Influence of Ultrashort Pulse Duration on Localization of Crosstalk Peak Values in PCB of Spacecraft Autonomous Navigation System

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***Abstract*— Importance of research on specific aspects of ultrashort pulse propagation and voltage peak values localization along printed circuit board (PCB) multiconductor bus is highlighted. Simulation of a trapezoidal ultrashort pulse propagating along the conductors of the spacecraft autonomous navigation system bus with a different number of excited conductors and a variation of the whole ultrashort pulse duration (3; 0.3; 0.03 ns) has been carried out. In the case of 2 excited conductors, the crosstalk maximum value is 29% of steady state level of 0.5 V and the greatest (by modulus) minimum value is 33.4% of 0.5 V. In the case of 4 excited conductors, the maximum values are located in the nodes but the greatest minimum value is 39.8% of 0.5 V. It is shown that significant signal excess is observed with decreasing of ultrashort pulse duration both for maximum and minimum, but they appear in one transmission line section of the PCB bus.**

Keywords— ultrashort pulse, printed circuit board, localization, voltage peak values, quasistatic analysis, spacecraft

I. Introduction

Electric signal propagation in multiconductor transmission lines (MCTL) is properly studied [1]. However particular aspects of ultrashort pulses propagation along conductors of high density printed circuit boards (PCB) are investigated insufficiently. It can be the reason of its uncontrolled propagation [2]. It is important to reveal and localize signal peak values because it may help to determine places of possible mutual parasitic influences and interference, thus it would be possible to take necessary measures in order to ensure electromagnetic compatibility (EMC). Moreover, it can help to choose places to install sensors for control of useful signals and monitoring of interference that is also important for improvement of radioelectronic equipment noise immunity and reliability [3].

It is effective to use computer simulation in such researches rather than measurements as it is necessary to obtain waveforms at various points along each conductor of complex structures. Besides, signal distortion by the input impedance of measuring probe has influence on the accuracy of voltage amplitude measurements.

The quasi-static approach is widely used for analysis of PCB interconnections, because the accuracy of circuit analysis often unacceptable, while electromagnetic analysis often requires large computation costs. Theoretical bases of quasi-static response calculation for an arbitrary network of MCTL sections are described in [4, 5]. Algorithms for calculation of time response based on this theory are developed [6] and allow calculation of current and voltage values only in network nodes.

Basic expressions and algorithm of current and voltage values calculation, that allow improved calculation of time response at any point along each conductor of MCTL section of an arbitrary network in TALGAT software, are implemented in [7]. This paper also contains the investigation of two-turn microstrip meander line that proves the necessity of more detailed research. For this reason, one-turn meander line in parameter range was examined [8].

Inasmuch single sections of ideal coupled lines are investigated in these papers, similar investigation of real PCB bus of autonomous navigation system [9] and ultrashort pulse maximum localization along bus conductors with variation of boundary conditions [10] have been carried out. The bus investigation with variation of ultrashort pulse duration has been carried out in [11], however only active conductors are investigated in this paper. Meanwhile, the crosstalk investigation with variation of ultrashort pulse duration is important for radio electronic equipment performance and interference immunity increasing. Indeed, for performance increasing duration of useful signals is decreased, while shorter interfering signals are more dangerous.

The purpose of this paper is to investigate the localization of maximum and minimum crosstalk peak values along PCB bus of an autonomous navigation system with pulse duration variation. To achieve the purpose, it is necessary to solve following tasks. First of all, it is necessary to describe shortly theoretical basis of simulation. Then it is useful to present the investigated bus and its circuit diagram, as well as the results of signal maximum and minimum localization along its conductors with variation of excitation duration. The main results of these tasks solution are presented in the next sections of this paper.

