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# Parametric optimization of the cables with the modal filtration effect

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**Abstract.** The work presents the results of simulation and optimization of multiconductor modal filters with a circular cross section. Four 2–5 conductor structures with a circular cross-section were considered. Optimization was performed according to the amplitude and time criteria. As a result, a complete decomposition of the exciting interference signal was achieved in all structures with a maximum attenuation of 4.18 times.

## 1. Introduction

The upward trend in the number of new radio-electronic (RE) devices every year exacerbates the problem of ensuring electromagnetic compatibility (EMC) [1]. It is associated, first of all, with the increasing influence of electromagnetic interference (EMI) of various nature on the RE devices functioning. Conducted interference, which propagates directly along the conductors, deserves special attention. An ultrashort pulse (USP) with a high voltage level and a subnanosecond rise time can be used as a dangerous source of conducted EMI. Due to the short duration and wide spectrum, USPs are able to penetrate into different RE devices, thereby disabling them. Despite the low energy of the USP, its localization in the critical nodes of the device can lead to the disruption of the RE devices operation. Therefore, the protection of such RE devices is relevant, in particular, in terms of devices, which provide safety and control of critical equipment. It is known that traditional protection devices at the equipment input have inherent disadvantages (low power, insufficient speed, parasitic parameters, short service life). Recently, to protect against powerful USPs, modal filtration technology has been proposed, which is used to decompose an excitation USP with a large maximum voltage into a sequence of pulses of lower voltage ( $U_i$ , where  $i=1, 2, \dots, N$  is the pulse voltage) due to the difference in mode delays [2–4] in multiconductor transmission lines. This technology is effectively applied in protective devices called modal filters (MF) [5].

It is known that the implementation of such devices was previously limited mainly to strip structures, while the implementation of MFs in cables has almost not been studied. However, in view of the fact that high-frequency transmission systems or measuring devices using various cables have become a standard element of RE devices, the use of additional protection measures in them is very important.

Meanwhile, the specificity of such structures in a symmetrical design does not allow for the complete decomposition (CD) of the excitation USP, because of the identical electromagnetic couplings between the active (A) and passive (P) conductors. Preliminary studies aimed at studying such structures have been limited to the tasks of achieving a CD of the USP without resorting to multicriteria optimization [2, 6]. The purpose of this work is to fill this gap.



## 2. Cross-sections and equivalent circuits of the structures under investigation

First of all,  $N$ -conductor structures with a circular symmetry were selected. The choice of the geometry of the structures under study was determined by the use of widespread cables: FiFix FTTH UDD, PBPPg (PUGNP), power cable of PVC-insulated conductor, both in industry and in household conditions. These cables are widely used primarily due to their high performance characteristics. To begin with, we built the geometric models (GM) of the structures cross-sections (CS). Then matrices  $\mathbf{C}$  and  $\mathbf{L}$  were calculated as in [2]. Losses at this stage of the study were not taken into account. Further, an equivalent circuit was compiled, loads ( $R$ ) and excitation values were set, and the output waveform was calculated in the range of specified parameters.

We studied the GM 1 ( $N=2$ ), GM 2 ( $N=3$ ), GM 3 ( $N=4$ ) and GM 4 ( $N=5$ ), which are presented in Figure 1 (the central conductor is the reference conductor), where  $\epsilon_{ri}$  is the relative dielectric permittivity (RDP) of the medium and  $r_i$  is the radius of the CS element. The following parameters were selected:  $r_1=0.9$  mm;  $r_2=1.6$  mm;  $r_3=3.45$  mm;  $r_4=0.95$  mm;  $\epsilon_{r1}=1$ ;  $\epsilon_{r2}=5$ ;  $\epsilon_{r3}=10$ ;  $\epsilon_{r4}=15$ . For GM 2, the value of  $r_3$  was taken equal to 3.45 mm, but for GM 4 – 3.55 mm. Equivalent circuits of GMs 1–4 are shown in Figure 2.

## 3. Simulation results

To calculate the parameters of the structures and obtain the waveforms, we employed the TALGAT system [7]. As an excitation, we used a source of trapezoidal pulse signals with the durations of the front, fall and flat top of 50 ps. Therefore, total duration (TD) was equal to 150 ps with an EMF of 5 V and the GM length ( $l$ ) of 1 m. To ensure the matching of the line with the path, the  $R$  values were taken equal to  $63 \Omega$  (for GM 1). Figure 3 shows the voltage waveforms at the GM 1–4 output.

