INFLUENCE OF THE SYNERGY OF NEUTRON AND GAMMA RADIATION AND FUNCTIONAL AGING ON THE EFFICIENCY OF A HYBRID PROTECTION CIRCUIT

by

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Technical paper
https://doi.org/10.2298/NTRP2203201K

Due to the shortcomings of commercial filters and non-linear components for overvoltage protection in the conditions of synergy of neutron and gamma radiation and functional aging, the behavior of the hybrid protection circuit under the same conditions was examined. In order for the experimental procedure to correspond as closely as possible to the real situation, the load of the hybrid circuit was not adjusted by impedance. The standard model of the hybrid protection circuit recommended in accordance with IEC 1.3 is simulated using the software package PSPICE. To that end, it is necessary to create a varistor with appropriate elements. The equivalent inductance parameters were found to be stable in relation to the experimental conditions. It was also established that due to the synergy of neutron and gamma radiation and functional aging, there is a change in the steepness of the varistor characteristic and the tangent of the loss angle in the capacitors. The overall effect of neutron and gamma radiation and functional aging was tested on the hybrid circuit and on individual components. The experiments were performed under well-controlled laboratory conditions, and the combined measurement uncertainty of the experimental procedure did not exceed 5 %.

Key words: neutron and gamma radiation, filter overvoltage protection, hybrid circuit for overvoltage protection

INTRODUCTION

Overvoltage protection elements can be divided into non-linear and linear. Non-linear overvoltage protection elements include various types of protective surge arresters such as gas surge arresters, varistors and overvoltage diodes. Linear elements of overvoltage protection include different types of filters. In practice, a combination of these elements is often used. This is because most commercial filters are not intended for use as protection against interference that reaches several thousand volts. In addition, it is very difficult to provide the required level of protection using the filter itself. Protective arresters by themselves have some disadvantages in the case when it is necessary to guarantee the protection of particularly sensitive semiconductor electronic components. This is the reason for the application of combined (hybrid) protection to compensate for the shortcomings of linear and nonlinear protection elements [1-10].

The basic properties of real elements of overvoltage protection are as:

– The response threshold of a real non-linear overvoltage protection element is gradual. This means that the nonlinear elements of surge protection have a finite value of the nonlinearity coefficient a. This coefficient is generally defined as $a = \log(I_2/I_1)/\log(U_2/U_1)$, where U_1, I_1 and U_2, I_2 coordinates of points from the volt-ampere curve, respectively. Real non-linear overvoltage protection elements are characterized by inertia, *i.e.* the time required for the element to react (when the voltage of the transient wave reaches the element's response value). The fact that the bandwidth of real electrical filters cannot be made infinitely small means that part of the frequency spectrum of the transient passes through the filter [11-14].
– The voltage value at the protected point of the device depends to a greater or lesser extent on the

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current passing through the non-linear protective element [15, 16].

– The possibility of absorbing the energy of real non-linear elements for protection against overvoltage is limited. In the case of electric filters, part of the energy is reflected back into the circuit, while the possibility of absorbing part of the energy in the active resistances of the filter is also limited [17-19].

Non-linear elements of overvoltage protection as well as electrical filters show aging properties, *i. e.* a change in characteristics as a function of the number of activations, the peak values of the current they conduct, as well as the duration of the transient. The change in the characteristics of these elements is also observed in conditions of change in ambient temperature and radiation [20-24].

– The influence of some elements of overvoltage protection on the normal operation of the device, in the absence of an overvoltage phenomenon, cannot be ignored, which can lead to the deterioration of the device's characteristics [25].

The purpose of the study is to investigate the influence of the number of activations (previous operations) and neutron and gamma radiation on the stability of the relevant characteristics of the hybrid protective circuit made according to the proposal of the standard IEC 77.C.1.3 by means of a real experiment and a numerical procedure [26]. In order to obtain results of maximum reliability, high-quality power sources and measuring instruments were used. The entire procedure was performed under well-controlled laboratory conditions and was fully automated. The combined measurement uncertainty of the measurement procedure was less than 7 % [27-30].