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II. Theory

A. Response Calculation

Frequency domain equations are used for calculation of voltage and current response in MCTL section [7]:

$$\mathbf{V}(x) = \mathbf{S}_V(\mathbf{E}(x)\mathbf{C1} + \mathbf{E}(x)^{-1}\mathbf{C2}), \quad (1)$$

$$\mathbf{I}(x) = \mathbf{S}_I(\mathbf{E}(x)\mathbf{C1} - \mathbf{E}(x)^{-1}\mathbf{C2}), \quad (2)$$

where $\mathbf{S}_V$ and $\mathbf{S}_I$ are the matrixes of modal voltages and currents; $\mathbf{E}(x)$ is the diagonal matrix $\{\exp(-\gamma_1 x), \exp(-\gamma_2 x), \ldots, \exp(-\gamma_{N_k} x)\}$ and γ_{N_k} is the propagation constant for k-th MCTL section, N_k is number of conductors of a k-th MCTL section, x is the coordinate along the MCTL section. Calculation of $\mathbf{S}_V$, $\mathbf{S}_I$ and $\mathbf{E}(x)$ is described in [6]. **C1**, **C2** are constant vectors calculated as

$$\begin{bmatrix} \mathbf{C1} \\ \mathbf{C2} \end{bmatrix} = \begin{bmatrix} \mathbf{S}_V & \mathbf{S}_V \\ \mathbf{S}_V \mathbf{E}(l) & \mathbf{S}_V [\mathbf{E}(l)]^{-1} \end{bmatrix}^{-1} \begin{bmatrix} \mathbf{V}(0) \\ \mathbf{V}(l) \end{bmatrix}, \quad (3)$$

where $\mathbf{E}(l)$=$\mathbf{E}(x)$ for x=l; l is the length of the MCTL section; $\mathbf{V}(0)$ and $\mathbf{V}(l)$ are constant vectors describing the voltage at the ends of the MCTL section, determined after the solution of equation for circuit with n MCTL sections with lumped elements at the ends:

$$\mathbf{V}(s) = \left(s\mathbf{W} + \mathbf{H} + \sum_{k=1}^{n} \mathbf{D}_k \mathbf{Y}(s)_k \mathbf{D}_k^t \right)^{-1} \mathbf{E}(s), \quad (4)$$

where s= $j\omega$, where ω is angular frequency; **W**, **H** are matrices of order $A\times A$ describing the lumped memory and memoryless elements of network, respectively (A is the number of parameters, which are calculated by modified node potential method); $\mathbf{D}_k = [i, j]$ with elements $l_{i,j} \in \{0, 1\}$, where $i \in \{1, \ldots, N_k\}$, $j \in \{1, \ldots, 2N_k\}$ with one nonzero value in each column, is the selector matrix that maps the terminal currents of the k-th MCTL section; $\mathbf{Y}(s)_k$ is the conductance matrix of the k-th MCTL section; $\mathbf{V}(s)$ is the vector of node voltage waveforms; $\mathbf{E}(s)$ is a constant vector with entries determined by the independent voltage and current sources.

The algorithm used for calculation of response is described in [6]. First of all, initial time domain excitation is transformed to frequency domain by means of forward fast Fourier transformation (FFT). Then calculations of (1)–(4) are carried out. The obtained result is transformed to time domain by means of inverse FFT.

B. Structure under Simulation

PCB bus of autonomous navigation system was taken as a structure for investigation. PCB fragment is presented in Fig. 1, and its circuit diagram in Fig. 2. 50 Ohm resistors are connected to the ends of each bus conductors. Conductor bend and via are approximately modeled as capacitance of 1 pF and inductance of 1 nH, respectively. Cross sections of each MCTL section are modeled and **L** and **C** matrixes are calculated according to PCB stack parameters. The calculation is made without losses.

Two cases different by number of voltage generators were considered. In the first case, 2 generators connected to the conductor 1 and 5 (Fig. 2) were used. In the second case, 4 generators were used and the conductor 3 (central) was passive (Fig. 3). In these figures, generators are shown by arrows, and conductors are enumerated. In both cases, calculations were carried out and signal waveforms were obtained along each of five conductors with different excitations, but results are presented only for passive conductors because crosstalk levels, theirs peak values and locations are of a major interest.

