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Complete ultrashort pulse decomposition in modal filters with circular symmetry

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Abstract. The work carried out simulation and optimization of structures with circular symmetry which is multiconductor lines to protect critical equipment from very fast acting pulses. Six cross section configurations of structures with circular symmetry are considered. Through parametric optimization, a complete splitting of the actuating pulse signal is achieved when the structures are matched with the path. The prospects of further investigations of structures with circular symmetry are shown.

1. Introduction

The rapid creation of advancing radio-electronic equipment (REE), its penetration into different areas of society and levels of EMI exacerbate the aspect of ensuring its electromagnetic compatibility (EMC). The regular EMI incidents at nuclear power plants, in the electrical grid facilities, in transport, with airplanes and spacecraft indirectly confirm this [1–3]. Therefore, the anticipatory development of effective ways for providing EMC of REE remains highly relevant. Specific attention should be paid to the steady increase in speed and density of installing radio engineering device interconnects, which makes them extremely susceptible to the effects of both external and internal electromagnetic interference. In addition, the operating frequency range is expanding, and the levels of electromagnetic effects and the number of radiation sources of various origins are increasing. All this leads to an increase in the susceptibility of modern REE to electromagnetic effects, particularly intentional ones.

An extremely dangerous conductive excitation is an ultrashort pulse (USP) which, as a rule, is characterized by a high input voltage (U_{in}) and a fast rise time (nanoseconds and subnanoseconds). Despite the USP has relatively low energy, its impact on a typical system can be significant. Experimental studies have confirmed that the energy induced on the critical REE is not characterized by the total duration (TD) of the USP, but its energy in a certain frequency range critical for the specific REE [4]. Protecting REE from dangerous USPs is a complex problem. Pulse signal protection devices that currently exist are often not able to provide the required REE protection from short-duration pulse signals, due to the insufficient response time (it often exceeds the rise time or the TD of such pulses), passing it to the critical REE nodes. In this regard, devices specializing in protection against such pulses, which are strip of the above disadvantages, are noteworthy. The operating principle of these devices, such as modal filters (MF) and protective meander lines, is lies in use of modal distortion to change in the very fast acting pulses form. It is meant it's splitting into multiple modes witch stretching with different speeds [5] for protecting REE critical elements. However, studies of such devices mostly limited by various variations of strip structures [6, 7]. Earlier, for protection against very fast acting pulses, transmission lines with circular symmetry with the quantity of conductors N>2 have been studied [8]. They have shown a significant (up to 4 times) decrease in the values of output pulse amplitudes (U_i) of the very fast acting pulse. However, a detailed study of the results shows that some modes that arrived at the end of the line propagated at the same speeds, which entailed the imposition of some pulses. Obviously, there is a resource to reduce the max (U_i) by completely splitting the very fast acting pulse in structures with circular symmetry (by which we mean the circular geometry of both the structural cross section (CS) elements and the CS as a whole) and optimization by heuristic search (HS_{opt}). Therefore, the purpose of the work is to execute such research.

2. Cross sections and structural scheme under investigation

For the current study, 4-conductor structures with a circular symmetry were selected. First, modeling of the CS is performed. Then, the matrix **C** and **L** are calculated as in [8]. The loss matrices in conductors and dielectrics are chosen as zero. Finally, a structural scheme is compiled, loads and excitation are set, and also calculated the waveform of the U_i in the range of specified parameters.

The CS (the central conductor acts as the ground conductor throughout the structure) are presented in figure 1, where ε_{ri} is the relative dielectric permittivity of the medium and r_i is the radius of the CS element. Their structural scheme is presented in figure 2. It is assumed that ε_{r1}=5, ε_{r2}=10, ε_{r3}=20 and ε_{r4}=3, and r_1=0.9 mm, r_2=1.7 mm, r_3=6.1 mm, r_4=0.91 mm and r_5=6.2 mm. The length (l) of the structures is 1 m and the values of the resistances R_G, R_L and R are selected to ensure matching on the criterion which asserts that the U_{in} equals half the EMF.