EXPERIMENT

As already mentioned, non-linear protection elements are often used together with filters. Most commercial filters cannot handle a large number of overvoltages without major changes in characteristics. This mainly refers to capacitors as filter elements. Also, the dielectric of the capacitor is sensitive to the effects of neutron and gamma radiation. On the other hand, it is difficult to provide effective protection in the case of applying only a non-linear protective element, since the peaks that pass through such protection may have enough energy to directly destroy the electronic component or a sufficient voltage level to indirectly destroy it. This can lead to disruptions in the operation of the protected device. For these reasons, hybrid protection circuits are often used. This is why it is necessary to examine the contribution of individual overvoltage protection components to the overall protection characteristic of the hybrid protection circuit. Although there are a large number of very different concepts of hybrid protective circuits, the principles of their operation are very similar. This means that the simulation of the influence of the stability characteristics of the overvoltage protection elements on one specific model of the hybrid circuit provides useful data for all other types of hybrid circuits. In this study, a hybrid circuit made according to the IEC 77.C.1.3 standard was used. The simulation was performed with the PSPICE software package.

Figure 1 shows an idealized scheme of the protective hybrid circuit used in the work. The circuit shown in fig. 1 is based on a varistor and an L-filter, as well as a simplified schematic of this circuit. The overvoltage source V_{imp} was simulated by a double-exponential unipolar pulse 1.2/50 s whose peak value was 5 kV. The input impedance of the circuit was a standard active resistance of 50 . In order for the analyzed circuit to match the real situation as much as possible, the filter load was not adjusted according to impedance. Since the used program algorithm does not have a suitable varistor model, it was created with elements R_{CV}, R_V, D_V, R_{DV}, V_{MN}, V_{MV}, V_{PV}, and I_{UV} so that the model corresponded to the varistor used in the experiment (d = 14 mm). The circuit $R_{CV}C_V$ determines the response time constant of the varistor (C_V represents its own varistor), the parameter R_{DV} represents the dynamic resistance of the varistor, the voltage generator V_{PV} determines the breakdown voltage of the varistor, and the I_{UV} represents the current controlled current source (zero electromotive force V_{MV} represents the ammeter of the control current iUPV of the I_{UV} source). The relationship between the control

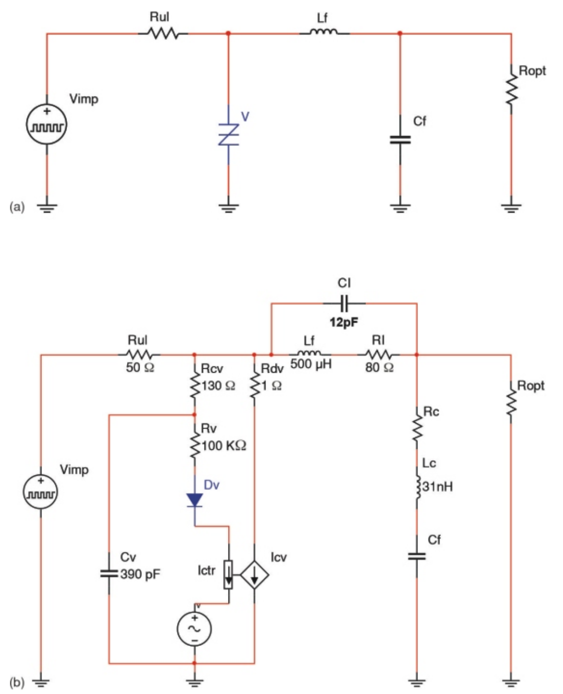

Figure 1. (a) Idealized scheme of the hybrid protection circuit and (b) a simplified equivalent diagram of a hybrid protected circuit

current i_{UPV} and the source current I_{UV} is given by the relation

$$I_{UV} \quad k i_{UPV} \tag{1}$$

where k is the linear coefficient of current amplification whose value is determined by the expression

$$k \quad \frac{R_{CV} \quad R_V}{R_{DV}} \tag{2}$$

The equivalent scheme of the varistor in this particular case is of the unipolar type, since due to the nature of the test pulse there was no need to introduce a bipolar model. It should be noted that the linear approximation (coefficient k) of the volt-ampere characteristic of the varistor gives satisfactory results in the current range from 1 mA up to about 200 A.

The simplified filter inductance replacement scheme is of the classic type and is set by the inductance L_f, the capacitance C_f representing the inter-turn parasitic capacitance and the series resistance R_e representing the equivalent of purely ohmic and dissipation losses. The synthesis of the equivalent inductance scheme was performed on the basis of [31] for a commercial choke of 500 H. The substitution scheme of the capacitor is represented by resistance R_c, self-inductance L_c, and capacity C_f, which in this case was 0.2 F.