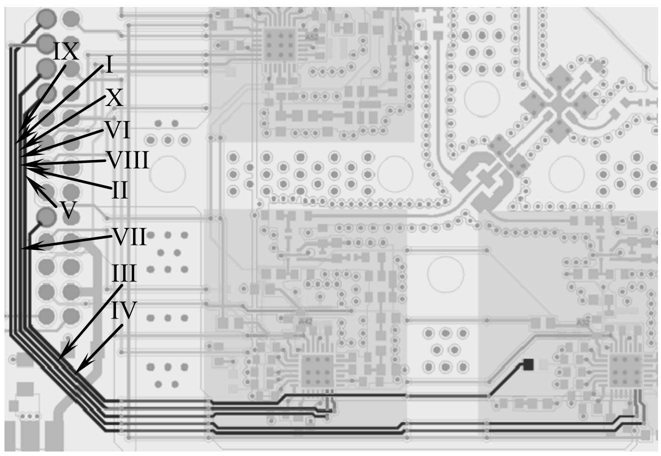

Fig. 1. Investigated bus and peak values locations on the PCB fragment

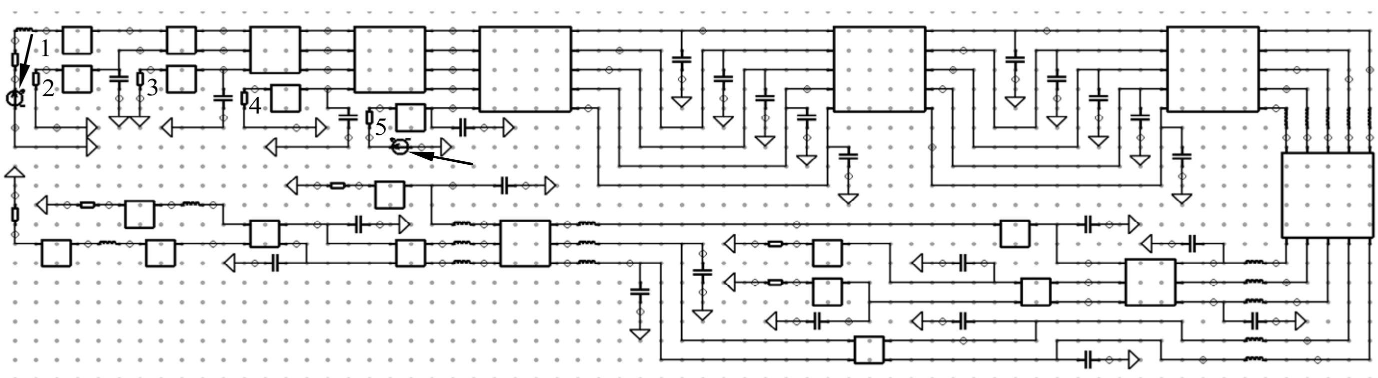

Fig. 2. PCB bus circuit diagram (with 2 generators which are pointed by arrows) in TALGAT software

To obtain signal waveforms along defined conductor, it is necessary to choose A and B points. Calculation will be carried out between these points, which are presented in Fig. 4 for the case with 2 generators when the response was calculated along the conductor 2.

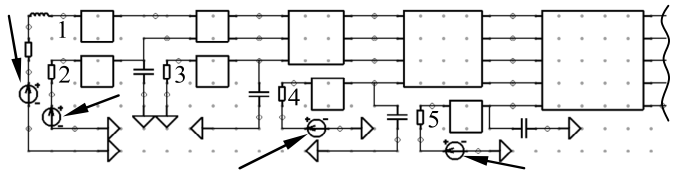

Fig. 3. Diagram fragment for the case with 4 generators

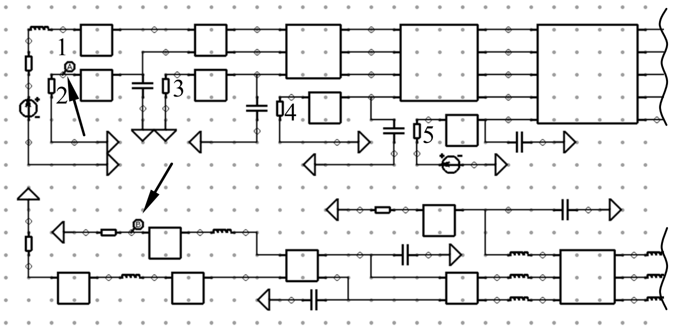

Fig. 4. A and B points for 2 generators

C. Excitation Parameters

Three types of ultrashort pulses, each with amplitude of 1 V are chosen as excitations. Waveforms of each pulse are presented in Fig. 5. The first pulse (U_1) has rise, top and fall times of 1 ns, the second (U_2) – 100 ps, and the third (U_3) – 10 ps, so the whole durations are 3; 0.3; 0.03 ns. Such choice of excitation parameters is determined by fact that in such way not only useful signals but interference are considered. Each pulse was successively fed to each generator so that pulses were the same simultaneously on the each generator.

