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Cheap Varistors or Expensive TVS-diodes?

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Abstract: *Varistors and suppressors (TVS-diodes) are well-known and widely-used in electronic equipment as components providing voltage surge protection. For very powerful but very short-lasting pulses of the nanosecond range, with steep raising edge (such as HEMP pulses), the suitability of varistors and TVS-diodes is questionable. Since the technical community did not reach any shared vision regarding this point, the author performed its own tests described below.*

Keywords: *varistor; TVS-diode; supressor; HEMP; EMP*

1. Introduction

Different components with nonlinear current-voltage characteristics are widely used to protect the electronic equipment against the voltage surge, since they are capable of reducing their resistance upon the voltage surge applied. The most popular components of this kind are as follows: gas-discharge tubes (GDT), metal-oxide varistors (MOV) and so-called suppressors (Transient Voltage Suppressors or TVS-diodes) based on the avalanche effect. GDT are characterized by the relatively long response time to the applied voltage surge, plus their breakdown voltage rises dramatically with the pulse raising edge steepness rise. Thus, their use is rather limited. MOVs and TVS-diodes are used more widely since they are free from such disadvantages. The advantages of MOV and TVS-diodes are especially relevant if we need to ensure protection against the powerful nanosecond range voltage surges. Such a pulse appears at electronic devices inputs and outputs upon the high-altitude nuclear explosion. A high altitude electromagnetic pulse (HEMP) of 2/25 nanoseconds generates the electric field up to 50 kV/m near the Earth's surface, and the numerous cables connected to the industrial electronic devices absorb the electromagnetic energy over the large area and deliver it directly to the inputs of the sensitive electronic equipment. Pulse amplitudes generated at such inputs far exceed the amplitude of the ordinary switching and atmospheric surges used as the basis to design the available protection. Thus, additional external protective measures are required to ensure the reliable HEMP protection, such as varistors and TVS-diodes.

However, powerful TVS-diodes are rather expensive. They may cost up to 100–150 USD each, while the varistors of comparable power are approximately 80–100 times cheaper. When it comes to shunting additional protection components in parallel to each input and output of electronic equipment with dozens of inputs and outputs, such as microprocessor-based protection relays, the relevancy of the headline of this article becomes obvious. If the cheap varistors can fix the problem as efficiently as the much more expensive TVS-diodes, it appears that they are preferable. The only question is do they cope with the problem no less efficiently than TVS-diodes?

2. Varistors vs. TVS-Diodes

Attempts to analyze the information regarding the comparative characteristics of varistor and TVS-diode capability of ensuring protection against the short voltage pulses of a nanosecond range available in technical literature are not a satisfactory conclusion, since their findings are exactly opposite. For example, in [1] TVS-diodes are known as the fast-response protective components, and the varistors – slow-response protective components. In [2] TVS-diodes are known as the fast-response protective components and the varistors – medium-fast protective components. In [4], the fantastic data is attributed to TVS-diode response rate – 0.01 nanoseconds and states that varistors respond approximately 50–100 times slower. In [5] it is stated that TVS-diodes have a significantly lower response rate, while in [6], it is argued that the exact opposite is concluded, based on the application tests of varistors and TVS-diodes production samples. There are some non-published reports on experiments on the capability of varistors to ensure the HEMP protection, stating the successful results of such experiments in defiance of numerous confirmations of their insufficient response rate.

Due to such ambiguity and the lack of the definitely confirmed data, was carried out our own research.

3. Testing of the Powerful Protective Components Under Conditions Closes to Reality

Under actual operating conditions of the industrial electronic equipment located inside the metal cabinets with long cables connected to its inputs and outputs, the parameters of circuits exposed to HEMP are significantly different from those existing under the isolated laboratory conditions.

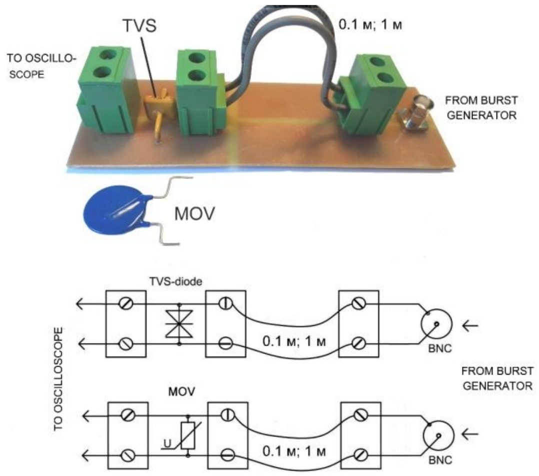

Figure1. *The appearance of the model with the tested components installed and the test pattern*

Thus, the tests were performed on the model in some way corresponding to the real conditions, see Fig. 1.

