Expensive HEMP Filters or Cheap Voltage Suppressors – That Is the Question…

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Use of special LC-filters to protect electric and electronic equipment from a devastating impact of HEMP is deemed to be a common means of protection described in various standards, reports and articles. This article questions the soundness of the common approach and suggests cheap voltage suppressors instead of expensive HEMP filters as the main means of protection, thus making protection of electric and electronic equipment much simpler and cheaper.

Keywords: *LC-filters, HEMP, voltage suppressor*

INTRODUCTION

Protection of electrical and electronic equipment from High Altitude Electromagnetic Pulse (HEMP) impact and Intentional Destructive Electromagnetic Interferences (IDEI) has now become very relevant due to the expanding application of microelectronics in basic fields of engineering, (e.g. power, water supply, communication, etc.) that constitutes the foundation of the country's infrastructure on the one hand, and success in reproduction of extra-power destructive electromagnetic fields – on the other hand [1].

The basic means of electric equipment protection from HEMP, which are capable of creating an electric field with the density of up to 50 kV/m at the ground surface, are well known and have been used in military systems for a long time. These means include filters, shielded cables, metal shielding shells (Faraday cages) and pulse voltage limiters. The same devices are also recommended as protection of critical industrial and power equipment [2, 3].

LC-FILTERS AS THE MAIN PROTECTION FROM HEMP

The LC-filters prevent penetration from HEMP into the critical equipment among the above mentioned protection means.

They are considered to be the main protection means and thus they are separately addressed in military and International Electrotechnical Commission standards. For example, MIL-STD-188-125 [4] suggests how to connect external cables to the protected equipment, *Fig. 1*. Special LC-filters protecting electric and electronic equipment from HEMP and IDEI are now considered so usual and mandatory that nobody questions the soundness of their use. Today, dozens of industrial enterprises produce hundreds of types of these filters, *Fig. 2*.

Moreover, the scope of these filters is not limited to just electronic communication, management and control equipment. They can also be used for high power equipment, *Fig. 3*.

This approach to the filters' use in various types of HEMP-protected equipment and the availability of different types of filters in the market (including those produced in the shape of a wall bushing, filters built-in into multi-pin connectors, etc.) make the developer of protected equipment realize the necessity of these filters. Consequently, diesel generators equipped with high power HEMP filters now exist, *Fig. 4*.

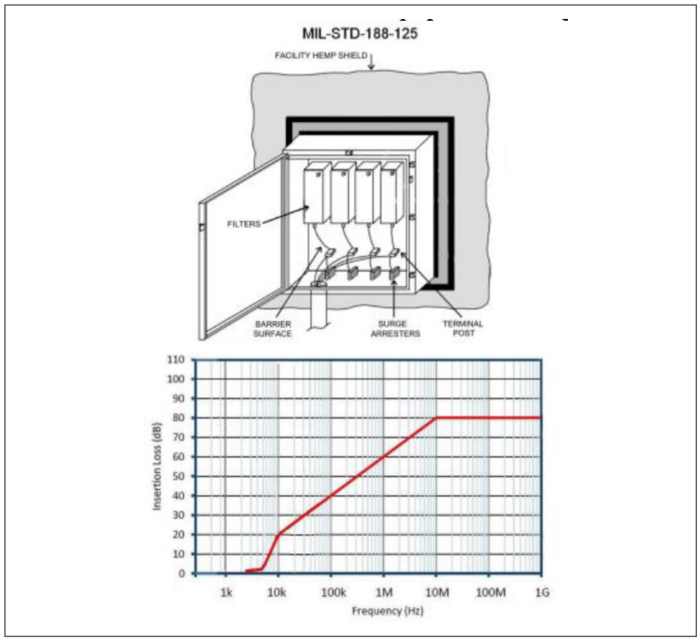

Fig. 1. A standard way of external cables' connection to protected equipment via filters and the required specifications of these filters (MIL-STD-188-125).

