Parametric Optimization of Shielded Multiconductor Modal Filters with Circular Cross Section

Anton Belousov
Television and Control Department
Tomsk State University of Control Systems and Radioelectronics
Tomsk, Russian Federation

Natalya Vlasova
Television and Control Department
Tomsk State University of Control Systems and Radioelectronics
Tomsk, Russian Federation

***Abstract*—For the first time, simulation and optimization of multiconductor shielded modal filters (MF) with a circular cross-section (CS) were performed. Four MFs with a circular CS and with 2–5 conductors were considered. The parametric optimization of four MFs was performed in order to ensure the complete decomposition (CD) of the exciting ultrashort pulse (USP). This was reached by providing different coupling between active and passive conductors. The optimization was carried out according to the amplitude and time (interval-time and range-time) criteria. As a result of optimization, a CD of the exciting USP was achieved in all MFs with a maximum attenuation of 4.3 times. In addition, the time intervals between the decomposition pulses were aligned.**

***Keywords*—multiconductor modal filters, circular cross section, shielding, ultrashort pulse.**

I. Introduction

Every year, the problem of electromagnetic compatibility (EMC) is aggravated due to the high growth rates of the number of various radio-electronic devices (RED) [1]. REDs are becoming more complicated, the circuit density is increasing, and the intentional electromagnetic interference (EMI) generators are getting more sophisticated [2]; thus, the EMC compliance requirements are becoming more stringent. The scientific problem of this work is the protection against powerful EMI, which is given special attention when creating REDs. It is known that devices that are traditionally used for protection against conducted EMI have their disadvantages. Often they are not only unable to provide EMC of REDs, but also worsen their mass and size characteristics [3]. Meanwhile, one of the most dangerous sources of conductive EMI is ultrashort pulses (USPs). The main energy of a USP is spent to increase the amplitude (due to the short duration), induced on critical nodes of REDs [4]. It has been experimentally proved that when penetrating into REDs, USPs can disable their critical circuits [5, 6]. In view of the above, the protection of critical REDs from the threat of intentional USPs is relevant.

Modal filtration technology has been proposed to protect against powerful USPs. Its main idea is to decompose the exciting USP into a sequence of pulses due to the difference in mode delays [7]. This technology is implemented in devices called modal filters (MFs) [8]. The traditional implementation of MFs implies their strip-structure versions. However, there are exists the version of the MFs in the form of structures with a circular cross-section (CS). For example, in [9], by means of parametric optimization, it has been proved that in the MFs configurations with a circular cross-section, complete decomposition (CD) of the USP at the output can be ensured, which had previously been impossible. Therefore, the novelty of this work lies in the possibility of using modal filtration not only in strip structures, but also in widespread cables, in which the use of additional protection is relevant. Meanwhile, the practical application of such MFs (protective cables) involves their implementation in the shield. However, it is known [10] that MF shielding reduces their protective characteristics. Thus, the aim of this work is to reveal the possibility of the USP CD in shielded MF configurations.

II. Simulation Approach

Simulation and optimization were performed in the TALGAT software [11]. Initially, the geometric models of the MF CSs were constructed. Then the matrices of per-unit-length coefficients of electrostatic (**C**) and electromagnetic (**L**) inductances were calculated. At this stage of the study, losses were not taken into account in order to exclude their influence. Next, the equivalent circuits for the simulation were drawn, loads (R) and the excitation were set, and finally, the output waveform was computed in the range of specified parameters.

III. Preliminary Simulation Results

To begin with, the MFs consisting of 2–5 conductors with circular symmetry were selected (Fig. 1), where ε_{ri} is the relative dielectric permittivity of the medium and r_i is the radius of the CS element. The choice of this MF design was determined by the common use of cables with such cross sections in both home and industrial applications. For example, cable FiFix FTTH UDD is considered a universal fiber-optic cable for indoor and outdoor installations, for example, to build broadband access networks. High performance characteristics allow the installation of such cables without difficulty. Cable PBPPg (PUGNP) is widely used for switching lighting equipment and connecting low-power devices. Power cable consisting of PVC-insulated conductors is widely used for transmitting and distributing the energy. It can be used in industrial premises, power plants, switchgear and lighting, as well as in normal residential areas as electrical wiring.

The reported study was funded by RFBR, project number 19-37-90075.