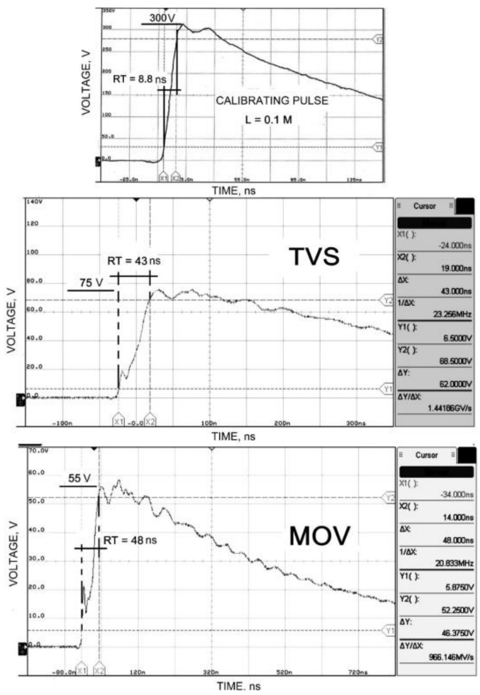

Figure2. *Oscillograph traces recorded upon the test of the two protection component types: TVS–diode (TVS) and varistor (MOV) on the model with the short conductors (0,1 m long); RT – pulse rise time.*

During the model test, the tested protective component (varistor – MOV and suppressor – TVS) and the length of the conductor (0.1 m and 1.0 m) were changed. The varistor type B72220S0600K101 was tested, with the rated voltage of 60 V (85 V DC) and the clamping voltage of 165V, the capacity of 3600 pF, and the equal in power TVS-suppressor type PTVS10-076-TH, with breakdown voltage of 85–95V, clamping voltage of 140V, and the capacity of 5600 pF.

The model included the standard terminal, ordinary insulated wire, and printed board. The protective components (varistors and TVS-diodes) are installed on this board. Obviously, such an arrangement of the model makes the high-frequency parameters (capacity, inductance, wave impedance) far from perfect and do not correspond to the pulse generator output and the oscilloscope input characteristics.

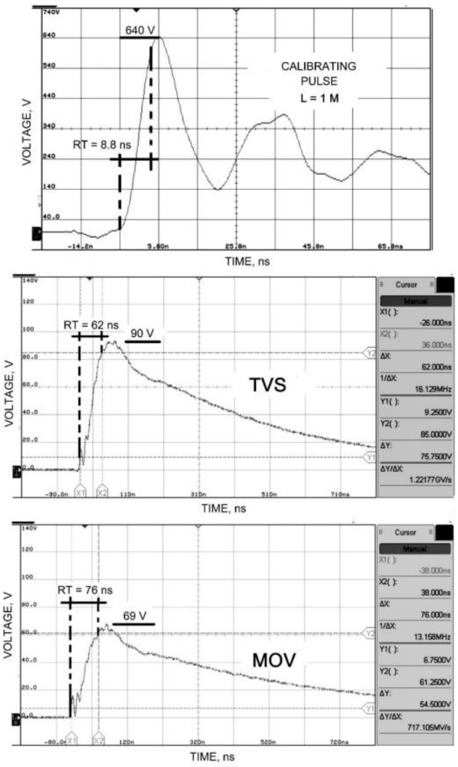

Figure3. *Oscillograph traces recorded upon the test of the two protection component types: suppressor (TVS) and varistor (MOV) on the model with the long conductors (**1 m** long); RT – pulse rise time.*

It was impossible to simultaneously record the signal sent by the generator and the signal remaining on the protective component with the oscilloscope, such as to assess the properties of the protective components using both signals and to compare the signals as planned. Thus, during the test, the calibration pulse was initially recorded after the protective component was unsoldered and removed. Then, the protective component was returned and the signal was repeatedly recorded without any changes to the circuit. The recorder oscillograph traces are depicted in Fig. 2.

The calibration pulse sent to the model with the protective component removed kept the high rise time within the nanosecond range, while the pulse width increased up to hundreds of nanoseconds. Both tested components (MOV and TVS) cut the input pulse amplitude down to the level approximately equal to their breakdown voltage. Upon that, the pulse amplitude rise time on the components was significantly changed and decreased by a factor of five, (approximately) probably under the influence of the capacity of the protective components.

