THE EFFICIENCY OF GAS-FILLED SURGE ARRESTERS IN THE ENVIRONMENT CONTAMINATED BY NON-IONIZING RADIATION OF FUSION REACTORS

by

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The research presents an experiment with a model of an electronic generator for energy injection into the plasma of a fusion reactor. By recording a non-ionizing field in the vicinity of a fusion reactor, it was determined that this field has an extremely high growth rate. At the site of the maximum intensity of the field of non-ionizing radiation, commercial surge arresters with a flexible model of surge arresters were used for experimentation. It has been found that the commercial surge arresters have an efficiency of about 20 %. For the efficiency of the flexible model, it was found to be slightly less than 40 % (and to be achieved by the application of alpha particle radiation). Since neither of these efficiencies guarantee reliable operation of the gas-filled surge arrester, it was concluded that essential electronics in the vicinity of the fusion generator must be protected. However, since this protection can only be implemented in a fusion reactor, the fact remains that the environment of such a reactor is extremely contaminated with non-ionizing radiation. Commercial surge voltages are isolated for testing since the protection of electronic circuits from fast overvoltages is a critical point for the functioning of modern electronics.

Key words: electromagnetic environmental contamination, gas-filled surge arrester, fusion reactor, electromagnetic field

INTRODUCTION

The growing need for energy leads to the need to introduce new energy plants. These new energy solutions certainly do not need to be based on fossil fuels. There are several reasons for this. The two main ones are that the reserves of quality fossil fuels are decreasing and that the use of fossil fuels significantly contributes to the contamination of the environment [1, 2]. The so-called green (alternative) energy sources are problematic because they produce electricity at a much higher price, and they are not completely without impact on the environment. In addition, and most importantly, such sources are low power and are not able to produce energy during their working life as much as is invested in their production [3, 4]. Nuclear reactors are proposed as a viable alternative solution to this problem. Nuclear reactors, thermal or fast, consume uranium (natural or enriched) as fuel, with energy obtained through nuclear fission. Due to the possibility of accidents with long-term consequences, nuclear reactors are very unpopular in most countries [4-6]. However, since uranium reserves are not large either and the disposal of spent fuel from fission reactors is a big problem, the definitive solution to humanity's energy problem is in fusion reactors [7, 8].

From the aspect of ecology, energy production based on the fusion reaction is almost entirely green energy as it does not produce any radioactive waste that could contaminate the natural environment. The nuclear fusion reaction has the appearance of gamma radiation in the decontamination process. This gamma radiation can be eliminated by protecting part of the fusion reactor with lead plates. However, the mechanism of heating the plasma by injecting energy into it with electron beams of power around TW, width of tens ns and growth rate of ns (and less) causes extremely undesirable electromagnetic contamination of the environment. The first attempt to avoid this was the project of injecting energy into the plasma with high-energy laser

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radiation. It has been shown that at some point, before reaching the fusion reaction threshold, plasma incandescence occurs. Such incandescent plasma behaves like a mirror that reflects electromagnetic rays, *i. e.* laser beams and prevents the injection of energy into the plasma and the crossing of the energy threshold for the fusion process. The electromagnetic field generated during the injection of the electron beam into the plasma endangers the technosphere and all the other aspects of the modern way of life. In relation to such fast electromagnetic fields, surge protection (so-called co-ordination of insulation at a low voltage level) becomes ineffective [9, 10].

Miniaturization of the electronic components greatly reduces their surge resistance. An overvoltage phenomenon due to very fast electromagnetic fields is induced in all (even the shortest) wire structures. Surge protection is not effective enough for extremely fast overvoltage phenomena, so overvoltage phenomena can cause damage to electronic elements, assemblies and entire devices. In addition to the electronic component damages, the transient overvoltages can also cause transient device malfunctions [11]. The effects of destruction are mainly related to semiconductor components, although insulation damage may occur on the other components. It should be noted that the destruction of electronic components coupled with antennas is common.

Surge protection elements can be generally divided into non-linear and linear. The non-linear elements of surge protection include gas-filled surge arresters (GFSA), varistors and discharge diodes. The linear elements of surge protection include different types of filters. The aim of this study is to check the efficiency of the GFSA – the most commonly used non-inear element for the co-ordination of insulation at a low voltage level of the radiation field of the electronic generator.

FUSION REACTOR (EXPERIMENTAL PLANT)

Fusion reactors are based on the fact that the binding energy per nucleus of the ^{4}He is maximum. This allows the physical process of fusion of deuterium and tritium nuclei to obtain a helium nucleus and release a significant amount of energy in the form of nucleons and gamma radiation [12, 13].