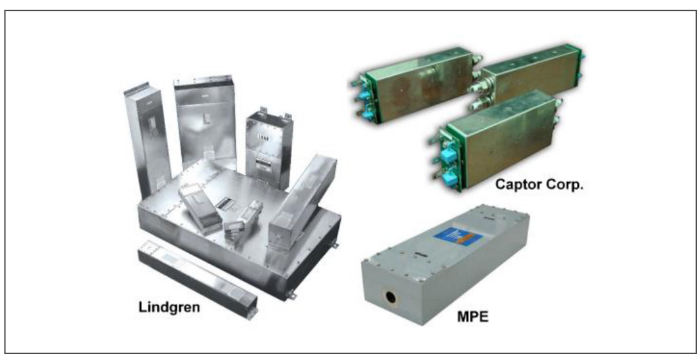

Fig. 2. Some types of HEMP filters produced by various companies

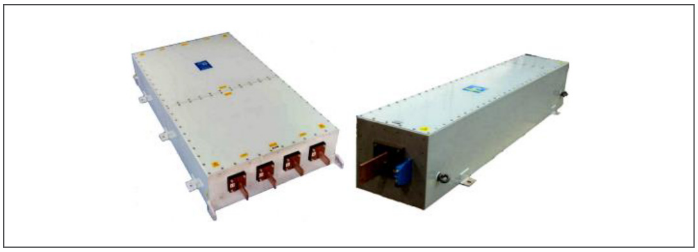

Fig. 3. Powerful HEMP filters for power circuits rated 800 and 1,200 A

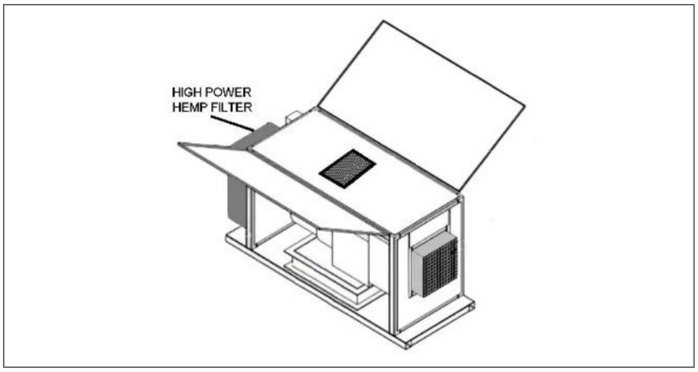

Fig. 4. Diesel generators produced by EMP Engineering equipped with a powerful HEMP filter.

HEMP FEATURES THAT AFFECT THE CHOICE OF PROTECTING EQUIPMENT

So, how do these filters protect equipment from HEMP? In order to address this, issue we need to clearly understand what HEMP is, *Fig. 5*.

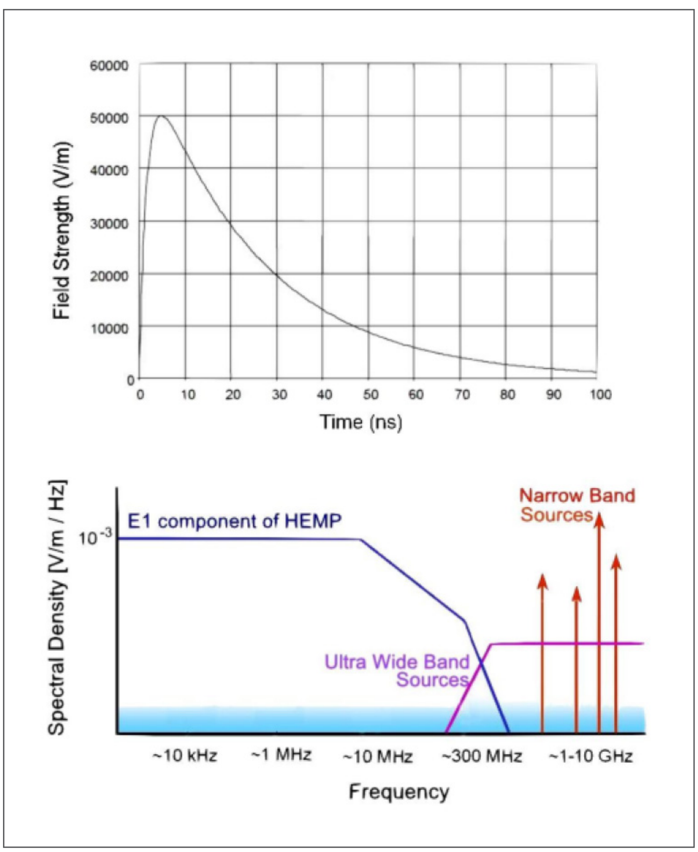

Fig. 5. Parameters of HEMP pulse (its E1 component) according to IEC 61000-2-9, IEC 61000-2-10, IEC 61000-2-11, IEC 61000-2-13 and MIL-STD-461F.

Having analyzed the specifications shown in *Fig. 5,* it is obvious that HEMP is a composite interference affecting equipment by high voltage and high frequency. Consequently, HEMP filters need to protect equipment both from HV pulse and high-frequency interference impacts. However, the majority of HEMP filters have limited operating voltage that does not exceed several hundreds of volts, whereas the HEMP's voltage amplitude can reach as high as 50 kV. This means that the filters will inevitably be damaged if they are directly connected into the HEMP-affected electric circuit. That is why the filters should be equipped with additional elements that protect from high amplitude pulse overload. The MIL-STD-188-125 stipulates the use of these protecting elements in combination with the filters, *Fig. 1*. Moreover, some filters are equipped with these protecting elements, mounted inside or outside the case.