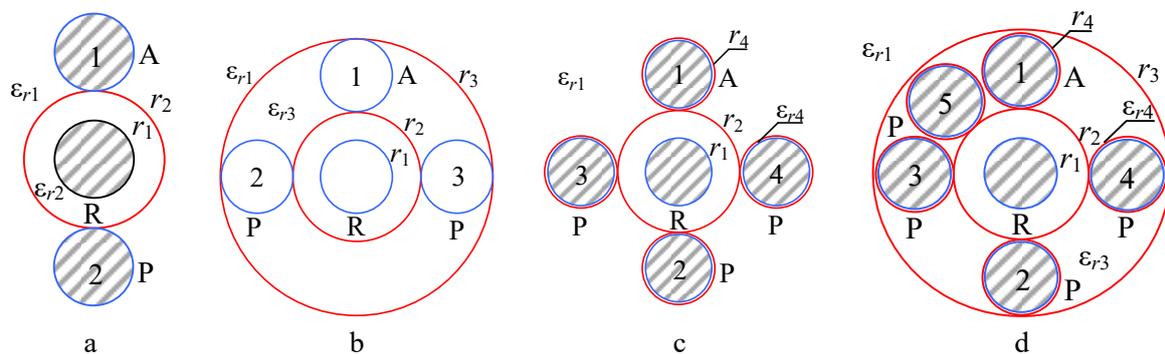


Figure 1. GM 1 (a), GM 2 (b), GM 3 (c), GM 4 (d) before optimization.

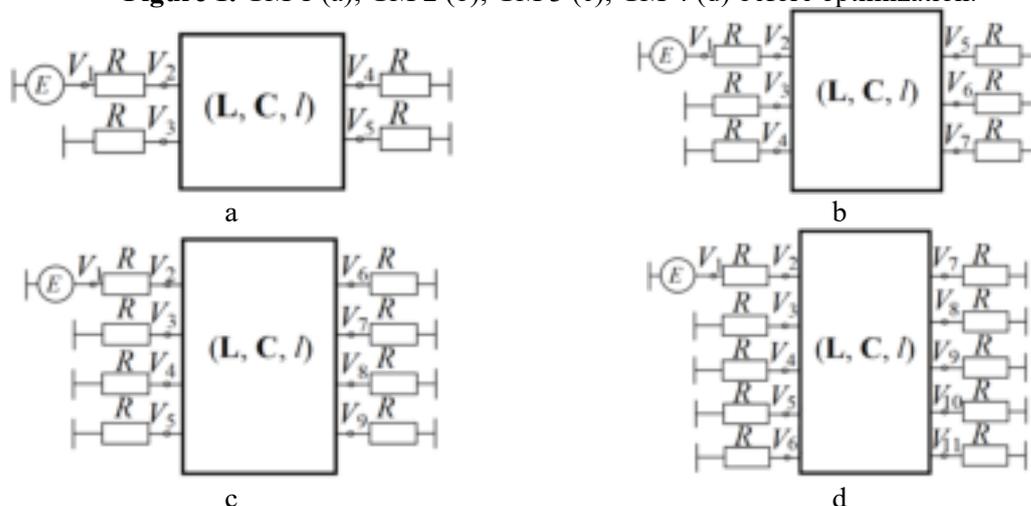
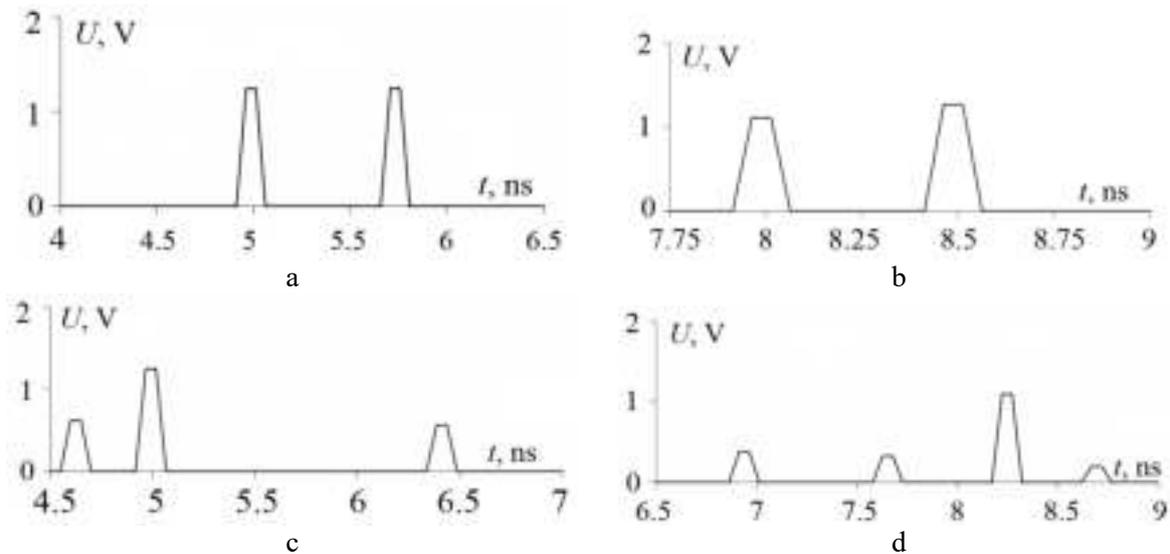