There are two problems with the fusion process: first, it is an exothermic process with a high energy threshold and second, the free path of the particle in the fusion process is very large. The first problem is solved by supplying energy to the gases to be fused until they reach a plasma state at a temperature above the fusion energy threshold. Since it was shown that the injection of energy into the plasma by laser is not effective due to the reflection of the laser beam from the surface of the red-hot plasma, it is switched to the injection of energy into the plasma by electron beams. The second problem is solved by putting the plasma particles in the fusion process in an extremely strong magnetic field. This results in the rotation of the particles around the magnetic induction vector and the possibility of crossing the mean free path for the fusion process in a small space. This simple solution is the reason why fusion reactors are not yet used for commercial purposes because the energy consumption needed to maintain that magnetic field is higher than the energy obtained by the fusion process.

At first glance, this principle of operation allows the obtaining of clean energy without any chemical or radioactive material that needs to be disposed of under special conditions. However, there is contamination by electromagnetic and nuclear radiation. The gamma radiation component in nucleons from this contamination is easily removed by appropriate protection of the fusion space. The issue of eliminating the non-ionizing component of electromagnetic radiation is harder to solve. This component is made by the electronic pulse generator and technically it does not pay to solve it with lead (and other) protective walls. For this reason, this component of electromagnetic radiation forms an electromagnetic field in the wider environment of the electronic generator, which significantly endangers the functioning of modern technical devices [14, 15].

The electronic generator generates pulses of power TW and width 1 ns. In order to obtain such pulses, the electronic generator is two-part. It consists of a vertical and a horizontal part. The vertical part is a standard Marx generator immersed in an insulating oil and adjusted most often to give pulses of atmospheric shape 1.2/50 μs. The horizontal part consists of a capacitor and a conductor to form the desired pulse shape. It is interesting that both the conductors and dielectrics of the capacitor in the horizontal part are often of the same material *i. e.*, deionized water [16]. On the horizontal part, there is also a voltage probe for monitoring the voltage shape of the electron pulse, fig. 1.

A voltage pulse monitoring probe is needed to synchronize the operation of about ten electronic generators that need to generate pulses simultaneously with minimal jitter. Figure 2 shows the layout of a single fusion reactor with eight electronic generators.

Since the electronic pulse is about 5 ns wide and up to 10 TW its growth rate is in the nanosecond (or subnanosecond) region. Pulses of such a growth rate induce in the wire structures of electrical components extremely fast overvoltages that can pass through overvoltage protection and destroy the protected components (especially for modern multilayer electronic circuits whose insulating layers are extremely thin and break by the voltages of the order of mV and V). This side effect occurs in an area several kilometers away from the fusion reactor.

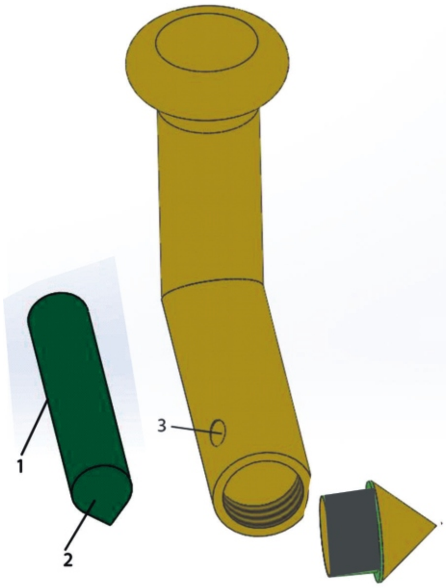

Figure 1. Electronic generator: 1 – pulse shaping circuit, 2 – 50 waveguide adapter resistance, and 3 – position for setting the measuring and control probe

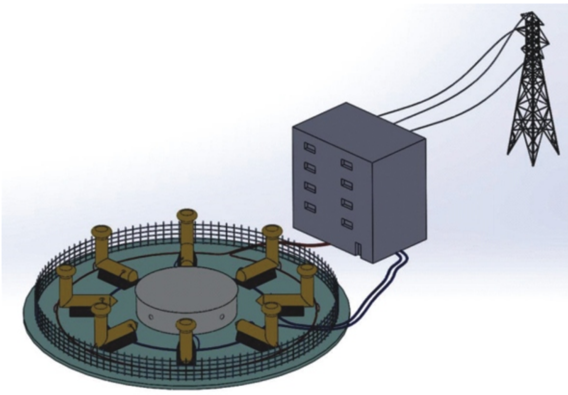

Figure 2. Schematic diagram of a fusion reactor with eight electronic generators

EXPERIMENT

The model of the horizontal part of the electronic generator powered by a cable generator was used for the experiment, fig. 3.