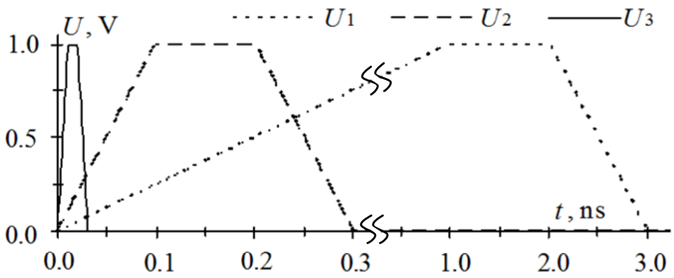

Fig. 5. Excited pulse waveforms

III. Simulation Results

In cases with 2 and 4 generators, 20 voltage waveforms were calculated in the each segment along each conductor of each MCTL section from Fig. 2. But only waveforms at the conductor beginning (U_b) and end (U_e) and also with voltage maximum (U_{max}) and minimum (U_{min}) values, appearing under each excitation, are presented. Therefore for the first case, voltage waveforms along the conductors 2, 3 and 4 are presented. For the second case waveforms only along the conductor 3 are presented.

Waveforms along the conductor 2 for the case with 2 generators under each excitation are presented in Fig. 6. Signal maximum coincides with the waveform at the input node under the excitation U_1, while minimums – under the excitations U_1 and U_2. Therefore their waveforms and locations are not shown in Fig. 6. The location of the minimum for U_3 signal is shown in Fig. 7, other locations are not shown because they are in the diagram nodes.

Simulation results for the same case but for the conductor 4 are shown in Fig. 8 and peak values locations are pointed in Figs. 9, 10, and 11. Likewise if a peak value is located in the node its location is not shown.

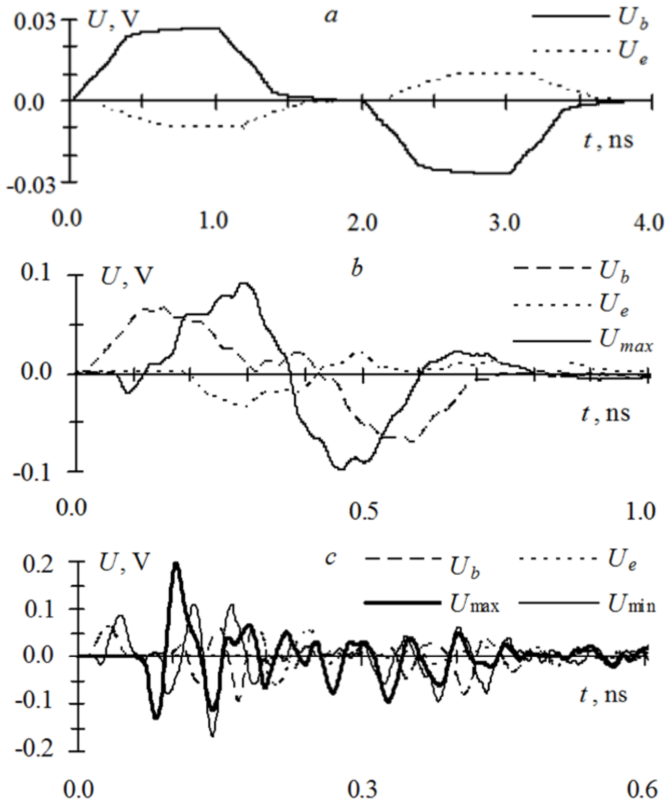

Fig. 6. Waveforms along the conductor 2 under the excitations U_1(*a*), U_2 (*b*), U_3 (*c*)