We can see similar protecting elements on filters produced by Captor Corp., *Fig. 2*.

The above mentioned seems to be very consistent and confirms the common approach to HEMP protection based on the widespread use of filters. However, considering that HV pulse and high-frequency interferences represent absolutely different types of impact, (based on their physical properties) and protection from them is ensured by absolutely different technical means, the soundness of the common opinion regarding the necessity of the widespread use of filters as the main HEMP protection is questionable.

These doubts only become stronger after reading researchers and HEMP filter manufacturers' statements :

- *"Filters are usually rated for hundreds of volts, but an EMP-induced signal may be many thousands of volts"* [5].
- *"High Voltage HEMP Filters are designed to protect sensitive electronics equipment during hazardous transient conditions. They are employed to absorb a potentially destructive overshoot voltage"* [6].
- *"Transient suppressors within HEMP filters are usually varistors"* [7].
- *"All the lines feature high energy varistor transient suppressors"* [8].
- *"All lines are individually filtered and featured necessary varistor transient suppressors* [9].

Some manufacturers, such as: Huber+Suhner, Meteolab, NexTec, Teledartner and others, equipped their HEMP grade filters with GDT instead of varistors, but according to [10]: "GDT device cannot protect any penetrating EMP noise. In other words, it is not suitable if we use GDT device to protect electronic systems against EMP", therefore such filters are definitely not a solution for HEMP protection.

Let us discuss both aspects (high voltage transient and high frequency impacts) separately.

Fig. 6. Some HEMP filters equipped with HV pulse protecting elements. VDR – varistor, GDT – gas-discharge tube.

PROTECTION OF EQUIPMENT FROM HIGH-FREQUENCY INTERFERENCE GENERATED BY HEMP

As known, all kinds of serious integral circuits (IC) intended for use in military and critical industrial applications must be tested on susceptibility to high frequency interferences according to group of standards IEC 62132, on radiated and conducted disturbances by different methods in the frequency range 150 kHz to 1 GH. The controllers and other electronic devices that include IC also must be tested to electromagnetic compatibility according to a group of standards IEC 61000. It is the reason for examination of the damage effect of the microcontroller during the HEMP event [11]. It is very interesting that in this paper the damage effect caused by impact of a high voltage pulse of the HEMP, only without frequency influence, is examined.

It is known that modern industrial and power equipment undergoes compliance checks with the requirements of electromagnetic compatibility (EMC) standards. These standards provide for testing of equipment's resilience to high-frequency, high voltage interferences, applied to equipment inputs (between different inputs and between integrated inputs and the body). For example, IEC 61000-4-12 stipulates equipment checks by applying a high-frequency voltage of 1 MHz, and the amplitude of 2.5 kV. IEC 61000-4-4 and IEC 61000-4-5 stipulate application of short pulses (i.e. high-frequency signal) with the amplitude of up to 4 kV to the circuits of the equipment being checked. IEC 61000-4-3 stipulates the checks of equipment resilience to high-frequency interferences in the frequency range of up to 2 GHz. In other words, as for high-frequency interference, the standard requirements shall ensure equipment resistance to these types of interference, including HEMP-generated interference. Some parameters of HEMP-generated pulse interference differ from those that are modeled during equipment EMC compliance tests. Indeed, the HEMP interference pulse is much shorter than the standard pulse used in common EMC tests. However, it is very unlikely that the relay protection, control and automation equipment, resistant to interference under the EMC standard, will fail under the HEMP-generated very short pulse. Moreover, the difference between such impact parameters for HEMP as EFT (Electrical Fast Transient) "quick pulse" resistance testing and EFT parameters of ordinary EMC tests is just the amplitude only of test pulses. Thus, the appropriateness of special LC-filters protecting equipment from HEMP-generated high-frequency interference is very questionable.

PROTECTION OF EQUIPMENT FROM HEMP-GENERATED HIGH VOLTAGE PULSE

The situation with HEMP-generated high amplitude voltage pulse applied to equipment circuits is different. The EMC requirements and the applied methods of compliance check are not even close to real overload levels that will affect the equipment under HEMP impact. However, there are well-known and widely used methods and technical means that ensure protection from high voltage pulses. These include zinc-oxide varistors, for example, *Fig. 7*.

Fig. 7. Some types of powerful varistors that ensure protection of AC and DC circuits from high voltage transients.