Fig. 3 shows the results of the test of the protective components where the long wire is connected to the input. As we see in the records, the calibration pulse rise time was not changed while the protective components pulse rise time was decreased even more compared to the short-wire arrangement. As before, both protective components were able to respond in proper time and limit the input pulse amplitude. Compared to the previous test, the voltage limiting level was a little higher due to the increase of the input pulse amplitude and, thus, of the current flowing through the protective components after their breakdown.

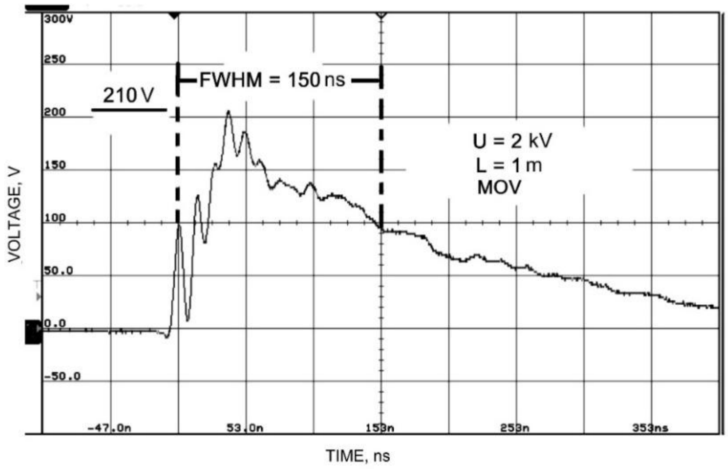

Figure4. *Oscillograph traces of varistor operation under the test pulse of 2kV amplitude. FWHM (Full Width at Half Maximum) – width of the pulse at the middle of the amplitude*

Finally, the varistor with a long wire was tested, see Fig. 4. The tests were performed under the test pulse amplitude increased up to 2 kV. The resulted oscillograph trace demonstrates that the varistor clamping voltage is significantly lower than the applied pulse amplitude (2kV), meaning that the varistor successfully responded and catted that pulse. However, it is obvious that the actual varistor clamping voltage amplitude significantly exceeded the nominal reference value of 165V for the first time. What does it mean? To answer this question, we need to understand the nature of the clamping voltage existing on the pulse protective component. This characteristic is indicated by the manufacturer. Logic suggests that it must be a voltage remaining on the protective component after its breakdown. Thus, this is the voltage applied to the equipment protected by this component. Such is indeed the case. But why did the clamping voltage significantly exceed the value shown in the specification during the test? Since varistor properties are far from perfect, the manufacturers use a trick and indicate the clamping voltage appears under the much lower current (1% or less) compared to the varistor design value in their specifications, see Fig. 1. Additionally, since the voltage drop on the protective component depends on the current flowing through it, it is clear that the clamping voltage should be low for the low current value. During the test described above, the current pulse flowing through the varistor upon the applied voltage of 2 kV exceeded the current value used by the manufacturer to measure the clamping voltage. Thus, the real clamping voltage of the varistor exceeded the rated value. Nevertheless, it means that under the actual operating conditions with unknown voltage amplitude and the current flowing through the varistor after its breakdown, it is not possible to define the voltage remaining on the varistor and on the protected equipment itself! Under the pulse currents of several kA, (used as a nominal value when designing the powerful varistors) the clamping voltage on the varistors may reach several kilovolts! Upon the impact of intensive HEMP, the effectiveness of the protection is hardly predictable without any relation to its response rate.

TVS-diodes are free from such disadvantages since, with some minor exceptions, (special diode types) the manufacturers' specifications show the value of the clamping voltage existing under their rated maximum pulse current (see Table 1).

Table1. *Current values used by manufacturers for clamping voltage measurement*

Type	Peak of Surge Current for 8/20 µs Pulse Waveform, A	Peak Current Used at Max. Clamping Voltage Measurement for 8/20 µs Pulse Waveform, A	Percent of Peak Current Used for Clamping Voltage Measurement, %
MOV			
V5E50P	800	5	0.6
MOV-20D680K	2.000	20	1
V20E50P	10.000	100	1
B72225S4301K101	20.000	150	0.8
V25S300P	22.000	100	0.5
B722240B0321K101	40.000	300	0.8
V321BA60	50.000	200	0.4

TVS			
TClamp2512N	120	100	83
SP03-6	150	100	67
AK1 (series)	1.000	1.000	100
AK3 (series)	3.000	3.000	100
PTVS-3 (series)	3.000	3.000	100
PTVS-10 (series)	10.000	10.000	100
AK15 (series)	15.000	15.000	100

Even the group of in-parallel varistors, see Fig. 5, does not help [7].