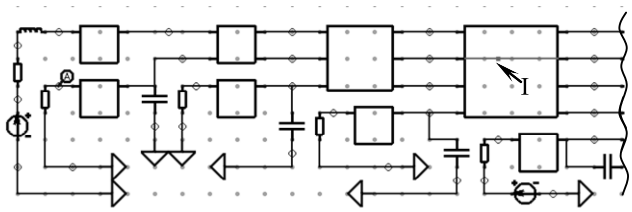

Fig. 7. Location of minimum for the signal from Fig. 6 *c*

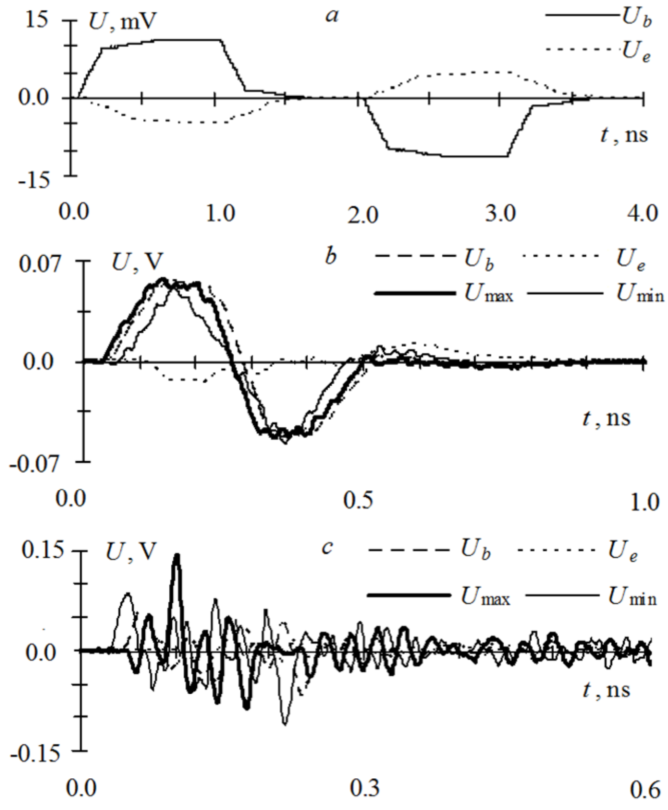

Fig. 8. Waveforms along the conductor 4 under the excitations U_1(*a*), U_2 (*b*), U_3 (*c*)

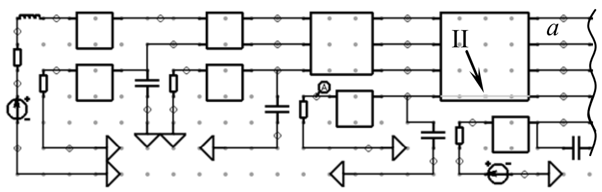

Fig. 9. Maximum location for signal from Fig. 8 *b*

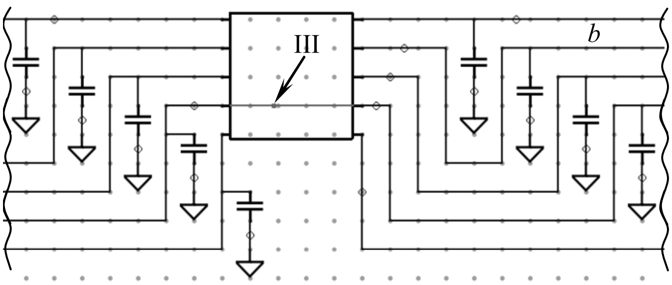

Fig. 10. Minimum location for signal from Fig. 8 *b*

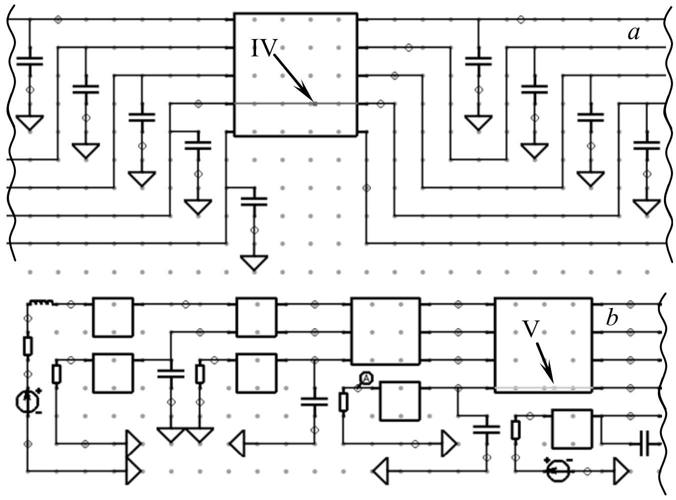

Fig. 11. Maximum (*a*) and minimum (*b*) locations for signals from Fig. 8 *c*

Simulation results for conductor 3 (central) with 2 generators are shown in Fig. 12 and their peak values are shown in Figs. 13 and 15. Simulation results for conductor 3 (central) with 4 generators are shown in Fig. 14 and their peak values are pointed in Fig. 15.