Figure 2. Equivalent circuits of MFs with GM 1 (a), GM 2 (b), GM 3 (c), GM 4 (d).



**Figure 3.** Voltage waveforms at the output of GMs 1–4 before optimization.

Based on the data presented in Figure 3, one can see the coincidence of some per-unit-length modal delay ( $\tau_i$ ) values (in the general case, in multiconductor MFs, the number of decomposition pulses (DP) is equal to the number of conductors). This means the simultaneous arrival of modes to the end of the A-conductor. Obviously, there was a superposition of pulses and, consequently, the resulting  $U_{\max}$  increased (to 1.26 V for GM 2, 1.25 V for GM 3, 1.05 V for GM 4). Therefore, it is advisable to perform the optimization.

Figure 4 shows GMs 2–4 after parametric optimization by a heuristic search (HS<sub>opt</sub>) [8] according to several criteria: the amplitude (to minimize the maximum output voltage), the time-interval (to equalize the time intervals (TI) between DP at the output) and the minimum- and maximum-time (to increase the maximum duration of the excitation USP which will completely decompose). Voltage waveforms at the output of GMs 2–4 after optimization are presented in Figure 5.

As a result of GM 2 optimization, the following values were obtained:  $\epsilon_{r1}=1$ ;  $\epsilon_{r2}=5$ ;  $\epsilon_{r3}=19$ ;  $r_1=0.9$  mm (the reference conductor and conductors 1 and 2);  $r_1=0.89$  mm (conductor 3);  $r_2=1.6$  mm;  $r_3=3.45$  mm. The  $R$  values were taken equal to 35  $\Omega$ . Changing the coordinates of the conductors 2 and 3 allows to provide a different coupling with the A-conductor and, as a result, to achieve CD of the USP at the output of GM 2. It was revealed that a change in the RDP of the external dielectric allows one to increase the TIs between pulses 1 and 2. A slight decrease in the radius of conductor 3 leads to an increase of the  $U_2$ , thereby making it possible to align the maximum voltages of the DP. Therefore, a CD of the exciting pulse into 3 pulses of lower maximum voltage was achieved.

As a result of the GM 3 optimization, the following values were obtained:  $\epsilon_{r1}=1$ ;  $\epsilon_{r2}=3$ ;  $r_1=0.9$  mm (the reference conductor and conductors 1, 2 and 4);  $r_1=1$  mm (conductor 3);  $r_2=1.6$  mm;  $r_4=0.95$  mm (conductors 1, 2 and 4);  $r_4=1.1$  mm (conductor 3);  $\epsilon_{r4}=60$  (conductors 1 and 3);  $\epsilon_{r4}=120$  (conductor 2);  $\epsilon_{r4}=20$  (conductor 4). The  $R$  values were taken equal to 68  $\Omega$ . Changing the RDP and the radius of the conductors allows you to provide a different coupling with the A-conductor and, as a result, to achieve CD of the USP at the output of GM 3. It was found that an increase in the radius of conductor 3 and the radius of the dielectric around it leads to a slight decrease of the  $U_2$ . An increase in the RDP of the dielectric around conductor 1 leads to an increase of the  $U_2$  and a slight decrease in the TI between pulses 1 and 2 and a significant increase of the  $U_2$ , and also to a decrease in the TI between pulses 2 and 3. An increase in the RDP of the dielectric around conductor 2 leads to an increase of the  $U_1$ , a significant decrease of the  $U_2$ , and a slight decrease of the  $U_3$ . As a result, a CD of the original pulse signal into 4 pulses of lower maximum voltage was achieved. To maximize the TIs between the DP, the RDP around conductor 4 was slightly increased, which also led to an increase of

the  $U_1$  and a decrease of the  $U_2$ . As a result of optimization, a complete DP was achieved, and the maximum voltage of the first 3 pulses was equalized.