It confirms the definitive advantage of TVS-diodes, but they cost…

Will it work if we try to limit the current flowing through the varistor upon the breakdown in order to reduce the varistor voltage drop? The solution should not be purely theoretical, it should be suitable for the real electronic apparatus cabinets and cover the whole HEMP frequency range.

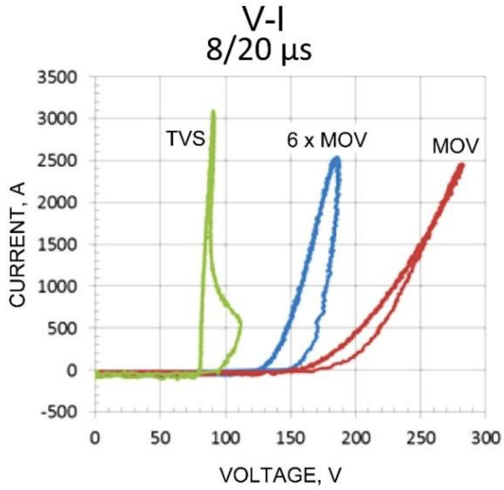

Figure5. *Volt-amps diagram of low-voltage protective components: TVS-diode and varistor (MOV) and groups of 6 in-parallel varistors (MOV) [6]*

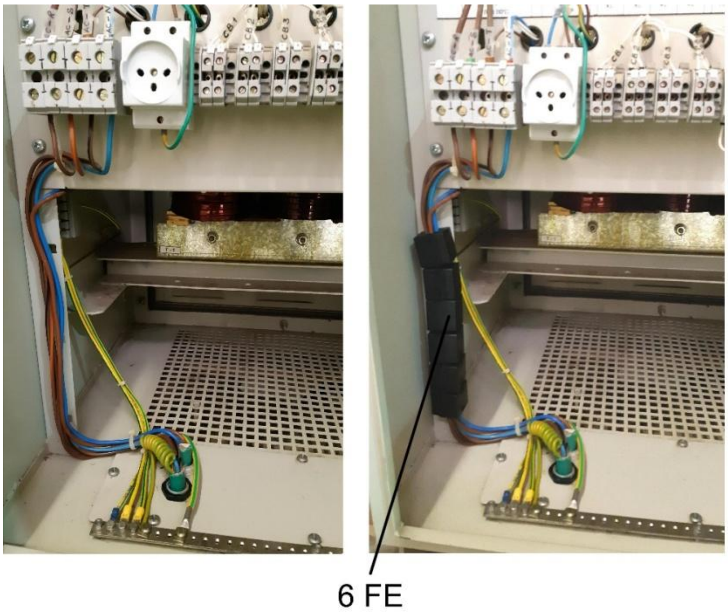

Figure6.*The arrangement of ferrite elements (FE) in the electronic equipment cabinet. Left – before installation, right – after installation.*

Such a solution exists – it consists of split snap-on ferrite beads [8], (that do not require cable cutting up) built into the latched plastic frame installed on the multicore control cables entering the cabinets containing electronic equipment, see Fig. 6.

Nevertheless, there was a need to assess how effective those filters were when it comes to the current limiting.

In order to get this information, certain types of ferrite bead filters designed for 300 kHz–100 MHz frequency range were tested. Additionally, the vector network analyzer Planar TR1300/1 connected to the PC was used, see Fig. 7.