Voltage peak values and the numbers of segments with their locations are summarized in Table I.

TABLE I. VOLTAGE PEAK VALUES AND ITS LOCALIZATION PARAMETERS

Generators number	*Conductor*	*Signal*	*Figure*	U_{max}		U_{min}	
				Value, V	*Segment (Figure)*	*Value, V*	*Segment (Figure)*
2	2	U_1	6 *a*	0.027	20	-0.027	1
2	2	U_2	6 *b*	0.092	20	-0.110	1
2	2	U_3	6 *c*	0.197	1	-0.167	7 (7)
2	4	U_1	8 *a*	0.011	1	-0.011	20
2	4	U_2	8 *b*	0.058	10 (9)	-0.057	7 (10)
2	4	U_3	8 *c*	0.145	13 (11 *a*)	-0.112	12 (11 *b*)
2	3	U_1	12 *a*	0.006	1	-0.006	1
2	3	U_2	12 *b*	0.027	9 (13 *a*)	-0.025	3 (13 *b*)
2	3	U_3	12 *c*	0.090	1	-0.120	10 (13 *c*)
4	3	U_1	14 *a*	0.031	1	-0.031	1
4	3	U_2	14 *b*	0.139	1	-0.126	5 (15 *a*)
4	3	U_3	14 *c*	0.292	1	-0.199	8 (15 *b*)

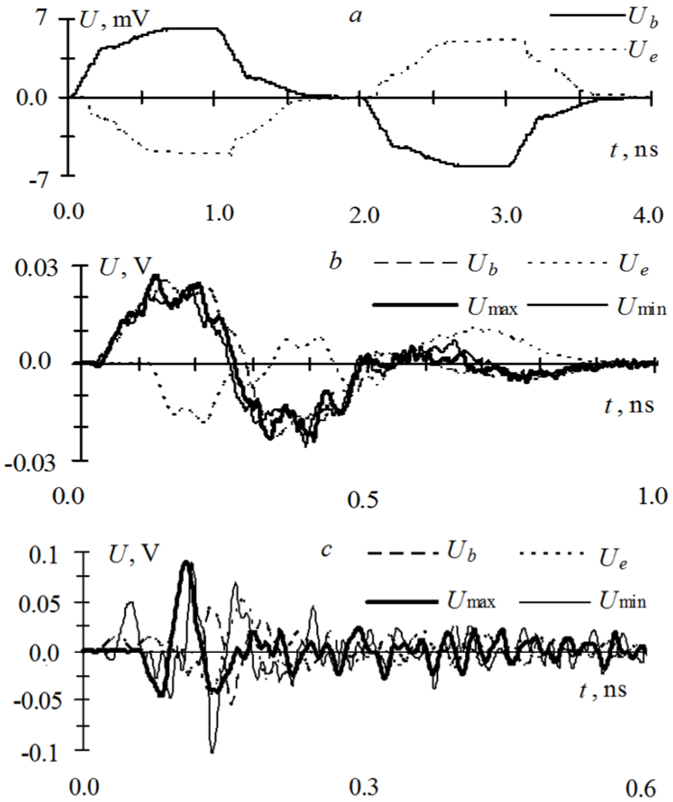

Fig. 12. Waveforms along the conductor 3 under the excitations U_1(*a*), U_2 (*b*), U_3 (*c*) with 2 generators