The model of the horizontal part had a builtin fast capacitive probe, fig. 4. The cable generator generated a rectangular voltage pulse with the following characteristics: 1 – the peak value of the rectangular pulse was 50 kV, 2 – the duration of the peak value of the voltage pulse was 600 ns, and 3 – the time of the rise and fall of the rectangular pulse was 1-3 ns.

The electromagnetic field in the vicinity of the horizontal part of the electronic generator was recorded with a Narda instrument, fig. 5 [17-21].

The gas-filled surge arrester was installed in place of the maximum value of the electric field, according to the scheme in fig. 6. The operation of the gas-filled surge arrester was checked by measuring the voltage on the resistor, R (100 M). The voltage is measured by a digital oscilloscope (1 GHz) housed in a protective cabin protection 100 dB [22, 23].

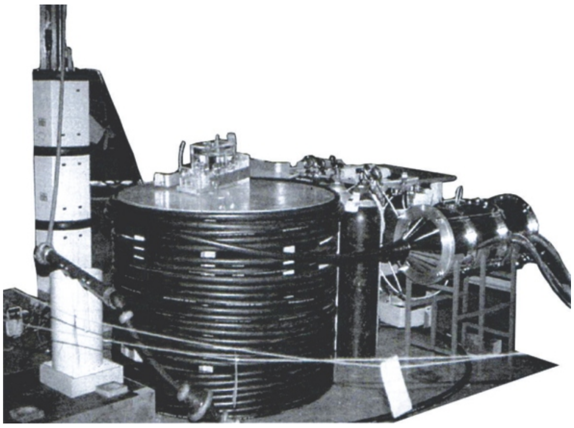

Figure 3. Cable generator for generating a rise pulse of about 1 ns

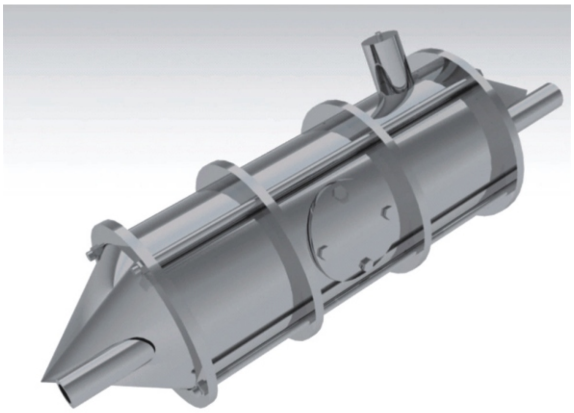

Figure 4. Model of the horizontal part of the electronic generator with a built-in fast capacitive probe

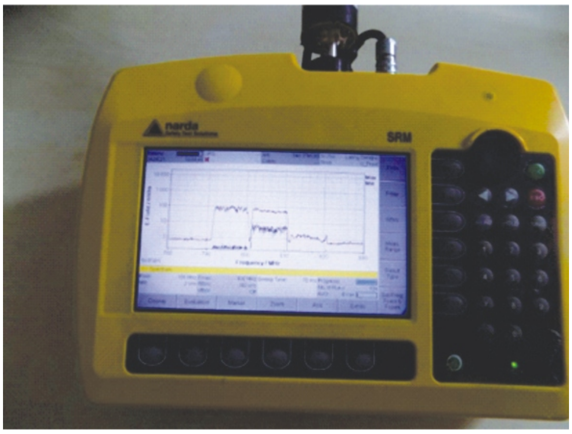

Figure 5. Non-ionizing electromagnetic radiation field generated by triggering a fusion generator model at a distance of 1 km from the experimental plant