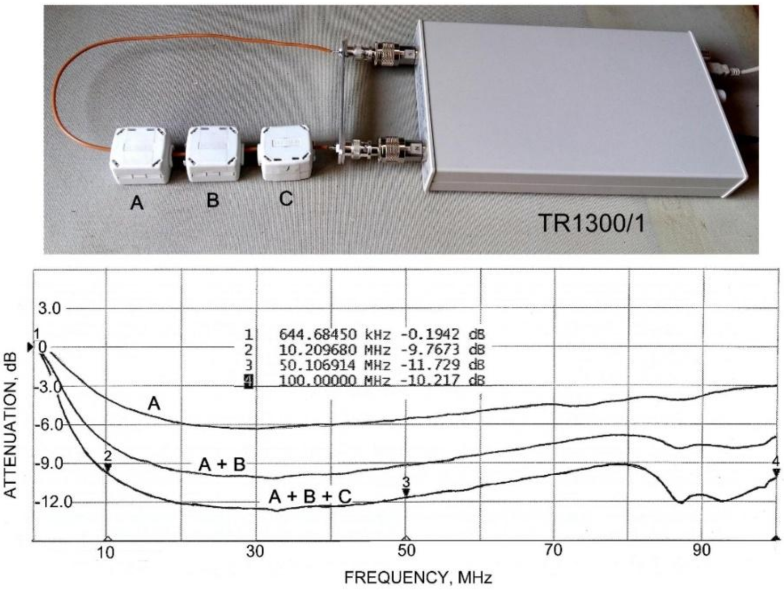

Figure7. *The effectiveness of high-frequency ferrite bead filters*

As ferrite elements (FE), Wurth Elektronik split snap-on ferrite beads were tested, built into the plastic frame with Star-Tec Snap 74271222 latches designed for installation onto the multicore control cable, with the outer diameter up to 12mm. These FE are rated for 1 MHz–1 GHz according to the manufacturer and cost approximately 6 USD each.

Our test showed that a single FE was not capable of providing any useful noise suppression. To get the significant attenuation up to 10 dB (threefold current attenuation and tenfold power attenuation of noise signal) within 10 MHz–100 MHz range, three similar ferrite beads installed in-series on the cable were required. However, as it is seen on the curves, such ferrite beads are not able to ensure the effective noise elimination within the lower frequency ranges. Therefore, in order to improve the overall effectiveness, it seems reasonable to install the additional ferrite bead designed specifically for such a low-frequency range. Usually, the lower limit of the frequency range of such ferrite beads is 150 kHz–300 kHz and the upper limit – is 30 MHz–100 MHz, according to the manufacturers' specifications. Nevertheless, despite the numerous different ferrite bead characteristics indicated in the manufacturers' specification, the ability of such ferrite beads to attenuate the noise within the certain frequency range is unknown and we were forced to perform additional tests.

The resulting attenuation level provided by the above low-frequency ferrite beads are shown in Fig. 8.

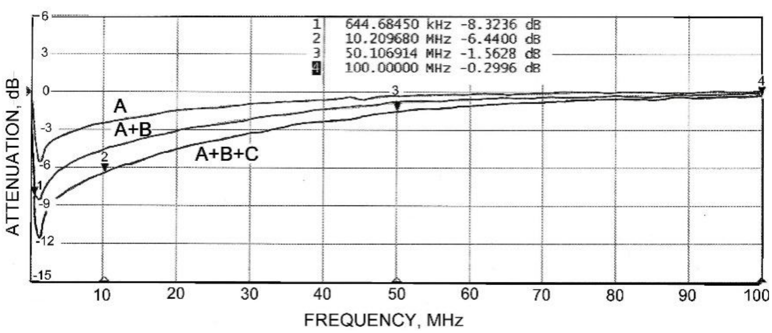

Figure8. *The effectiveness of filters based on the one, two, and three low-frequency ferrite beads*

Fair-Rate low-frequency split snap-on ferrite beads built into the plastic frame with latches type 0475164181 made of material 75 designed for installation onto the multicore control cable with the outer diameter up to 12mm were tested. These ferrite beads are rated for 200 kHz–30 MHz range according to the manufacturer and cost app. 10 USD each.

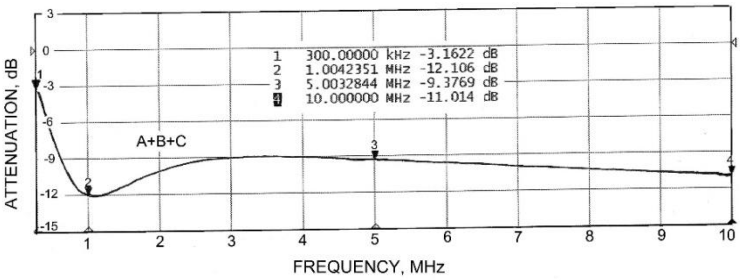

Figure9. *Resulting performance of three in-series low-frequency ferrite beads types 0475164181 installed on the cable and acting near the frequency range lower limit (up to 10MHz).*