The examination of the influence of the stability of overvoltage protection elements on the ROPT output voltage under the effect of an overvoltage pulse at the input of the circuit and the effect of neutron and gamma radiation was performed under the assumption that the parameters of the equivalent inductance (C_e, L_f, R_e) remained stable in relation to the initial conditions. The steepness of the varistor was changed by increasing the dynamic resistance. Also, the appropriate value of the breakdown voltage, capacitor capacity and loss resistance are changed. These changes were determined by measuring the synergistic effect of neutron and gamma radiation and the number of previous impulse loads [18-21].

The experimental procedure was performed by loading the varistor and the capacitor with 1, 100, 200, 300, 400, 500, 600, 700, 800, 900, and 1000 pulses, after which the change in the volt-ampere and volt-ohm characteristics of the varistor was recorded, with the number of loads as a parameter. After that, the varistors were irradiated and the volt-ampere and volt-ohm characteristics of the varistors were recorded again. The observed changes in the equivalent components of the varistor scheme were recalculated and inserted into the simulation program to evaluate the influence of the synergy of neutron and gamma radiation and the number of operations on the protective characteristics of the hybrid circuit.

During the experiment, a varistor with a disk diameter of 14 mm was used, intended for permanent load with alternating voltage. The capacitor used had a film dielectric made of polystyrene, insulation resistance 100 T and a value of tg of 0.0015. The source of neutron and gamma radiation was the isotope californium ^{252}Cf. The source was made in the form of a Cf_2O_3 capsule, and its mass was 2265 g. Figure 2 shows the neutron spectrum S_n of the applied source. Figure 3 shows the gamma spectrum S of the applied source. Table 1 gives the values of fluence (F_n neutron and F gamma radiation) that were deposited during the experiment (N_f).

RESULTS AND DISCUSSION

Figure 4 shows changes in the volt-ampere characteristic depending on the number of operations (pulses) and the fluence of neutron and gamma radiation. Figure 5 shows changes in the volt-ohm characteristic depending on the number of operations (pulses) and the fluence of neutron and gamma radiation.

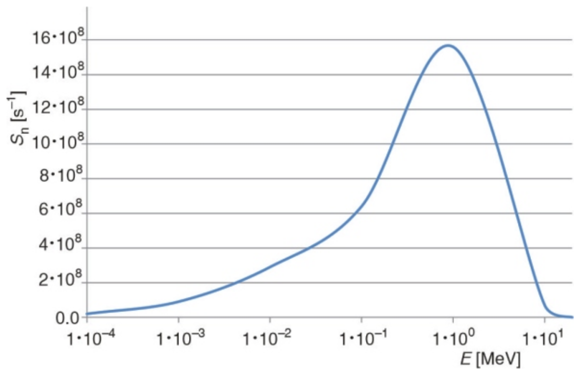

Figure 2. Neutron spectrum of the applied source

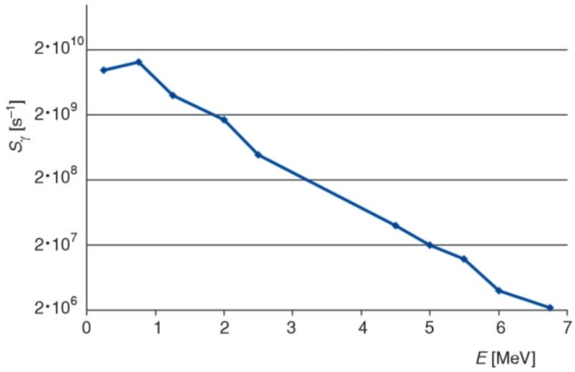

Figure 3. Gamma spectrum of the applied source

Table 1. Fluence values (neutron and gamma radiation) deposited during the experiment (N_f)

