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Ultrashort pulse decomposition in reflection symmetric meander line of four cascaded half-turns

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Abstract. The paper considers the protection of critical electronic equipment from an ultrashort pulse (USP) by means of modal filtering technology. Decomposition of the USP in a reflection symmetric meander line consisting of four cascaded half-turns is investigated for the first time. Quasi-static simulation of two half-turn connection diagrams has been performed. The output of the circuits shows the presence of negative polarity pulses, as well as additional pulses with time delay values non-multiple of per-unit-length time delays. It has been revealed that these values are linear combinations (arithmetic means) of per-unit-length time delays of the line modes.

1. Introduction

Currently, radio-electronic equipment (REE) is massively introduced in almost all domains of human activity. However, the vulnerability of electronic equipment to electromagnetic effects may entail undesirable consequences, for example, regular malfunctions of critical installations. This problem is regularly discussed at AMEREM EUROEM/ASIAEM conferences. For example, at the ASIAEM 2015 conference, the section “IEMI Threats, Effects and Protection” was allocated and even special sections were created (Design of Protective Devices and Test Methods. Evaluation of HEMP/IEMI Impacts on Critical Infrastructure). In addition, in some articles of the famous journal “IEEE Transactions on EMC”, where the results of the newest EMC research in the world are published, there are many valuable results that can be used to create a noise immunity technology for critical REE. Thus, a new threat to civil society in the form of intentional electromagnetic interference was considered [1]. One of the reasons for REE mulfunctioning can be conducted interference, which can penetrate into REE directly through the conductors [2]. Recent investigations have shown the possibility of interrupting the normal functioning of IT networks using high-power electromagnetic interference through the low-voltage-power network [3] and the local area network cables [4]. The analysis of the impact of a commercially available powerful source of damped sinusoids on a computer network was presented [5]. A typical example of a dangerous conducted interference is an ultrashort pulse (USP) [6]. This is an ultrawideband pulse of high power and short duration, having both natural and man-made origin. The results obtained in the investigation of local area networks for Fast Ethernet and Gigabit Ethernet exposed to nanosecond electromagnetic interference were presented [7]. The devices for electronic system protection against natural or man-made electromagnetic interferences with high energies and amplitudes, in particular ultrawideband (UWB) pulses, based on nonlinear protection elements were presented [8].

Traditional devices that are used for pulse interference protection, for example, voltage suppressors, varistors, passive RC- and LC-filters are known. However, such protecting devices have a number of disadvantages (low radiation resistance, short service life, failure to operate at high voltages, insufficient operating speed, etc.), making it difficult to protect against powerful USP. Thus, there is currently no effective protection of REE against USP.

A technique of modal filtration has been proposed to protect REE against ultrashort pulses (USPs). This technique is based on modal decomposition of a pulse signal into pulses of lower amplitude and can be implemented through the use of modal filters (MF) and meander lines (ML) [9].

In addition, the approach to improve modal filtration using reflection symmetry is also well-known. This approach is implemented in a device called a reflection symmetric MF. In the cross section it consists of 5 identical and rectangular conductors on a dielectric layer, with the conductors 1 and 2 located on one side, two additional conductors placed reflection-symmetrically relative to the conductors 1 and 2 on the reverse side of the dielectric layer, and the grounded conductor 5 located in the dielectric layer at an equal distance from the external conductors [10] (Figure 1). The reflection symmetric MF is noteworthy inasmuch as, providing both the edge and broad-side couplings between the conductors at certain parameters, it allows to obtain USP decomposition pulses at the line output with nearly equal values of the amplitudes of the pulses and the time intervals between the decomposition pulses (Figure 1).