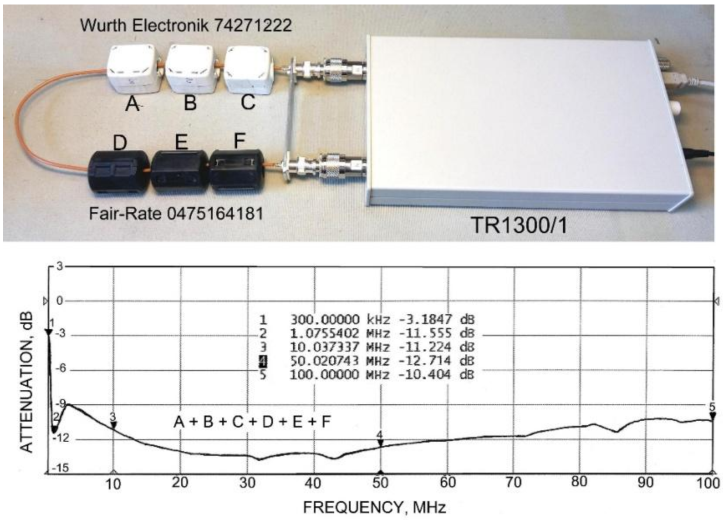

Figure10. *The effectiveness of the filter based on the combination of three high-frequency and three low-frequency ferrite beads.*

For illustration purposes, Fig. 9 shows the resulting performance of three in-series low-frequency ferrite beads installed on the cable and acting near the frequency range lower limit. As can be seen in Fig. 9, the most significant attenuation the low-frequency ferrite beads provide is within the frequency range where the high-frequency ferrite beads are not effective.

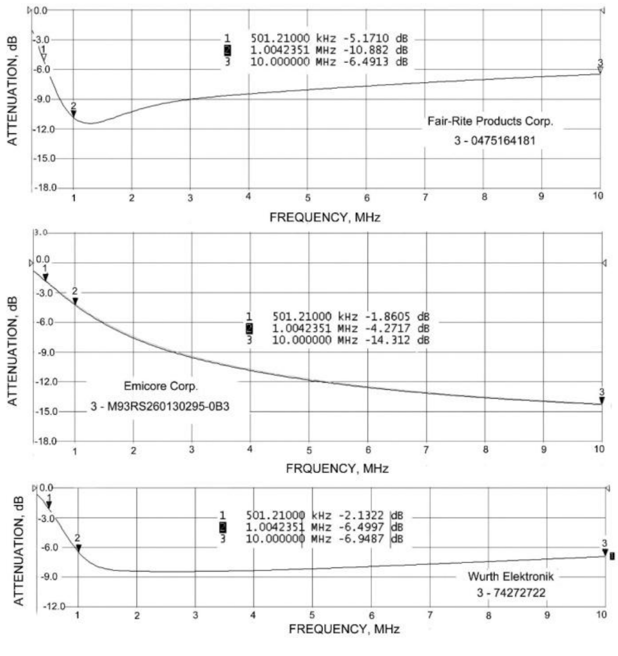

Figure11. *Attenuation within the frequency range up to 10 MHz ensured by the sets of 3 different ferrite beads.*

At first glance, it confirms the previous conclusion regarding the usefulness of the combination of high- and low-frequency ferrite beads installed on the same protected cable. The resulting performance of the full set of six in-series ferrite beads installed on the cable is shown in Fig. 10.

The comparative tests with the samples of ferrite bead type M93RS260130295, manufactured by Chinese Company Emicore Corp., were also performed. According to the promotion, the bead of this type is made of the new M93 material designed especially for the medium frequency range, see Fig. 11.

As can be seen in the resulting frequency characteristics, see Fig. 11, the samples of Emicore Corp. ferrite beads are not very effective within the low-frequency range. However, when the frequency rises above 10 MHz they show the increasing signal attenuation, while other bead samples trend towards attenuation decreasing.

As in the previous tests, it was assumed that the combination of the three new samples with three low-frequency Fair-Rate or Wurth Elektronik beads must ensure the best result. Indeed, three medium-frequency Emicore Corp. ferrite beads, enforced with three low-frequency Fair-Rate or Wurth Elektronik ferrite beads, ensure the significant correction of the performance of the initial samples, as can be clearly seen from Fig. 12.