N_f	F_n [cm^{-2}]	F [cm^{-2}]
0	0	0
1	3.55	8.66
2	7.10	17.3
3	10.66	26

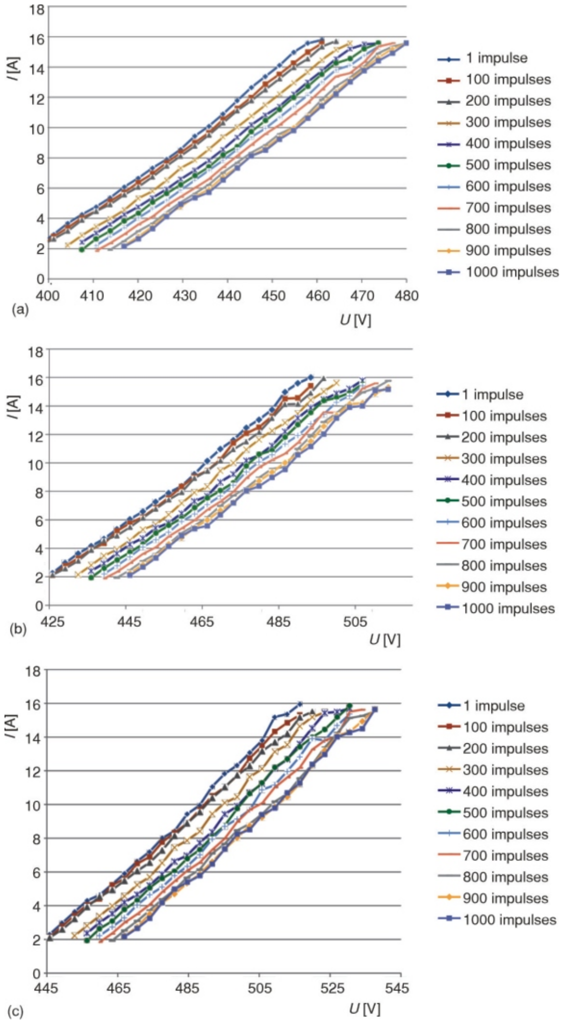

Figure 4. Changes in the volt-ampere characteristic depending on the number of operations (pulses) and the fluence of neutron and gamma radiation; (a) fluence = 0, (b) fluence = 1, and (c) fluence = 2

Based on the results obtained by examining the effects of neutron and gamma radiation and the number of pulses on varistors and capacitors, the effects of the worst case on the equivalent components of the hybrid protection circuit were calculated. The following results were obtained: 1 – increasing the dynamic resistance of the varistor from 4.5 to 10 , 2 – reduction of the varistor breakdown voltage from 388 V to 378 V, 3 – reduction of capacitor capacity from 0.2 F to 0.14 F, and 4 – increasing the resistance of the capacitor from 0.2 to 2.5 . With these changes, the influence of the worst case synergy of neutron and gamma radiation and the number of pulses on the voltage on the varistor, fig. 6 and on the normalized frequency spectrum on the load, fig. 7, was determined by a numerical simulation.

Figures 6 and 7 show the changes in the varistor voltage and the normalized frequency spectrum before the effects of the changes and the changes in the worst case. In fig. 6, Curve 1 gives the shape of the voltage on the varistor before the changes, Curve 2 gives the shape of the voltage on the capacitor before the

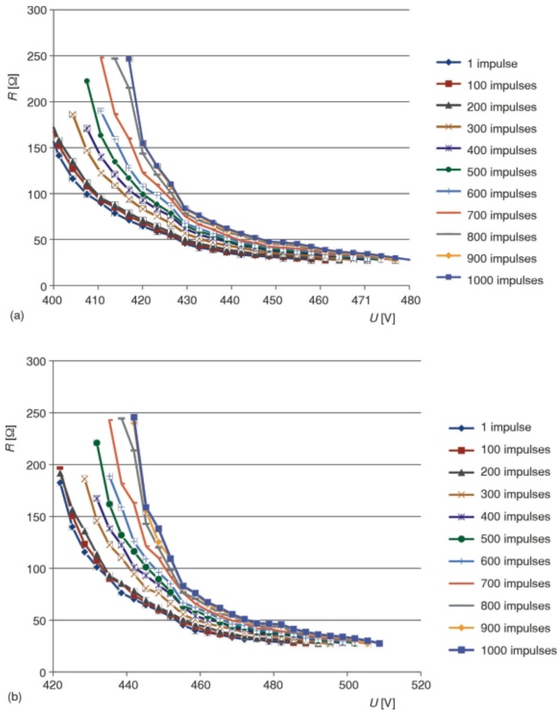

Figure 5. Changes in the volt-ohm characteristic depending on the number of operations (pulses) and the fluence of neutron and gamma radiation, (a) fluence = 0 and (b) fluence = 1

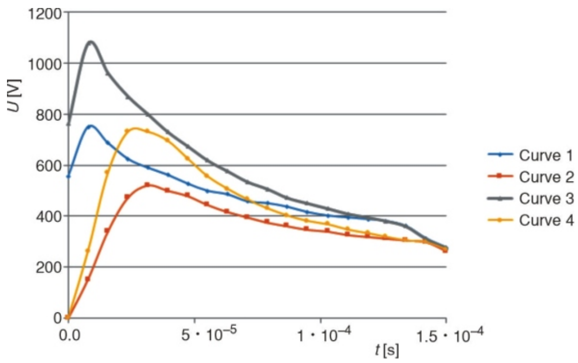

Figure 6. Voltage forms on the varistor (Curves 1 and 3) and the load before and after the changes (Curves 2 and 4)