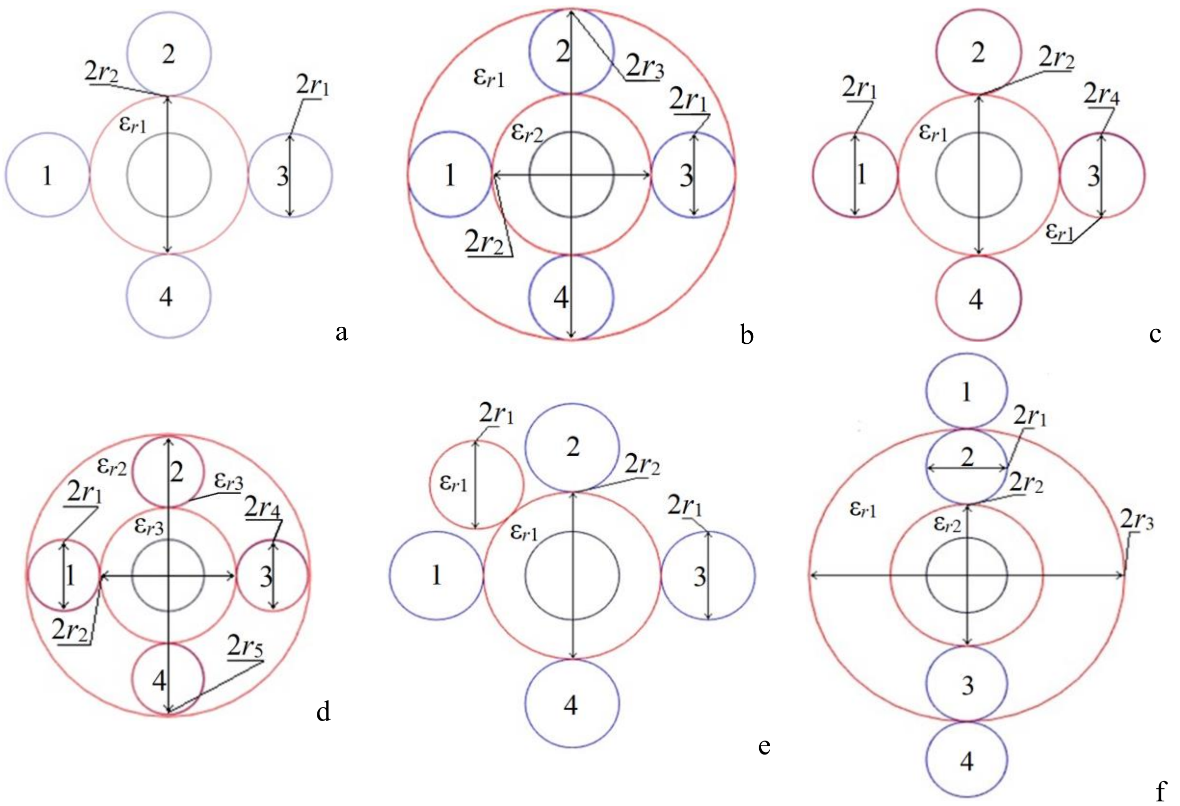

Figure 1. Circular CSs of structures (S 1–5):1 (a), 2 (b), 3 (c), 4 (d), 5 (e), 6 (f).

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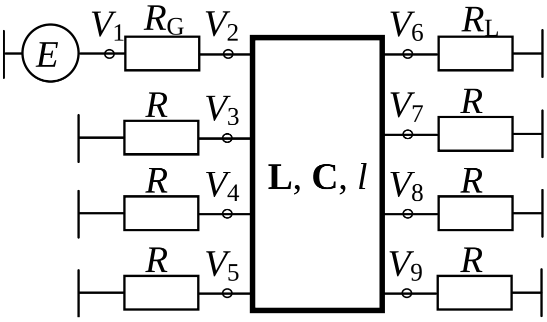


Figure 2. Structural scheme of structures under investigation.