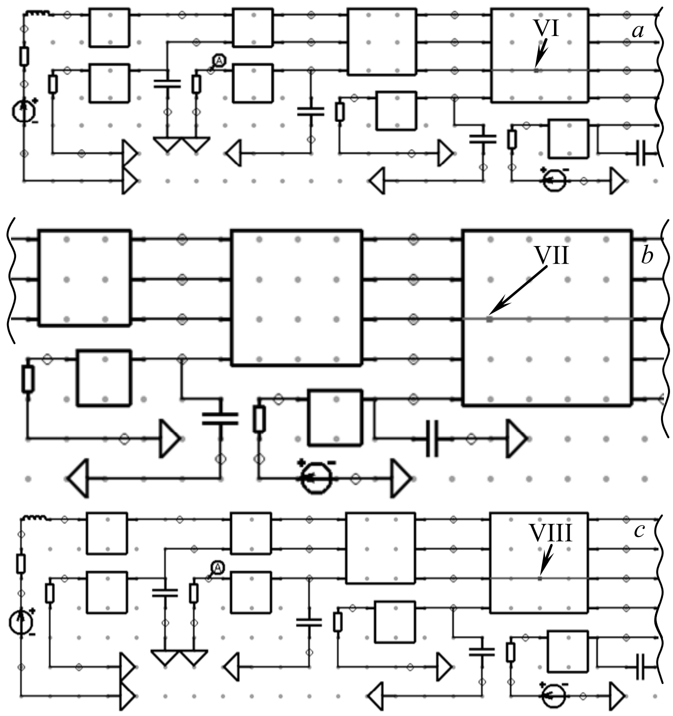

Fig. 13. Maximum (*a*) and minimum (*b*) locations for signal from Fig. 12 *b* and minimum (*c*) location for signal from Fig. 12 *c*

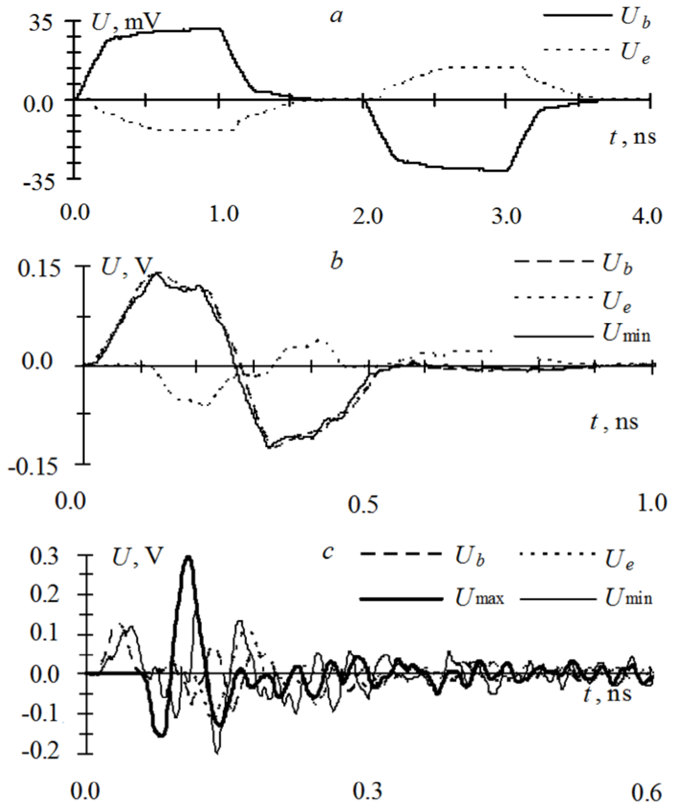

Fig. 14. Waveforms along the conductor 3 under the excitations U_1(*a*), U_2 (*b*), U_3 (*c*) with 4 generators

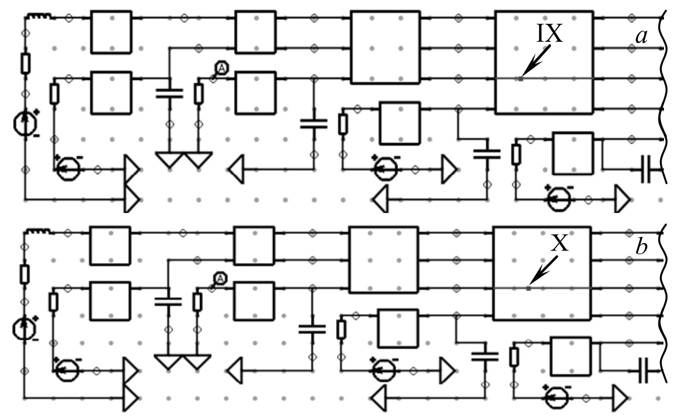

Fig. 15. Maximum locations for signals from Fig. 14 *b* (*a*) и Fig. 14 *c* (*b*)

IV. Discussion of Results

Let us consider the useful signal excitation (U_1). For the conductor 2 the revealed waveforms are presented in Fig. 6 *a*, but peak levels and locations coincide with waveforms at the ends of conductor. The situation for the conductor 4 is similar due to fact that revealed waveforms which are presented in Fig. 8 *a* also coincide with signals at the ends of conductor. The same situation is observed for the conductor 3 both with 2 (Fig. 12 *a*) and 4 (Fig. 14 *a*) generators. The differences consist in absolute values of amplitudes. So the maximum voltage value (35 mV or 7% of a steady state level of 0.5 V in active conductor) for the cases described above is observed in conductor 3 with 4 connected generators (Fig. 14 *a*).