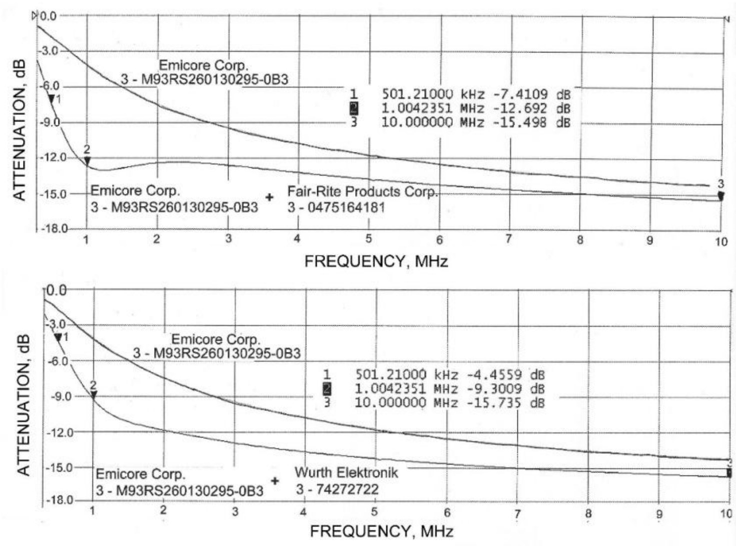

Figure12. *Correction of the resulting performance of the filter based on the combination of three Emicore Corp. ferrite beads enforced with three low-frequency Fair-Rate (top) and Wurth Elektronik (bottom) ferrite beads.*

As can be seen in Fig. 12, low-frequency Fair-Rate ferrite beads are more effective compared to Wurth Elektronik devices within the frequency range up to 1 MHz. Also, the comparative test within the full frequency range was made, see Table 2, Fig. 13.

Table2. *Attenuation ensured by the different types and combinations of ferrite beads. The number of ferrite beads is shown in the brackets*

Frequency MHz	Attenuation, dB			
	Emicore M93RS260130295–0B3 (6)	Emicore M93RS260130295–0B3 (3) + Fair–Rite 0475264181 (3)	Emicore M93RS260130295–0B3 (3) + Wurth Elektronik 74272722 (3)	Fair–Rite 0475264181 (3) + Wurth Elektronik 74271722 (3)
0,5	−4	−6,3	−3,9	−4
1	−8,5	−12,3	−9,1	−11,6
10	−19,4	−15,5	−15,7	−11,2
50	−19,5	−14,3	−14,5	−12
100	−18	−10,2	−10,4	−10,4

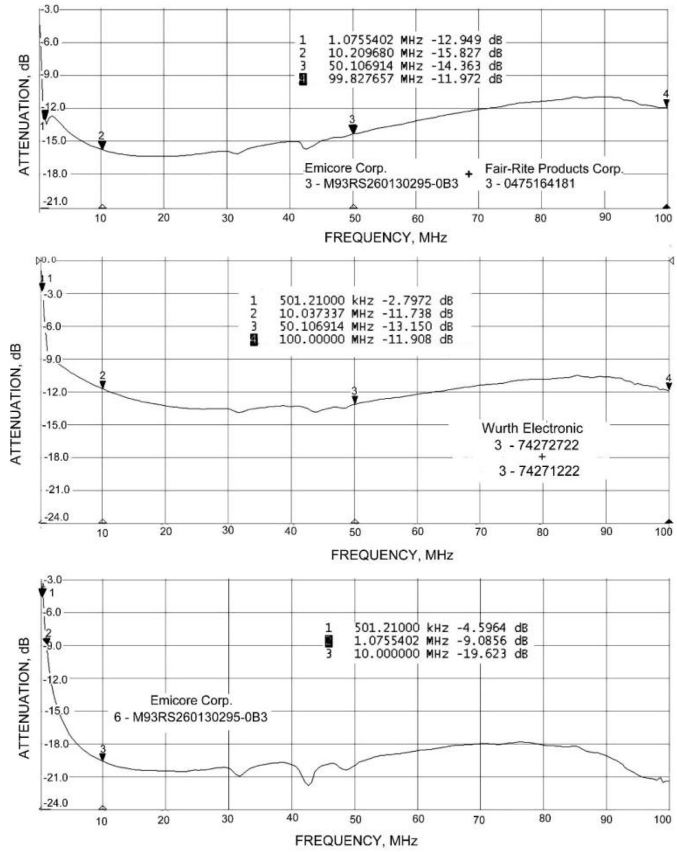

Figure13. *Attenuation within the full frequency range ensured by the sets of 6 different ferrite beads.*

As can be seen in the resulting data, Emicore Corp. samples demonstrated better results within the full frequency range, while Fair-Rite Products Corp. samples showed better results on the initial range section. In other words, six Emicore Corp. ferrite beads of the same type appeared to be much better than the combination of three low-frequency and three high-frequency ferrite beads of different types.