The so-called suppressors (TVS – transient voltage suppressors) based on avalanche diodes, *Fig. 8*, are more advantageous compared to varistors in terms of response time (which is very important in case of a short HEMP pulse).

Fig. 8. Some types of fast powerful suppressors based on avalanche diodes

Varistors and suppressors feature the so-called clamping voltage, i.e. the voltage remaining on a varistor and the protected device connected to it in parallel after the varistor's actuation. As the common EMC standards require resilience to high voltage transient with the amplitude of 2.5-4 kV, the powerful varistors (or TVS-diodes) with the clamping voltage of 500-600 Volts will ensure reliable protection of equipment from HEMP impact without any high frequency HEMP filters. Why is that important?

Because:

- HEMP filters are expensive, especially powerful filters designed for high currents
- In case of multiple circuits requiring protection, the standard approach will need many HEMP filters that occupy a lot of space, which is not often available.
- HEMP filters are connected into the cut of control and power cables, and in case of multiple circuits, this hampers filter installation and makes the work more expensive and more difficult.

Small and inexpensive varistors, protecting control and power circuits from HEMP impact connected parallel (rather than into the cable cut) to the protected devices, make the protection significantly simpler and cheaper. In addition, it must be stressed that most industrial electronic devices are already equipped with varistors in their input circuits, for example, power supply, logic inputs of relay protection, etc., *Fig. 10*.

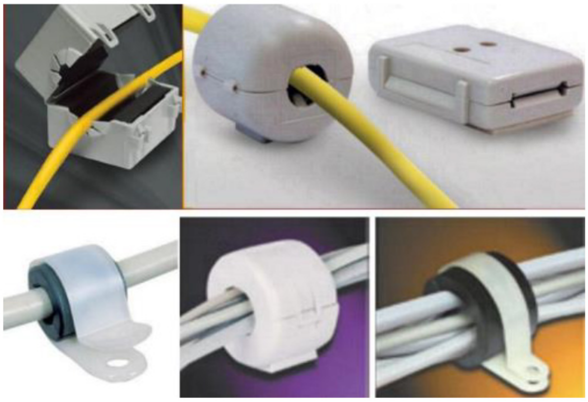

Fig. 9. Modular ferrite rings put onto the cable for additional protection of extra-sensitive electronic equipment from electromagnetic interference.

Sometimes, the power dissipation of such small varistors is not enough for protection against very high power HEMP, therefore many circuits must be protected with addition powerful varistors, for example current-carrying bus bars AC and DC, common power supplies, etc.

Fig. 10. Usage varistors in power supply (up) and logic inputs (down) of digital relay protection

Sometimes, when extra-sensitive equipment is used, it is possible to use modular ferrite rings (cylinders) that are put on the outside of the protected cable, *Fig. 9* [12].

The problem can arise only when the protected object features very low internal resistance, such as accumulator battery. When a HEMP-generated voltage pulse is applied to this device, the voltage dip may be not sufficient for the varistor's actuation. However, the current flowing through such a device can be significant enough due to low internal resistance. In this case, an inductive choke with impedance negligible for a DC current, but high enough for a high-frequency signal (short pulse), should be connected in series with the protected device.

FEATURES OF TELECOMMUNICATION EQUIPMENT PROTECTION

In a many old facilities existing telecommunication equipment based on galvanic coupling via copper-conductor cables. Standard HEMP-protection (stipulated by standards and offered by multiple manufacturers) of this equipment is represented by special filters that efficiently suppress electric signals above a certain frequency level. However, as above suggests that the use of special expensive filters to suppress a single short pulse lasting for parts of microsecond is absolutely unnecessary. Additionally, the frequency range of many modern communication and data transfer systems falls within the HEMP spectrum, which should be suppressed by these filters, whereas the filters themselves are often represented by low-voltage devices, which do not allow application of high-voltage pulses to their input. Thus, telecommunication equipment needs to be protected from the impact of high-voltage pulse only.

There are devices incorporating the elements that significantly reduce their impedance in case of higher (compared to nominal) voltage applied to them. They protect electronic equipment from high voltage pulses and include:

- Gas Discharge Tubes (GDT)
- Metal Oxide Varistor (MOV)
- Thyristor Surge Suppressor (TSS; Sidac)
- Transient Voltage Suppressor (TVS-diode)

Comparison of the best in class (based on our survey) elements based on the aggregate of key parameters that make them appealing for use in telecommunication systems is provided in *Table 1.*