3. Simulation results

It was assumed that the TEM wave propagates in the considered structures. Simulation and HS_{opt} were performed in the TALGAT software [9, 10], which gives acceptable accuracy in solving such tasks.

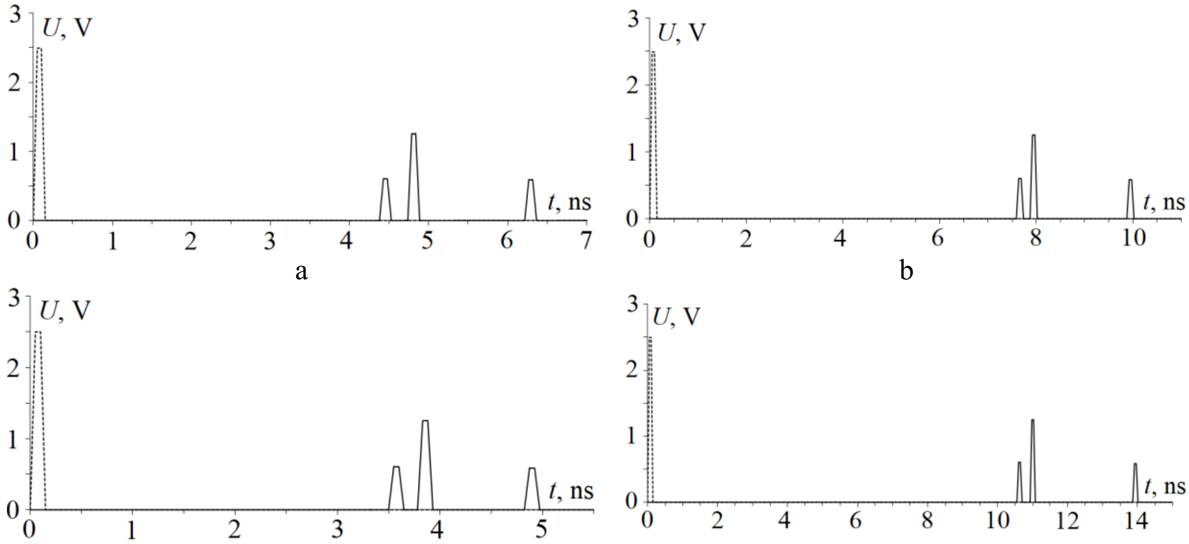
As an excitation, we used a trapezoidal pulse with an EMF of 5 V TD equals 150 ps, to compliance with typical very fast acting pulse. For S 1–5, the spacing between the conductors (1-2, 2-3, 3-4, 4-1) is 3.68 mm. The values of R_G, R_L and R are chosen as 63, 38, 80, 27.5, 60, and 36 Ω, respectively. Table 1 shows the values of U_{in} and U_i, per-unit-length modal delays (τ_i), as well as their minimum (min (Δτ)) and maximum (max (Δτ)) differences for S 1–6.

Table 1. The calculated pulse voltages (V) and τ_i (ns/m) for S 1–6.