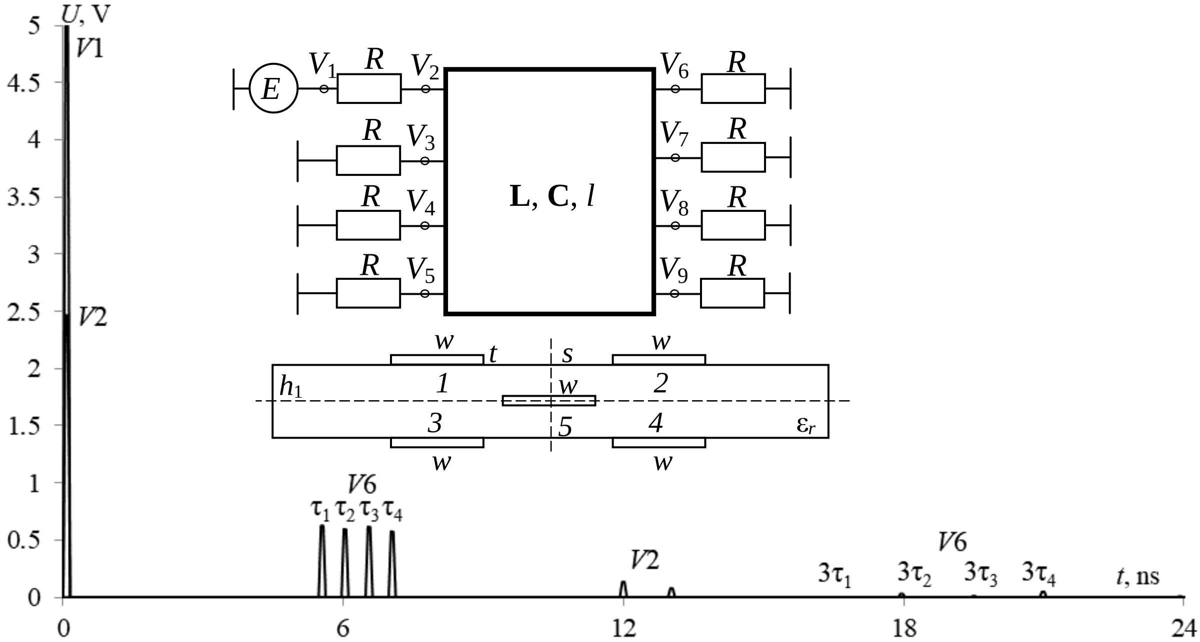

Figure 1. The schematic diagram, cross section and decomposition of the USP in the reflection symmetric MF.

Thus, it seems possible to investigate the ML on the basis of the reflection symmetric MF. So far, such configuration has not been considered as a protection device. Meanwhile, the analysis makes it possible to single out several variants of its circuit design, depending on the way how half-turns with the length l are connected. The aim of this work is to investigate the possibility to decompose the USP in reflection symmetric MLs, where the USP passes the maximum path (from the generator to the load) for a length of $4l$, i.e. along 4 cascaded half-turns.

2. Structures under investigation

Figure 2 shows the structures with the diagrams under investigation. Let us perform a quasistatic simulation with l=1 m and R=50 Ω in the TALGAT software [11] which gives acceptable accuracy and does not require high computational costs [12].

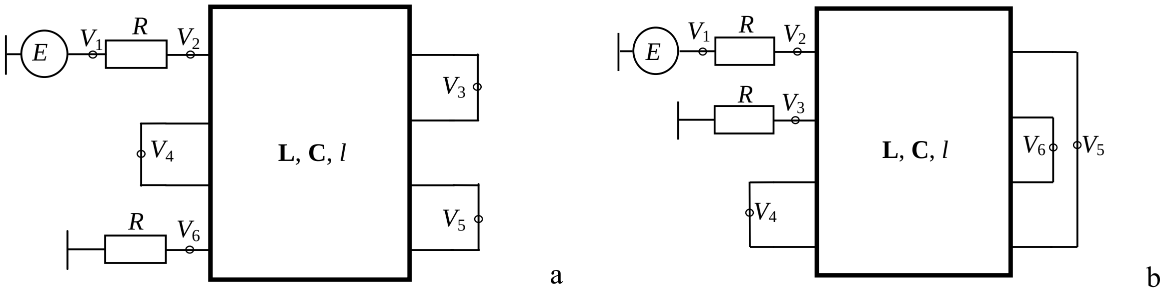

Figure 2. The schematic diagrams of half-turns connection: 1 (a) and 2 (b).

The losses in conductors and dielectrics at this investigation step were not taken into account. A trapezoid EMF source with an amplitude of 5 V with front, fall and flat top durations of 50 ps was used as an excitation, so the total duration was 150 ps (*V*1 in Figure 1). The cross section of these structures is shown in Figure 1, where *w* is the width of the conductors, *s* is the separation, *t* is the thickness of the conductors, *h* is the thickness of the dielectric and ε_r is the relative permittivity of the substrate. Simulation was performed with *s*=510 μm, *w*=1600 μm, *t*=18 μm, *h*=500 μm, ε_r=4.5.