Attenuation to 18 dB provided by the set of Emicore Corp. ferrite beads within the wide frequency range means eightfold reduction of noise signal amplitude and sixtyfold decrease of the signal power. These figures are satisfactory considering in particular that these beads are very cheap and widely available.

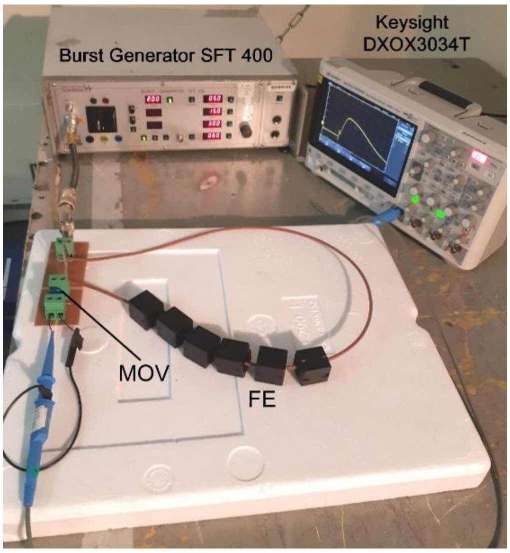

Figure14. *Design of the test-bed used to test the interoperation of a varistor and the set of six ferrite beads.*

It is possible that the set of six medium-frequency Fair-Rite Products Corp. ferrite beads of type 31 is no less efficient than the set of six Emicore Corp. devices.

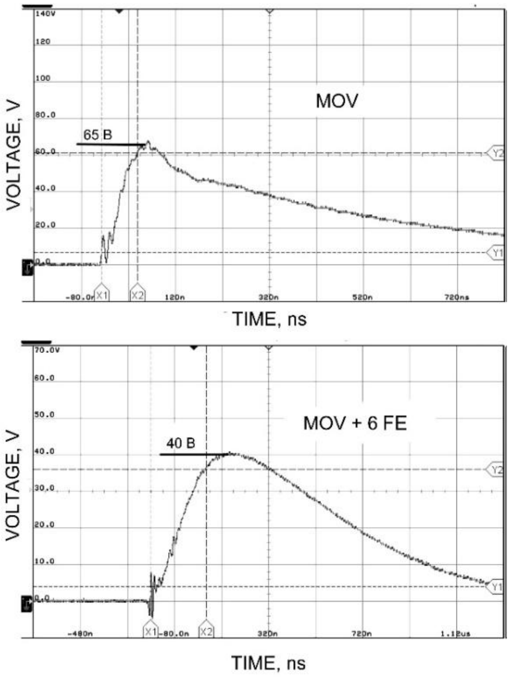

Figure15. *The voltage on the varistor (MOV) without ferrite beads (top) and with ferrite beads (bottom)*

However, since discuss the industrial (not military) use and a very large number of ferrite beads, the price becomes the most significant factor. Emicore Corp. ferrite beads are much less expensive than Fair-Rite Products Corp. ones, while the quality is very high. Besides, many American companies working within the EMC field or manufacturing the EMC-related products, are subjected to different export restrictions and must receive from the buyers the official statements confirming that their products will not be used for military or nuclear weapon purposes.

Clearly, it will be hardly possible to get such devices if we want to use them for HEMP protection.

Selected ferrite beads (of Emicore Corp.) were mounted on the model described above, and tested together with a varistor, see Fig. 14.

The tests show a rather significant positive effect of ferrite beads on varistor performance, see Fig. 15.

4. Conclusion

- The test shows that due to their responsiveness, both varistors and TVS-diodes built on the avalanche effect are capable of being used for providing the basic protection of the cabinet enclosed industrial electronic equipment against HEMP.
- Powerful TVS-diodes are more high-quality and reliable in terms of protection compared to varistors. However, since varistors are less expensive, an alternative is needed when it comes to the wide application.
- Such an alternative solution may be realized with the combination of varistors and ferrite beads, and such ferrite beads must be connected before the varistors on the cable at its entrance to the cabinet.
- Additional ferrite beads installed on the control cable ensure the raising edge steepness reduction and reduce the amplitude of the current flowing through the protective component after its breakdown. This allows to reduce the voltage drop on such a component, thus significantly improving the effectiveness of the varistor providing the equipment protection.

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He is the author of more than 200 professional papers and 13 books and holder of nearly 120 patents in the field of electrical engineering and power electronics. In 2006 he was Honorable Professor with the Kharkov Technical University.

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