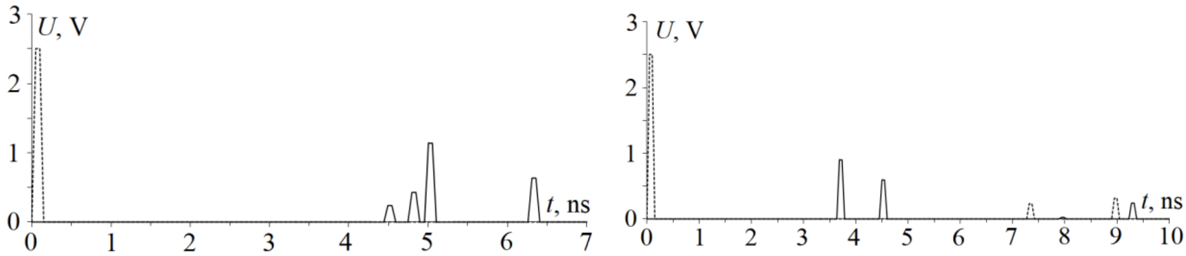
№	U_{in}	U_1	U_2	U_3	U_4	τ_1	τ_2	τ_3	τ_4	min (Δτ)	max (Δτ)
1	2.49	0.6	1.26		0.59	4.37	4.73	4.73	6.21	0	1.48
2	2.49	0.6	1.25		0.59	7.58	7.87	7.87	9.87	0	2
3	2.5	0.6	1.25		0.59	3.49	3.78	3.78	4.82	0	1.04
4	2.49	0.6	1.25		0.59	10.55	10.93	10.93	13.86	0	2.93
5	2.5	0.23	0.42	1.13	0.63	4.44	4.74	4.95	6.26	0.208	1.35
6	2.51	0.9	0.59	0.02	0.24	3.63	4.44	7.88	9.22	0.81	3.43

Relied on the data presented in table 1, we can conclude that the max (U_i) are 1.26 V (S 1), 1.25 V (S 2–4), 1.13 V (S 5) and 0.9 V (S 6), which are 1.97, 2, 2.21 and 2.78 times, respectively, less than the U_{in}, which, in turn, is equal to half the EMF and indicates that the structures are matched with the path.

Figure 3 shows the waveforms of U_{in} and U_i for S 1–6.



c d

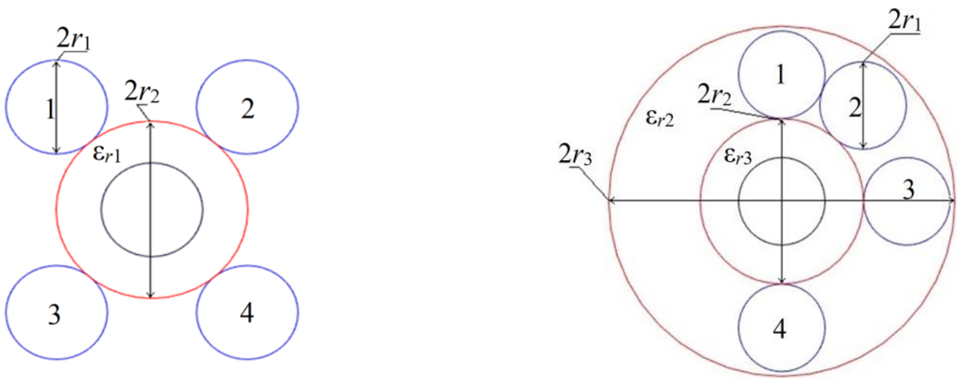


e f

Figure 3. Voltage waveforms of U_{in} (· · ·) and U_i (—) of S 1 (a), S 2 (b), S 3 (c), S 4 (d), S 5 (e), S 6 (f) with a circular CS.

Relied on the data presented in table 1, the data presented in table 1 and figure 3, we can also conclude that the min (Δτ) values for S 1–4 are 0 ns/m, which means that some values of τ_i coincide (τ_2 and τ_3), and the resulting attenuation coefficient decreases. This is due to the same coupling value between the active (A) and passive (P) conductors. From figure 1 it follows that in S 1–4, conductor 1 (A) is located at the same distance from conductors 2 and 4 (P), regardless of the change in the dielectric layers number and their ε_r, which causes the values of τ_i to coincide. From figure 3 (e, f) it follows that the coupling between the A and P conductors is different. This is achieved by adding a dielectric between conductors 1 and 2 (structural optimization of S 5) and vertical arrangement of conductors (parametric optimization of S 6). Also in S 6 there appear pulses which are reflected from the end of the line and arriving to its beginning (figure 3). Thus, by establishing a different coupling between the A and P conductors, it was possible to achieve complete splitting of the very fast acting pulse. As a result, for S 5 and S 6, the values of min (Δτ) are 0.208 and 0.81 ns/m, respectively, which allows increasing the TD of the very fast acting pulse to 208 ps (S 5) and 810 ps (S 6) with the same attenuation coefficient.