3. Simulation results

Figures 3 and 4 show the obtained voltage waveforms at input (nodes V_2 in Figure 2) and output (nodes V_6 in Figure 2 and V_3 in Figure 2), respectively.

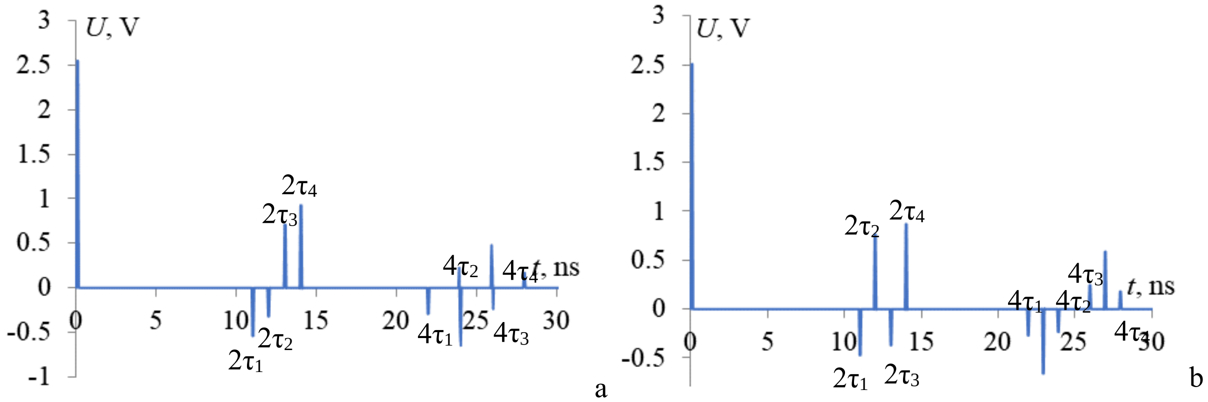

Figure 3. The voltage waveforms at the input of schematic diagrams 1 (a) and 2 (b).

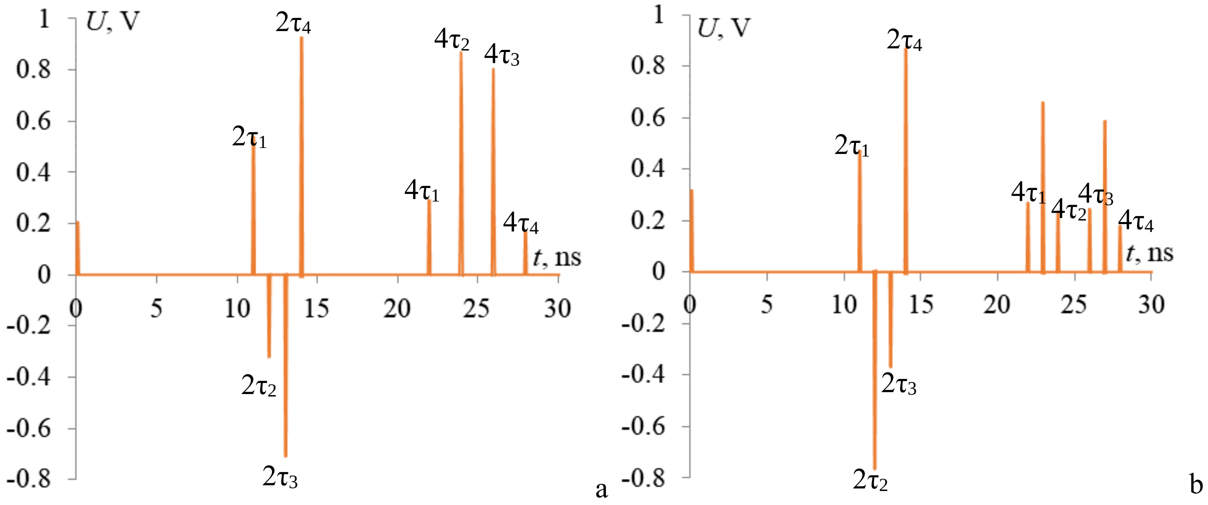

Figure 4. The voltage waveforms at the output of schematic diagrams 1 (a) and 2 (b).