As a result of the GM 4 optimization, the following values were obtained:  $\varepsilon_{r1}=1$ ;  $\varepsilon_{r2}=70$ ;  $\varepsilon_{r3}=6$ ;  $r_1=1.22$  mm (the reference conductor);  $r_1=0.9$  mm (conductors 1 and 4);  $r_1=0.3$  mm (conductors 2 and 3);  $r_1=0.55$  mm (conductor 5);  $r_2=1.9$  mm;  $r_3=4$  mm;  $r_4=0.95$  mm (conductors 1, 4 and 5);  $r_4=0.92$  mm (conductor 2);  $r_4=0.69$  mm (conductor 3);  $\varepsilon_{r4}=5$  (conductor 1);  $\varepsilon_{r4}=3$  (conductor 2);  $\varepsilon_{r4}=10$  (conductor 3);  $\varepsilon_{r4}=27$  (conductor 4);  $\varepsilon_{r4}=15$  (conductor 5). The  $R$  values were taken equal to  $33 \Omega$ . Changing the RDP of the internal dielectric made it possible to obtain a complete DP. Changing the RDP of the external dielectric made it possible to slightly increase the TIs between pulses 2, 3, and 4. Changing the coordinates of P-conductors made it possible to reduce the  $U_1$ , increase the  $U_2$ , and decrease the TI between pulses 4 and 5, which also led to a slight decrease in the TI between pulses 1 and 2, 3 and 4. A decrease in the radius of P-conductors, as well as an increase in the radius of the A-conductor and the radius of dielectrics around all conductors, made it possible to reduce the  $U_2$  and increase the  $U_5$ , but also uniformly reduced the TIs between the first 4 pulses. A decrease in the RDP around conductors 1 and 2 made it possible to reduce the  $U_3$ . An increase in the RDP of dielectrics around conductors 3, 4, and 5 made it possible to decrease the  $U_5$ , increase the TIs between the DP, and equalize the maximum volages of the first 4 DP.

The optimization results are summarized in Table 1. Because of the differences in per-unit-length delays ( $\Delta\tau_i$ ) presented in Table 1, we can see that it was possible to achieve a CD of the exciting pulse in the structures of GMs 2–4. Meanwhile, the optimization of GM 1 was not performed since obviously optimal characteristics satisfied the specified criteria.

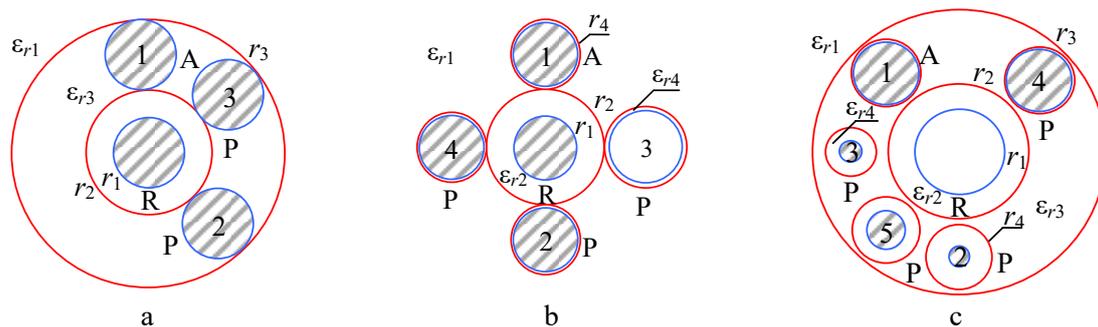


Figure 4. GM 2 (a), GM 3 (b), GM 4 (c) after  $HS_{opt}$ .