Parameter \ Kind (group) of element	GDT	MOV	TSS	TVS
Best type of element in the kind (group)	2020-15T	V05E11P	TISP4011H1BJ	S03-6
Max. Operating voltage, V	-	11	5.25	6
Min. Activation voltage, V	60 (650)	18	10.5	6.8
Residual (clamping) voltage, V	52	36	3	15
Max. Pulse power, W	-	-	-	2800
Max. Pulse current, A (2/10 µs)	4000	500	500	150
Reaction time	-	-	-	-
Capacitance between electrodes, pF	2	1300	110	25

Table 1. Some main parameters of protective elements of different kinds

Response time (reaction time) of the element is one of the most important indicators, which is rarely indicated in catalogs explicitly. This is connected with many reasons, in particular, with the dependence of this time on the speed of voltage pulse rise and on the shape and the length of leads of specific elements. If this time is indicated in catalogs, it does not make a lot of sense as the manufacturers often use the semi-product (in fact, they use the material, from which the element is manufactured without leads and covering) to reduce it. Furthermore, the response time of the element in real circuits will depend on the parameters of a circuit that it is protecting. It is known, however, that TVS-diodes feature the best response time (several nanoseconds). They are followed by thyristor surge suppressors with their dozens of nanoseconds, followed by varistors with response time of several dozens of hundreds of nanoseconds. The last in this row are gas discharge tubes (GDT) with a response time of 0.2 – 0.5 ms (the rise time of the HEMP voltage pulse is several nanoseconds and length of the current pulse amounts to dozens - hundreds of nanoseconds). Other disadvantages of gas discharge tubes include high actuation voltage and residual voltage. Moreover, actuation (gas breakdown) voltage of the lowest-voltage gas discharge tubes increases sharply with the increase of steepness (decrease rise time) of applied voltage pulse.

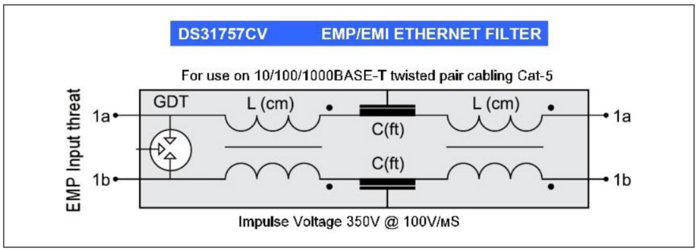

Fig. 11. Circuit diagram of a device protecting Ethernet network from HEMP based on gas discharge tube (GDT) manufactured by MPE Company.

For example, according to IEC 61643-311 [13], the minimum GDT's discharge voltage rises from 75 V to 650 V if the rate of applied voltage increase as 1 kV/μs. Obviously, this value will be even higher for HEMP pulse with its high steepness (rate of increase). Now it becomes clear that GDTs themselves cannot ensure protection of electronic equipment from HEMP. Due to this, various HEMP-protection devices marketed by some manufacturers seem very weird as their main (and often the only) element protecting from over-voltage is represented by GDTs, *Fig. 11.*

One of the manufacturers explain upon our request that they are aware that GDT cannot provide protection from HEMP, but it is preferable to use these imperfect protecting devices rather than not to use any at all. This proves that we should not rely on promotion brochures only. We need to conduct a thorough analysis of the internal structure of the offered device and the applied hardware components.

Varistors that are widely used in electric engineering are also not suitable for telecommunication systems, however, the reason is different: they are not suitable due to their high capacitance (for low-voltage elements). High capacitance connected to high-frequency circuits of telecommunication systems results in significant distortion and weakening of a useful signal. Thus, it is not acceptable to use high-capacitance protection elements in these systems. *Table 2* shows maximum permissible capacitance values for various signals recommended in [14].

Gas discharge tubes feature the best parameters from the minimum capacitance point of view (i.e. minimum impact on the circuit being protected). This feature, combined with high switching capacity (discharge currents can reach several or even dozens of kiloamperes) does not allow the developers of protecting equipment to disregard them completely. Nevertheless, it is necessary to look for workarounds of using them to protect telecommunication equipment.

Furthermore, according to many manufacturers of protecting devices, this workaround has been found. The idea was to combine high current, but a slow gas discharge tube, with a fast but low current suppressor (*Fig. 12*).

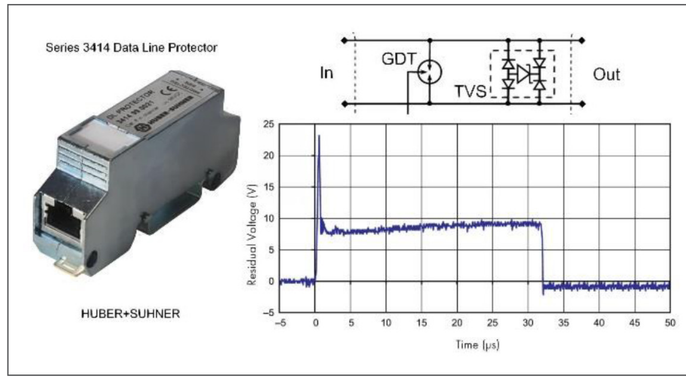

Fig. 12. Design of electric circuit of one channel and actuation oscillogram of Series 3414 protecting device manufactured by HUBER+SUHNER Company [15].