Figure 4 presents the CSs of S 1 and S 2 after HS_{opt} according to the criterion of minimizing the max (U_i). By analogy with multiconductor strip MFs, it is conceivable that this is achievable by adequation the U_i of the splitting pulses.



a b

Figure 4. Circular CSs of S 1 (a), S 2 (b) after HS_{opt}.

For S 1 (after HS_{opt}), the spacing between the conductors 1-2 and 3-4 are 3.38 mm, between 1-3 and 2-4 – 3.94 mm, and between 1-4 and 2-3 – 5.2 mm. For S 2 (after HS_{opt}), the spacing between the conductors 1-2 are 1.85 mm, between 1-3 – 2.95 mm, and between 1-4 – 5.2 mm. The values of R_G, R_L and R for S 1–2 (after HS_{opt}) are chosen as 61 and 17.7 Ω, respectively. Table 2 shows the values of U_{in} and U_i, τ_i, min (Δτ) and max (Δτ) for S 1–2.

Table 2. The calculated pulse voltages (V) and τ_i (ns/m) for S 1, 2 after HS_{opt}.

№	U_{in}	U_1	U_2	U_3	U_4	τ_1	τ_2	τ_3	τ_4	min (Δτ)	max (Δτ)
1	2.49	0.61	0.62	0.62	0.59	4.49	4.79	4.97	6.29	0.18	1.317
2	2.5	0.75	0.35	0.22	0.31	4.8	5.24	5.74	7.22	0.44	1.476

Table 2 shows that the max (U_i) are 0.62 V (S 1) and 0.75 V (S 2), which is 4.03 and 3.33 times, less than the U_{in}. In this case structures are matched with the path.

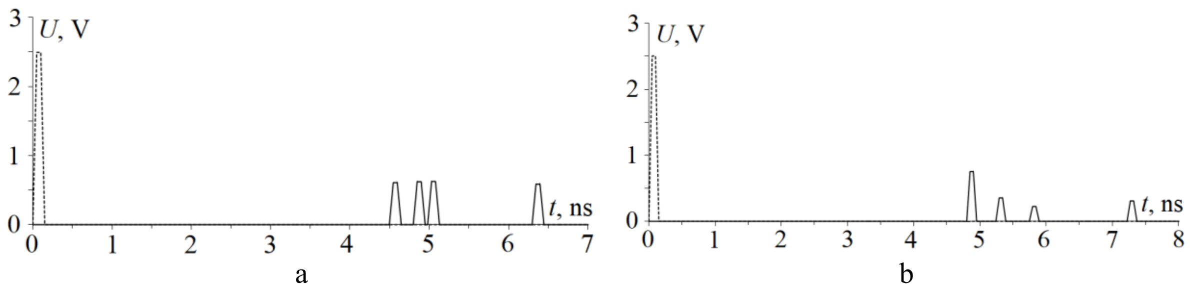


Figure 5. Voltage waveforms of U_{in} (· · ·) and U_i (—) of S 1 (a) and S 2 (b) with a circular CS (after HS_{opt}).

The min (Δτ) values obtained by simulation of S 1 and S 2 (after HS_{opt}) are 0.18 and 0.44 ns/m, respectively. Consequently, the TD of the U_{in} can be increased to 180 and 440 ps for S 1 and S 2 with the same attenuation.

4. Conclusion

Multiconductor structures with circular symmetry were simulated and optimized by HS in order to study their effectiveness for protecting REE against very fast acting pulse. Six different structures with circular symmetry were investigated and the reason for the coincidence of some values of τ_i was revealed. After HS_{opt}, we obtained the structures, in which complete splitting of the pulse signal is achieved with minimized U_i.

It seems promising to further investigate such devices with circular symmetry. Especially, it is advisable to profound inquiry optimization of such structures according to another criteria, their cascading (including the ones with strip lines), as well as their performance when they are shielded.

Acknowledgments

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