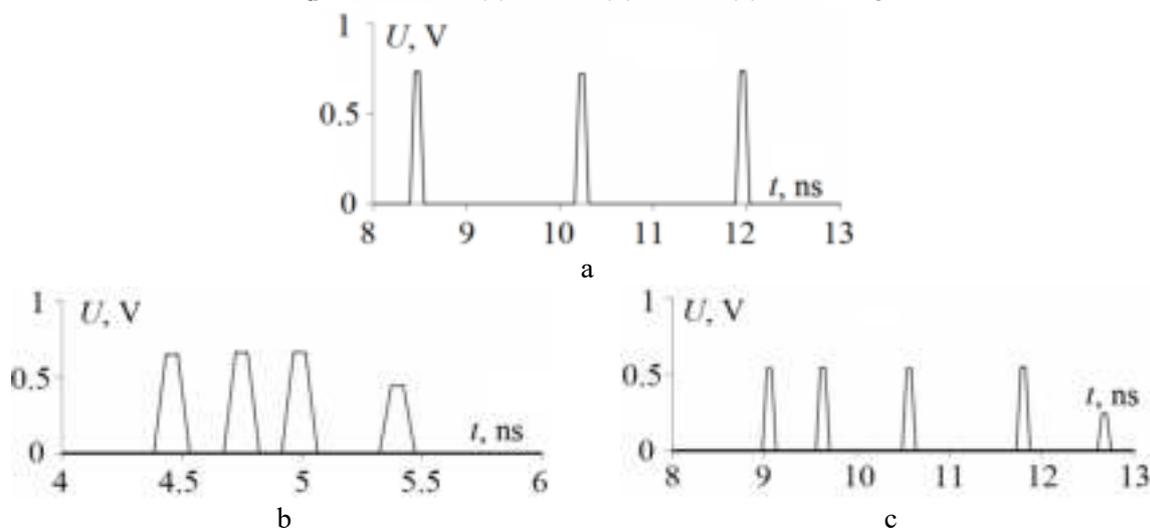


Figure 5. Voltage waveforms at the output of GM 2 (a), GM 3 (b), GM 4 (c) after  $HS_{opt}$

**Table 1.** Characteristics of waveforms at the input ( $U_{in}$ ) and output of GM 1 before optimization and GMs 2–4 after  $HS_{opt}$ 

GM	$U_{in}, V$	DP amplitudes, V					Differences in per-unit-length delays $\Delta\tau_i, ns/m$			
		$U_1$	$U_2$	$U_3$	$U_4$	$U_5$	$\Delta\tau_1$	$\Delta\tau_2$	$\Delta\tau_3$	$\Delta\tau_4$
1	2.49	1.24	1.25				0.6			
2	2.2	0.73	0.72	0.73			1.6	1.58		
3	2.4	0.65	0.66	0.67	0.45		0.14	0.09	0.26	
4	2.3	0.54	0.54	0.54	0.55	0.25	0.43	0.78	1.08	0.75

The  $\min(\Delta\tau_i)$  values obtained by the simulation of GM 1 before optimization and GMs 2–4 after  $HS_{opt}$  are 0.6, 1.58, 0.09, and 0.43 ns/m respectively. It is clear that the  $\max(U_i)$  values are 1.25, 0.73, 0.67 and 0.55 V for GMs 1–4, respectively (which is 2, 3.01, 3.58 and 4.18 times less than  $U_{in}$ ). These results show that the TD of the USP (taking into account the partial overlap of the fall edge and the rise edge of the adjacent DP) can be increased to 0.744, 1.73, 0.249 and 0.58 ns for GMs 1–4, respectively, with the same attenuation maintained.

#### 4. Conclusion

Thus, multiconductor MFs with circular cross-section were simulated, and parametric optimization of these structures was also performed. Four different structures with circular symmetry were investigated. To ensure a CD of the USP at the output, parametric optimization was performed using the amplitude and two time criteria (for GMs 2–4). As a result, in the simulation which did not take into account the losses, we showed the possibility of attenuation by 2, 3.01, 3.58 and 4.18 times, with the TD of the USP being increased to 0.744, 1.73, 0.249 and 0.58 ns for GMs 1–4, respectively.

When optimizing GMs 2–4, the focus was placed on establishing different and individual couplings between A and P-conductors. Due to this, a CD of the excitation USP in all GMs was achieved. It seems promising to further conduct a full-scale experiment.

#### Acknowledgments

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