However, this technical solution is rather puzzling. Transient voltage suppressors (TVS-diode in the diagram) are known to actuate (i.e. switch into conducting low impedance state upon increased voltage pulse impact) much quicker than gas discharge tubes (GDT in the circuit diagram). But upon the TVS suppressor's actuation, the gas discharge tube will never actuate due to low residual voltage on open TVS. This voltage is not enough for gas breakdown in the GDT (minimum GDT breakdown voltage is about 60 V [13]). Lack of conditions for GDT actuation is also confirmed by an oscillogram, which clearly shows that the voltage in this circuit does not ever reach minimum voltage value necessary for GDT breakdown. Another attempt to solve the problem was made by introducing additional resistors into the circuit (*Fig. 13*).

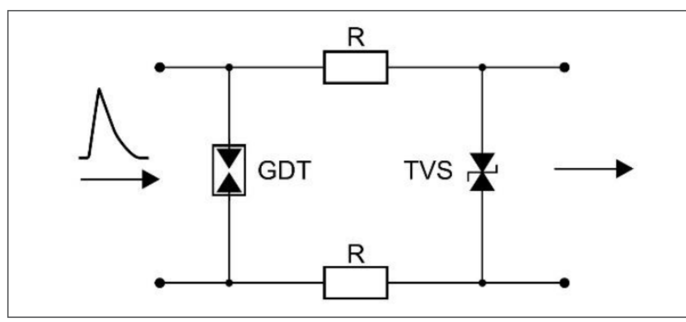

Fig. 13. A circuit diagram of compound two-stage protective device with additional resistors R

The idea of the developers was that when high voltage pulse with high steepness of the leading edge arrives at the input of this device, the first one to actuate would be the TVS, which would limit the voltage amplitude of a device being protected. Furthermore, current flowing through it will result in the voltage drop on R resistors. The total voltage drops on resistors connected in series and the TVS suppressor should be sufficient for GDT breakdown. This will bypass the input of the device after its actuation and take the current off the TVS. Thus, developers expected the device to combine advantages of a TVS (fast response) with high switching capacity of a gas discharge tube, while the total capacitance of a device was expected to remain low. This design became very popular in many various types of protecting devices, manufactured by different companies (*Fig. 14*).

Similar designs with GDT in the first stage (sometimes with different non-crucial changes and additions) are used in many protecting devices, promoted as special HEMP-protecting tools, such as those of Meteolabor and many other companies. But deeper analysis of the situation reveals hopelessness of this technical solution of a HEMP protector. This is connected with a short duration of HEMP voltage pulse (up to several dozens of nanoseconds). The action of this short pulse will finish prior to gas discharge of the tube's actuation. Thus, the GDT is not important and the lack, of or its availability, will not affect operation of the protective device.

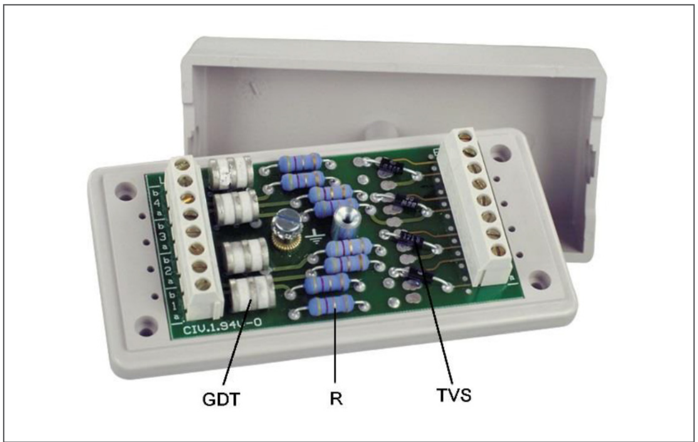

Fig. 14. A sample of compound two-stage protective device designed as shown in Figure 4 manufactured by the industry. GDT – gas discharge tubes; R – resistors; TVS – transient voltage suppressor diode.