On the resulting voltage waveforms, there are two groups of pulses, which time delays are multiples of 2 and 4 per-unit-lengths time delays, respectively. Consider them separately.

In the first group, a pair of negative polarity pulses is observed. Earlier, when simulating an ML [13] and a reflection symmetric MF, such pulses were not observed. For diagram 1, these are pulses of modes 1 and 2 of the input signal and modes 2 and 3 of the output signal. For diagram 2, these are pulses of modes 1 and 3 for the input signal and modes 2 and 3 for the output signal. The presence of such pulses can be explained by reflections from bridges (cross connections) on the right end of the circuit. In the reflection symmetric MF, resistors are located at all ends of the conductors, which improves the matching of all modes, while the bridges in the reflection symmetric ML provide a short circuit for some modes and an open circuit for others.

In the second group of pulses, among pulses with time delays that are multiples of 4 per-unit-lengths time delays for diagram 2, one can observe additional pulses with time delays non-multiple of per-unit-length time delays. It can be assumed that such pulses exist also for diagram 1. This can be judged by the increase in the total amplitude of modes 2 and 3, whose time delays are multiples of 4 per-unit-lengths time delays. To clarify this assumption, we will increase the *l* value from 1 to 8 m for diagram 1. The fragments of time responses with pulses whose delays are multiples of 32 per-unit-lengths time delays are shown in Figure 5.