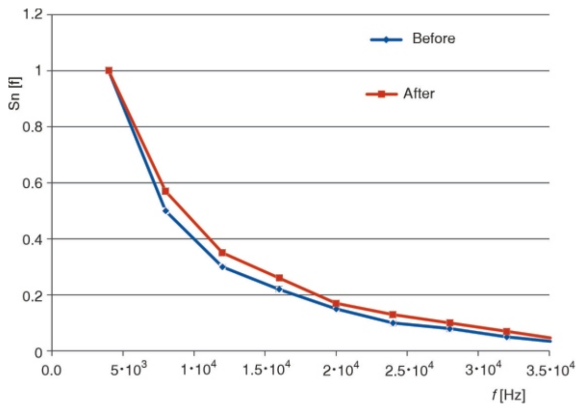

Figure 7. Change of the normalized frequency spectrum before action and change in the worst case

changes, Curve 3 gives the shape of the voltage on the varistor after the changes in the worst case, and Curve 4 gives the shape of the voltage on the capacitor after the changes in the worst case. Curve 2 shows an increase in the value of the residual voltage on the varistor due to an increase in its dynamic resistance, which is particularly visible in the area of higher voltages and currents. At the output of the filter, the voltage value also increases, which is a consequence of the increase in the voltage at the input, but also the content of higher harmonics (fig. 7 shows the normalized content of harmonics in relation to 4 kHz), which is caused by the increase in losses and the decrease in the capacity of the capacitor. Both phenomena (increase in voltage and increased presence of higher harmonics at the output) represent a danger to the protected system in terms of easier penetration of higher overvoltage harmonics into its circuits, which increases the possibility of disruption or failure.

CONCLUSION

The results of testing the synergy of neutron and gamma radiation and the number of pulses on the hybrid protection circuit showed that the synergy is negative. It is shown that changes in the components of the hybrid protection circuit due to the effect of neutron and gamma radiation and the number of pulses increase the number and intensity of higher harmonics at the output. This phenomenon represents a real danger to the protected element or system, which can lead to its dysfunction or destruction. This must be taken into account when applying hybrid protective circuits in the fields of neutron and gamma radiation, since the effects of this radiation cause dominantly observed phenomena. For this reason, it is recommended to choose hybrid protection circuit components that are more resistant to the effects of neutron and gamma radiation. These are components made on the basis of molecules of greater mass, since in this case the effect of displacement of molecules (which is the main effect of the interaction of neutron and gamma radiation with the material) is less possible.

ACKNOWLEDGMENT

This work is supported by the Ministry of Education, Science and Technological Development of the Republic of Serbia.

AUTHORS' CONTRIBUTIONS

N. M. Kartalović gave the idea for the experiment which was carried out by A. R. Jusić and A. D. Žigić. All the authors analyzed the results and participated in preparation of the final version of the manuscript under supervision and guidelines of N. M. Kartalović.

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Received on November 18, 2022
Accepted on January 24, 2023

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УТИЦАЈ СИНЕРГИЈЕ НЕУТРОНСКОГ И ГАМА ЗРАЧЕЊА И ФУНКЦИОНАЛНОГ СТАРЕЊА НА ЕФИКАСНОСТ ХИБРИДНОГ ЗАШТИТНОГ КОЛА

Услед недостатака комерцијалних филтера и нелинеарних компонената за заштиту од пренапона у условима синергије неутронског и гама зрачења и функционалног старења испитано је понашање хибридног заштитног кола под истим условима. Да би експериментални поступак што више одговарао реалној ситуацији оптерећење хибридног кола није било прилагођено по импеданси. Стандардни модел хибридног заштитног кола препоручен у складу са IEC 1.3 симулисан је помоћу програмског пакета PSPICE. У том циљу нужно је креирати варистор одговарајућим елементима. Установљено је да су параметри еквивалентне индуктивности стабилни у односу на услове експеримента. Такође је установљено да услед дејства синергије неутронског и гама зрачења и функционалног старења долази до промене стрмине карактеристике варистора и тангенса угла губитака у кондензаторима. Укупни ефекат дејства неутронског и гама зрачења и функционалног старења је испитан на хибридном колу и на компонентама појединачно. Експерименти су вршени под добро контролисаним лабораторијским условима комбинована мерна несигурност експерименталног поступка није прелазила 5 %.

Кључне речи: неутронско и гама зрачење, филтерска заштита од пренапона, хибридна кола за заштиту од пренапона