Some manufacturers use chokes instead of resistors in a diagram depicted in *Fig. 13*. The idea is to delay the process of voltage rise on a TVS suppressor; bring the moment of its actuation closer to origination of discharge in the gas discharge tube, and thus limit time for heavy current flow through the suppressor. These chokes, featuring high impedance for a short pulse, will also limit the amplitude of current flowing through the TVS. However, the problem is that these chokes will present significant attenuation into a useful high-frequency signal that falls into the megahertz range. Thus this idea is not very suitable for telecommunication equipment.

Another problem, or more correct – a paradox, is the fact that various measures of equipment protection which weaken the HEMP's impact will result in reduction of the HEMP's pulse current amplitude. Comparatively long cables with copper cores of a small section used in telecommunication systems (i.e. with relatively high impedance) can additionally limit the HEMP's current amplitude. When the current amplitude flowing through the TVS suppressor and low-resistance resistors R (resistance of several ohm) is not sufficiently high, the voltage drop on them may not achieve the value required for GDT breakdown, i.e. 650-700 V and higher (at high rate of voltage increase applied to the gas discharge tube at HEMP impact), while a wider (due to chokes' inductance affect) current pulse will go through the suppressor causing thermal overload of its internal structure and even its destruction.

Unfortunately, these debates cannot be either confirmed or contradicted with the figures due to the lack of real initial data about a HEMP pulse in each specific case and each specific location of equipment, the level of its protection, etc. Also, there are no data about the parameters of each copper couple of telecommunication system's multicore cable running through different intermediate connections. However, a probability of unpredictable behavior of rather expensive devices, which are extensively promoted as a reliable means of protection conforming to MIL-STD-188-125, MIL-STD-461F standards, should alarm the specialists. At the same time, there is a question of how these devices have passed the conformity tests, if according to the above discussion they will not work as intended by their manufacturers. A deeper analysis reveals that there is a pitfall here as well. Indeed, manufacturers of these devices test them using a standard lightning current pulse of 8/20 milliseconds, instead of using a HEMP current pulse of 20/500 nanoseconds, as prescribed by the standards, i.e. the test pulse is flatter and longer. As an excuse, manufacturers state [16] that it is very difficult to simulate a HEMP pulse, and in order to do so special expensive equipment is required. At the same time, generators of a standard lightning current pulse are readily available in the market and they are easy to use. Since the lightning current pulse is much wider than a HEMP pulse, its energy is even stronger than that of the HEMP pulse, thus it creates higher loads for a protecting device. Then they suggest [7] that if a device withstood the test with a more powerful lightning current pulse, it will definitely withstand the short HEMP pulse. But the advocates of this test method bashfully conceal that the behavior of a gas discharge tube under long and short pulse impact will be absolutely different. Gas discharge tubes are reliable under a rather long lightning current pulse featuring a relatively flat leading edge, whereas in case of a much shorter and steeper leading edge of a HEMP, they will not have sufficient time to actuate due to:

- their natural "sluggishness"
- sharp increase of dielectric strength of gas contained in a GDT and consequently due to sharp increase of its breakdown voltage.

THE NEW METHOD OF PROTECTION IN EXISTING TELECOMMUNICATION EQUIPMENT

In our opinion, a solution is to use simple, very cheap, non-recyclable, but predictable protecting devices, based on a special transient voltage suppressor (TVS-diodes) that feature all the parameters necessary for efficient protection of telecommunication systems, such as: fast response time, low capacitance and low actuation voltage. In case of a HEMP impact, the internal p-n-junction of a TVS will breakdown as it is affected by a high current pulse flowing through it, whereas the circuit that it protects will be bypassed (short-circuited). Given the fact that a HEMP event is extraordinary and a pulse is single, non-repeating, this algorithm of protecting the device's operation is quite acceptable as it will protect the equipment from the HEMP impact, and will allow it to return to operation by just disconnecting the damaged protecting device during the recovery period, which is inevitable in case of global HEMP impact.

The only technical issue is to ensure selective action of the protecting device. In other words, TVS breakdown should occur under a HEMP impact only and not under the impact of other, weaker repeating overvoltage transients.

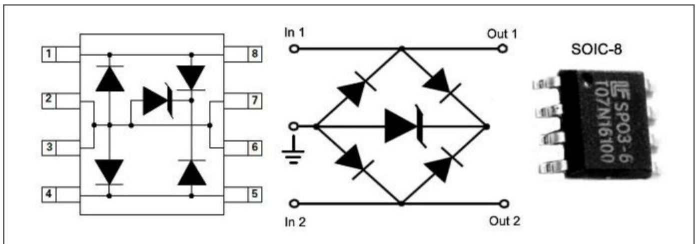

Fig. 15. Transient voltage suppressor diode (TVS) SP03-6 type.