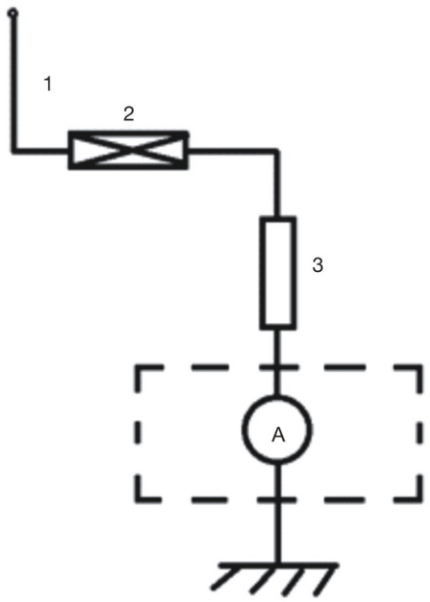

Figure 6. Experimental scheme: 1 – antenna, 2 – gas-filled surge arrester, 3 – grounding resistance, and 4 – cabin for protection against electromagnetic waves greater than 100 dB

Commercial gas-filled surge arresters and a flexible model were used. The flexible model is shown in fig. 7. At the flexible model of the gas-filled surge arrester, it was possible to change the shape of the electrodes, electrode materials, the insulating gas and the interelectrode distance.

Standard cylindrical electrodes were used *i. e.*, electrodes with a cavity filled with a radioactive source ^{241}Am. The gas pressure in the flexible model could be changed. The gas used was He. The circuit for filling and adjusting the pressure in the flexible chamber is shown in fig. 8. The operating point of the flexible chamber is set to the same operating voltage as the operating voltage value of commercial surge arresters [24-26].

The measurements were performed under well-controlled laboratory conditions. Since it was measured the complementary quantity (GFSA operating – GFSA not operating), the measurement uncertainty typeA and typeB was zero [27, 28].

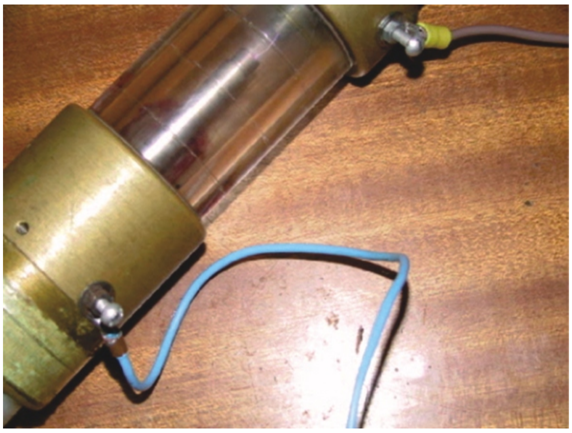

Figure 7. Flexible model of the gas-filled surge arrester

RESULTS AND DISCUSSION

Table 1 shows the results of testing the efficiency of removal of induced overvoltages caused by triggering the electronic generator model. The results in tab. 1 are given for three types of commercial GFSA of different manufacturers with the same nominal voltage.

Comparing the impulse characteristics of commercial GFSAs and the GFSA model showed that the GFSA model has a faster response to overvoltages. The response of the GFSA model was the fastest in the case of using a combination of the hollow cathode effect and by the application of a radioactive source of ionizing alpha radiation ^{241}Am.

There was also a rapid response when either the hollow cathode effect or the ionizing alpha radiation effect was used. The explanation for increasing the response rate by applying the effects of a hollow cathode and ionizing radiation is in the increase in the number of free electrons (potentially initial) in the GFSA

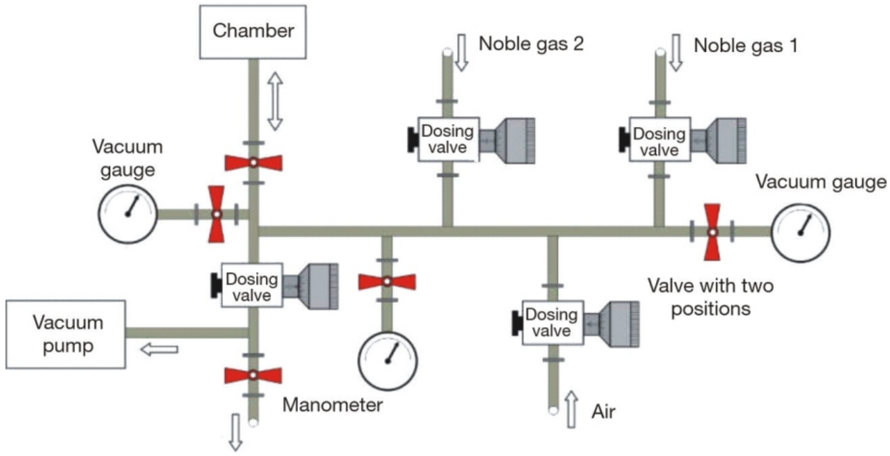

Figure 8. Gas circuit for charging the gas-filled surge arrester

Table 1. Experimentally obtained efficiency probability values of commercial GFSA; *p* is the probability that GFSA responds to an overvoltage wave and 1-*p* – the probability that GFSA does not respond to an overvoltage wave

