \cong 1{,}59 \cdot 10^5\ [Hz] \qquad (17)$$

A frequency of the input voltage of 10^4 [Hz] gives a current of:

$$I = \frac{U}{\sqrt{R^2 + \left(\omega L - \frac{1}{\omega C}\right)^2}} \cong 1[mA] \qquad (18)$$

The following current shall cross the barrier at the resonant frequency:

$$I_0 = \frac{U}{R} = 0.1[A] \qquad (19)$$

which is one hundred times bigger than the current gained with the equation (18).

The above said calculation was made for the following values of the electric parameters:
- input voltage: U = 1[V] (unit step);
- inductance of the line: $L = 10^{-4}$ [H];
- capacitance of the line: $C = 10^{-8}$ [F];
- true resistance of the barrier: R = 10 [Ω].

5. Conclusion

Intrinsic Safety methodology inserts an energy-limiting interface in the wiring between safe and hazardous areas.

This restricts the electrical energy in the hazardous-area circuits so that potential electrical sparks or hot spots are too weak to cause ignition. The interface passes signals in both directions but limits the voltage and current that can reach the hazardous area under fault conditions.

Intrinsic Safety became popular for many applications in the early 1960s with the introduction of the 'shunt diode safety barrier' based on the Zener diode, and is now the preferred solution in most applications for several reasons:

- Advances in semiconductors allow increasingly complex electrical operations to be carried out in hazardous areas at very low (typically 1 watt) power levels.
- Hazardous-area equipment can be calibrated and serviced 'live'.

- Ordinary instrument wiring can be used in hazardous areas.
- It is inherently safe for personnel due to the low voltages employed.
- International standards governing the design of Intrinsically Safe equipment allow the same product to be sold and used in many countries.
- With a certified IS interface, safe-area equipment needs no certification and the user can choose or change the hazardous-area equipment within wide limits.

As a conclusion, it is better to avoid the latter situation when both the current and the voltage that crosses the barrier become oscillating because:
- the electrical cable presence at the intrinsic safety barrier output affecting this behavior in atmospheres with explosion hazard.
- the uniform distributed parameters of electric cables influences the electric intrinsic safety barrier comportment
- this working condition can give birth to overvoltages around the value of the supply voltage, fact that may jeopardize the intrinsic safety of the barrier;
- the uniformly distributed reactive elements can give birth to electric resonance phenomena, aspect that can produce overvoltages or overcurrents and finally the loss of the intrinsic safety characteristic of the barrier.

An important conclusion of this study paper is the manner used to select the value of the resistor in the barrier: even if this selection relies on the ignition curves stated by the standards that deal with the intrinsic safety, the above said oscillating working condition shall be avoided.

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