This selectivity can be achieved primarily by selecting quite powerful TVS, and secondly by limiting the current flow through it by means of a resistor. Analysis of parameters of available TVS with low actuation voltage and very low capacitance values suitable for telecommunication systems, revealed that S03-6 type TVS-diodes (*Fig. 15*) manufactured by Littelfuse (USA) are the most powerful among others. They are more powerful compared to the TVS of other manufacturers, with the same operating voltage and capacitance values and that allow flowing of pulse currents up to 150 A.

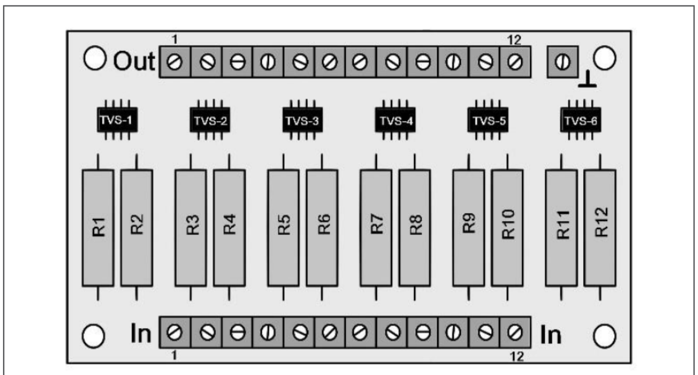

Fig. 16. A drawing of a printed circuit board of the offered protective device for 6 twisted pairs that includes TVS and current-limiting resistors. The circuit board should be coated with a high-voltage varnish.

One small chip like this protects a single twisted pair from HEMP of both common (in relation to the reference potential) and differential (between conductors) modes. The price of one element is about 2 US Dollars, however, in the case of wholesale purchase – less than 1 US Dollar.

Resistance of a resistor connected with a suppressor in series (see a circuit diagram in *Fig. 15*, where the resistor is connected in series with each input) should be about 20 Ohm, in order to limit the maximum permissible current pulse flowing through a suppressor in case the pulse transient interference with an amplitude of several kilovolts impacts the protecting device's input. The current-limiting resistors should be non-inductive and should be intended for pulse current of the following types: AW, 234AS, RT818 and others.

This design of a protective device makes it very simple in terms of engineering (*Fig. 16*) and cheap. The same principle can be used to protect the inputs of sensitive equipment connected through a socket (*Fig. 17*).

These simple devices can be produced by any manufacturer of printed circuit boards at a very affordable price. A range of Chinese companies will quickly produce the required quantity of these devices with excellent quality and at a minimal price. The latter is very important for civil branches of the electric power industry and production sector; as high cost of a HEMP protection is still a key factor that restrains practical adoption of such protection.

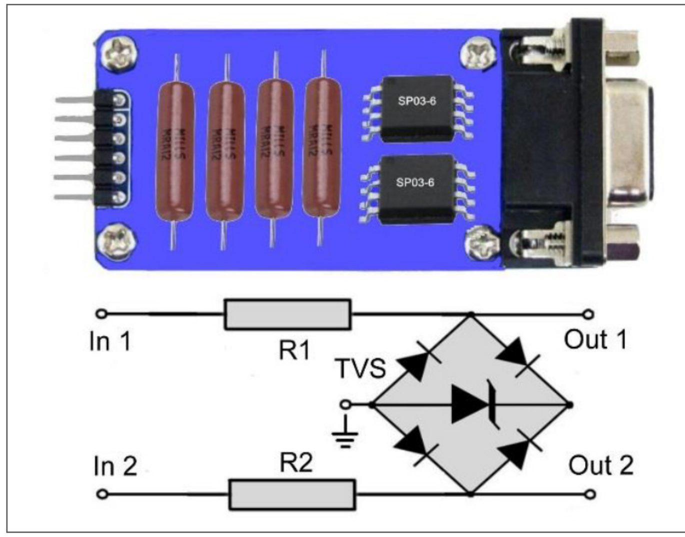

Fig. 17. An example of a simple protecting device for two twisted pairs (for E1 signal) and a diagram of one channel (for single pair) for circuits connected to the equipment via a socket.

CONCLUSIONS

It is much more important for effective protection of equipment against HEMP to use correct transient voltage suppressing rather than high frequency filtering. The above-mentioned approach means that regardless of the widespread approach to protection of electric and electronic equipment against HEMP, it is not necessary to employ special expensive filters acting as basic protection means. Alternatively, simple elements protecting from high voltage pulse (e.g. varistors or suppressors) will do a good job. Moreover, combination of the latter with other known protective means and methods will make protection of equipment from HEMP much easier and significantly cheaper.

AUTHOR BIO

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He is the author of more than 200 professional papers and 15 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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