	p	1-*p*
Type A	18	82
Type B	16	84
Type C	23	77

Table 2. The experimentally obtained values of the probability of the GFSA model efficiency, Model 1 is the hollow cathode effect together with the ionizing radiation effect, Model 2 is the effect of ionizing radiation, Model 3 is the hollow cathode effect, *p* – the probability that GFSA responds to an overvoltage wave, and 1-*p* is the probability that GFSA does not respond to an overvoltage wave

	p	1-*p*
Model 1	37	63
Model 2	31	69
Model 3	29	71

interelectrode space. However, a GFSA constructed using these effects would not guarantee effective protection of electronic circuits and electronic components. This can be seen from tab. 2, which gives the results of testing the removal efficiency of the induced overvoltages caused by triggering the electronic generator model.

CONCLUSION

The paper shows that the protection of electronic components using GFSA is not effective in the vicinity of an electronic generator of the fusion reactor. This is a consequence of the fact that such a generator gives pulses with rise and fall of 1 ns. When such a rapidly changing field is induced in an antenna (or any wire structure), an overvoltage wave is created in the subnanosecond region (since the overvoltage wave is actually an inductive peak that is mathematically represented by differentiating the induced current). It is not possible to start microscopic processes of electrical discharge (which can be of microsecond duration) in such short time intervals. As for the application of a hybrid drainage scheme with a gas arrester, a drain diode (very similar to a Zener diode) and a varistor, one cannot hope for great reliability. The reason is that taking the full voltage from the drain diode leads to its physical destruction. The result presented in this paper undoubtedly shows a higher efficiency of surge arresters with a radioactive source. However, this solution should be avoided because in this way the uncontrolled use of alpha radioactivity is introduced into nature, which is extremely dangerous if it enters the food chain. For this reason, all electronics that control the fusion generator should be protected with lead shielding. This measure would ensure reliable operation of fusion reactors but would not prevent its environment from being contaminated with rapid non-ionizing radiation, which would result in the impossibility of using modern electronic devices in it. This does not mean that fusion reactors will not in the future produce high electromagnetic contamination of the environment in their vicinity, especially in the domain of the technosphere.

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AUTHORS' CONTRIBUTIONS

P. V. Osmokrović performed measurements in the high voltage laboratory in Karlsruhe and in the IRCE EnergoInvest Sarajevo. N. M. Arandjelović, U. R. Ramadani and D. P. Nikezić analyzed the results and participated in preparation of the final version of the manuscript. The figures and tables with parameter fitting were prepared by I. M. Lazović and N. S. Mirkov.

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ЕФИКАСНОСТ ГАСНИХ ОДВОДНИКА ПРЕНАПОНА У СРЕДИНИ КОНТАМИНИРАНОЈ НЕЈОНИЗУЈУЋИМ ЗРАЧЕЊЕМ НАСТАЛИМ У ФУЗИОНИМ ГЕНЕРАТОРИМА

Рад је експерименталног карактера. Формиран је модел електронског генератора за инјектовање енергије у плазму фузионог реактора. Снимањем нејонизујућег поља у околини оваквог генератора утврђено је да је то поље изузетно велике брзине пораста. На месту максималног интензитета тог поља нејонизујућег зрачења експериментисано је са комерцијалним одводницима пренапона и флексибилним моделом одводника пренапона. Установљено је да комерцијални одводници пренапона имају ефикасност око 20 %. За ефикасност флексибилног модела установљено је да је ефикасност нешто мања од 40 % (и да се постиже применом радиоактивног зрачења алфа честица). Пошто ниједна од тих ефикасности не гарантује поуздани рад гасом пуњеног одводника пренапона закључено је да битна електроника у близини фузионог генератора мора бити заштићена. Међутим, пошто се та заштита може спровести само код фузионог реактора остаје чињеница да је околина таквог реактора изузетно контаминирана нејонизујућим зрачењем. Комерцијални одводници напона су изоловани за испитивање пошто је заштита електронских склопова од брзих пренапона критична тачка за функционисање савремене електронике.

Кључне речи: електромагнетна контаминација животне средине, гасом пуњени одводник пренапона, фузиони реактор, електромагнетно поље