Let us consider the interference signals to which we can relegate the excitations U_2 and U_3. The durations of these excitations are shorter than of useful ones. For the conductor 2 under the excitation U_2, the voltage maximum is 0.092 V (Fig. 6 *b*) that is 18.4% of the steady state level of 0.5 V and the voltage minimum is minus 0.11 V that is 22% of 0.5 V. But the peak values described above are located in the diagram nodes. Under the excitation U_3, the voltage maximum is 0.197 V or 39.4% of the 0.5 V and is located in the node. The voltage minimum is minus 0.167 V (Fig. 6 *c*) or 33.4% of 0.5 V and is located in segment 7 (Table I).

Let us consider the voltage waveforms along the conductor 4 under the same excitations. Under the excitation U_2, voltage maximum is 0.058 V (Fig. 8 *b*) that is 11.6% of 0.5 V and is located in segment 10 (Table I). The minimum is minus 0.057 V (11.4% of 0.5 V) and is located in segment 7. Under the excitation U_3, the voltage maximum is 0.145 V (Fig. 8 *c*) or 29% of 0.5 V and is located in segment 13 (Table I). The minimum is minus 0.112 V or 22.4% of 0.5 V and is located in segment 12.

Let us consider the voltage waveforms along the conductor 3. With 2 generators and under the excitation U_2, voltage maximum is 0.027 V (Fig. 12 *b*) or 5.4% of 0.5 V and is located in segment 9 while the minimum is minus 0.025 V (5% of 0.5 V) and is located in segment 3. Under the excitation U_3, the voltage minimum is minus 0.12 V (Fig. 12 *b*) or 24% of 0.5 V and is located in segment 10. With 4 generators, all revealed voltage maximums are located in the diagram nodes. Under the excitation U_2, the voltage minimum is minus 0.126 V (25.2% of 0.5 V) and is located in segment 5, while under the excitation U_3 is 0.199 V (39.8% of 0.5 V) and is located in segment 8.

V. CONCLUSION

The investigation shows specific aspects of peak values appearance and localization for ultrashort pulses with different durations. For instance, the greatest maximum value (0.145 V – 29% of 0.5 V) that is not located in the node appears in the conductor 4 in the case with 2 generators as we can see in Table I (the whole pulse duration was 0.03 ns). The greatest minimum value (minus 0.199 V – 39.8% of 0.5 V) is in the conductor 3 (the whole pulse duration was the same) but with 4 generators. However, the most locations of peak values (excluding the III, IV and VII) are in the one MCTL section (Fig. 1). Let us consider the fact that the maximum acceptable crosstalk level in the PCB bus of autonomous navigation system should be less than 10% of signal amplitude in active conductor. According to this fact, it follows that all revealed peak values (excluding the conductor 3 under the excitation U_2) dissatisfy this condition. Also, if we consider the maximums in the nodes then for the case with 2 generators the greatest voltage maximum (0.197 V – 39,4% of 0.5 V) is in the conductor 2. For the case with 4 generators the greatest voltage maximum (0.292 V – 58.4% of 0.5 V) is in the conductor 3. These maximums also dissatisfy the condition (less 10%) and exceed it in almost 4 and 6 times respectively.

Inference should be drawn that for complex investigation of PCB, it is useful to consider not only useful but interfering signals because in such case stronger changes of waveform and amplitude are observed. It follows from the results analysis that there are no peak values along the conductors of MCTL sections under the durations of ultrashort pulse which can be relegated to useful signals. Also the response should be calculated not only along the active conductors but along the passive ones because there is significant crosstalk in them. It will allow increasing of radio electronic equipment efficiency and failure reliability.

This paper considers only three duration variants of one trapezoidal excitation, but it is easy to consider any other excitation, for example, electrostatic discharge, Gaussian pulse, etc. However, we investigated the fragment of real PCB that should be gone into production and embedded into spacecraft airborne electronic equipment. Obtained results will help to update this PCB and exclude its failure in future.

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