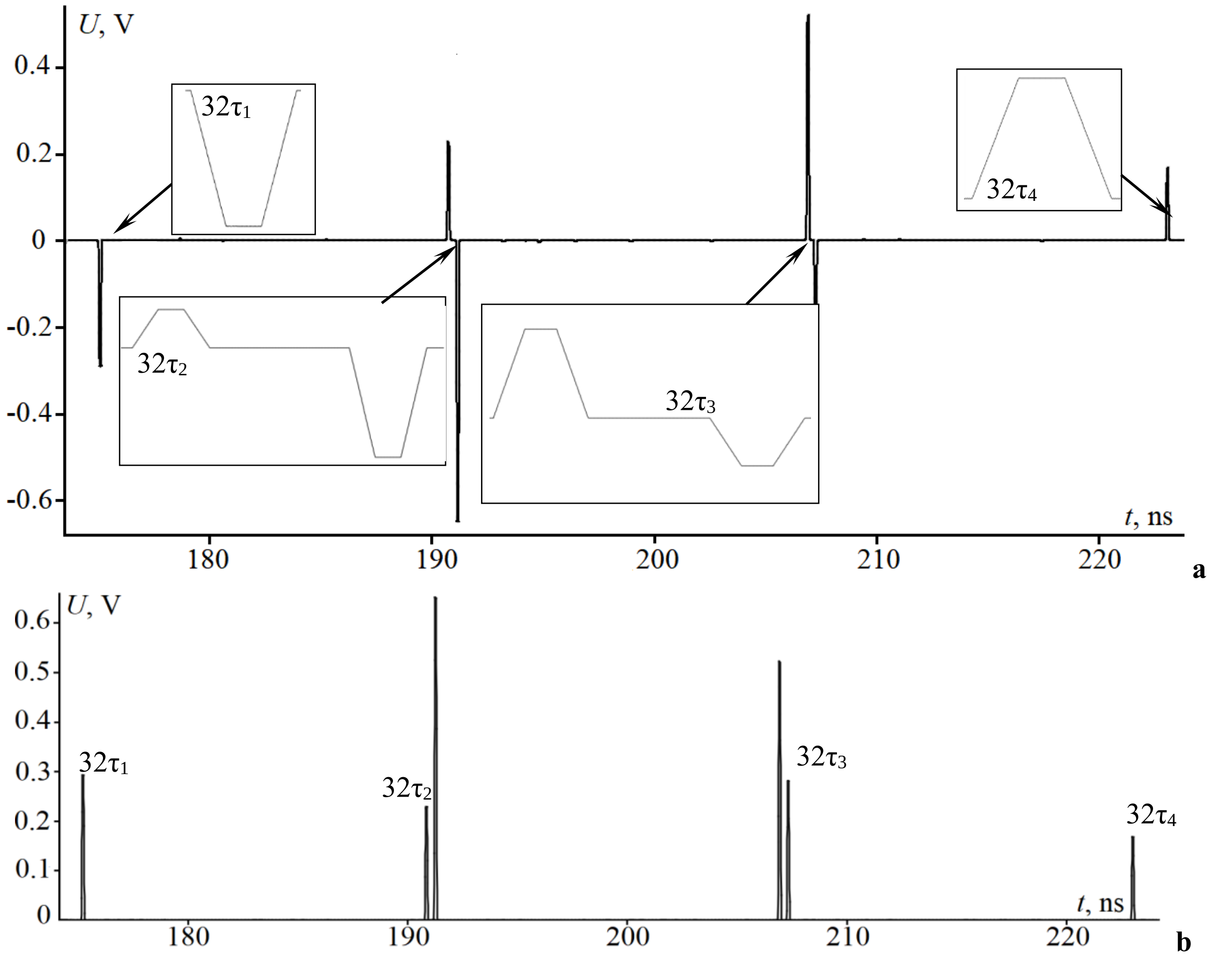

Figure 5. The voltage waveforms at the input (a) and output (b) of diagram 1 for *l*=8 m.

The simulation results confirm the assumption about the presence of additional pulses in diagram 1. Table 1 shows the values of per-unit-length time delays of modes 1–4 multiplied by 1, 2, 4 and 32, since the time delays of the pulses at the input and output of the reflection symmetric ML are multiples of 2 and 4 of per-unit-length time delays for *l*=1 m and 32 for *l*=8 m.

Table 1. Values of per-unit-length time delays (ns/m) of modes 1–4, multiplied by 1, 2, 4, 32

Multiplier	1	2	3	4
1	5.4698	5.9591	6.4746	6.9687
2	10.9398	11.9183	129.493	13.9376
4	21.8795	23.8366	258.987	27.8752
32	175.036	190.693	207.189	223.001

From the analysis of Table I and Figure 5 it can be seen that the time delays of the additional pulses are equal to the linear combinations (arithmetic means) of the per-unit-length time delays of the modes. Thus, for diagram 1, these delays are $(4\tau_1+4\tau_3)/2=23.8891$ ns and $(4\tau_2+4\tau_4)/2=25.8559$ ns, and for diagram 2 these delays are $(4\tau_1+4\tau_2)/2=22.85805$ ns and $(4\tau_3+4\tau_4)/2=26.88695$ ns. These completely coincide with the values obtained in the simulation of time responses.

Furthermore it can be seen in Figure 4 that the first impulse (with zero time delay) is a crosstalk, with an amplitude smaller than the amplitudes of the decomposition pulses. It follows from this that, by increasing the amplitude of the crosstalk pulse, it is possible to reduce the amplitudes of the subsequent decomposition pulses, which can be realized by means of optimization with the pulse amplitude equalization criterion. Obviously, the reflection symmetric ML must be optimized separately, despite the fact that it is based on the cross section of a reflection symmetric MF with optimal parameters. Moreover, since the time intervals between the decomposition pulses in the reflection symmetric MF were equalized, it was impossible to observe the presence of additional pulses in diagram 1. Thus, it is useful to optimize the reflection symmetric ML by the criteria of equalizing the time intervals between all decomposition pulses (including additional pulses) and minimizing the maximum amplitude at the ML output, in order to increase the USP attenuation. As for attenuation of the considered cases, the output voltage peak values are about 0.9 V, which is defined by the pulse amplitude with the time delay of $2\tau_4$.

4. Conclusion

For the first time, a quasistatic simulation of two half-turn connection diagrams for a reflection symmetric ML was performed in the time domain. In these structures, the possibility of additional pulses to appear in the output signal was revealed, whereas earlier they had not been detected in the reflection symmetric MF or the ML turn. It is shown that time delays of additional pulses, which are non-multiple of per-unit-length time delays, are linear combinations (arithmetic means) of per-unit-length time delays of the line modes.

In the future, it is planed to consider other diagrams of a reflection symmetric ML. In addition, multicriteria optimization of their parameters will be performed.

Acknowledgments

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