In this study, we investigated four modal filters: MF 1 (with the number of conductors (N) equal to 2), MF 2 (with N=3), MF 3 (with N=4), and MF 4 (with N=5). MF 1 (Fig. 1*a*) is a shielded air-filled structure with a dielectric in the center. The conductors are located on the outside of the dielectric. MF 2 (Fig. 1*b*) is a shielded dielectric-filled structure. The other dielectric is located in the center of the structure; the conductors are located radially on the outside of the central dielectric. MF 3 (Fig. 1*c*) is a shielded air-filled structure with a dielectric in the center. The conductors are arranged radially on the outside of the central dielectric. Every conductor is covered with a dielectric. MF 4 (Fig. 1*d*) is a shielded dielectric-filled structure with a dielectric in the center. The conductors are arranged radially on the outside of the central dielectric. Every conductor is covered with a dielectric. Initial parameters of the selected MFs are the following: r_1=0.9 mm; r_2=1.6 mm, r_3=3.5 mm; r_4=3.6 mm; r_5=0.95 mm; ε_{r1}=1; ε_{r2}=5; ε_{r3}=10; ε_{r4}=15. The length of the cross-sectional element segment is 1200. For MF 2 and MF 4 the r_3 values are taken equal to 3.6 mm, and r_4 – 3.5 mm. As an excitation, we used a source of trapezoidal pulse signals with EMF 5 V and total duration equal to 150 ps (as a typical idealized USP duration for preliminary simulation). The values of the loads were chosen from the condition of the line matching with the path (the signal amplitude at the beginning of the line V_2 should be equal to half the EMF of the signal source V_1). The equivalent MF circuits with length of 1 m are presented in Fig. 2, and the voltage waveforms at the MFs 1–4 outputs before optimization – in Fig. 3. Table I shows the main characteristics of MFs 1–4 after simulation with the parameters before optimization.

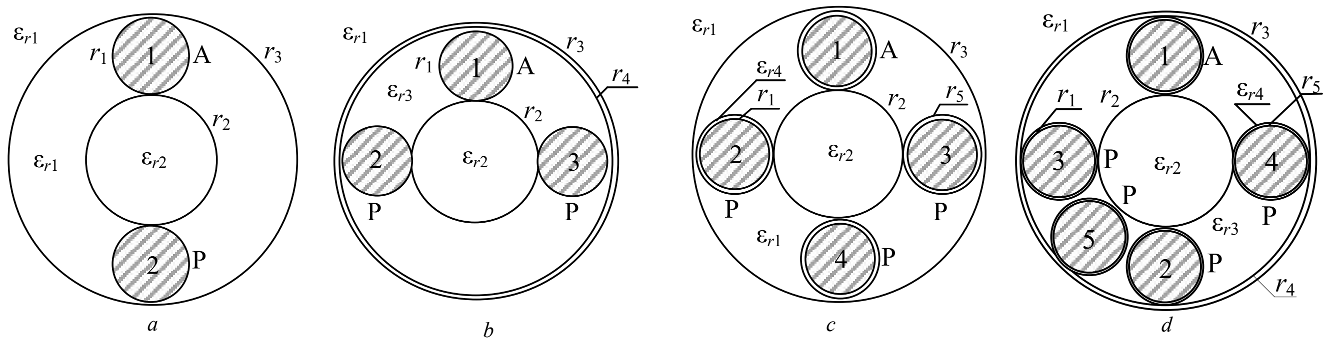

Fig. 1. Cross sections of MF 1 (*a*), MF 2 (*b*), MF 3 (*c*) and MF 4 (*d*) before optimization.

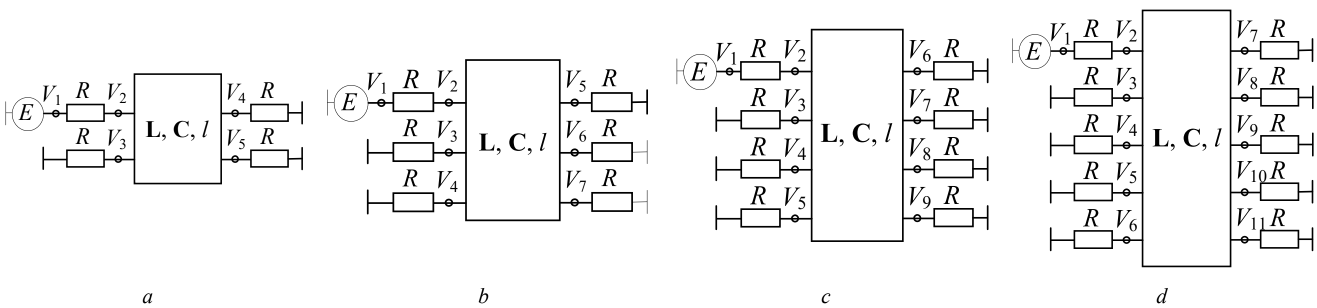

Fig. 2. Equivalent circuits of MF 1 (*a*), MF 2 (*b*), MF 3 (*c*) and MF 4 (*d*).

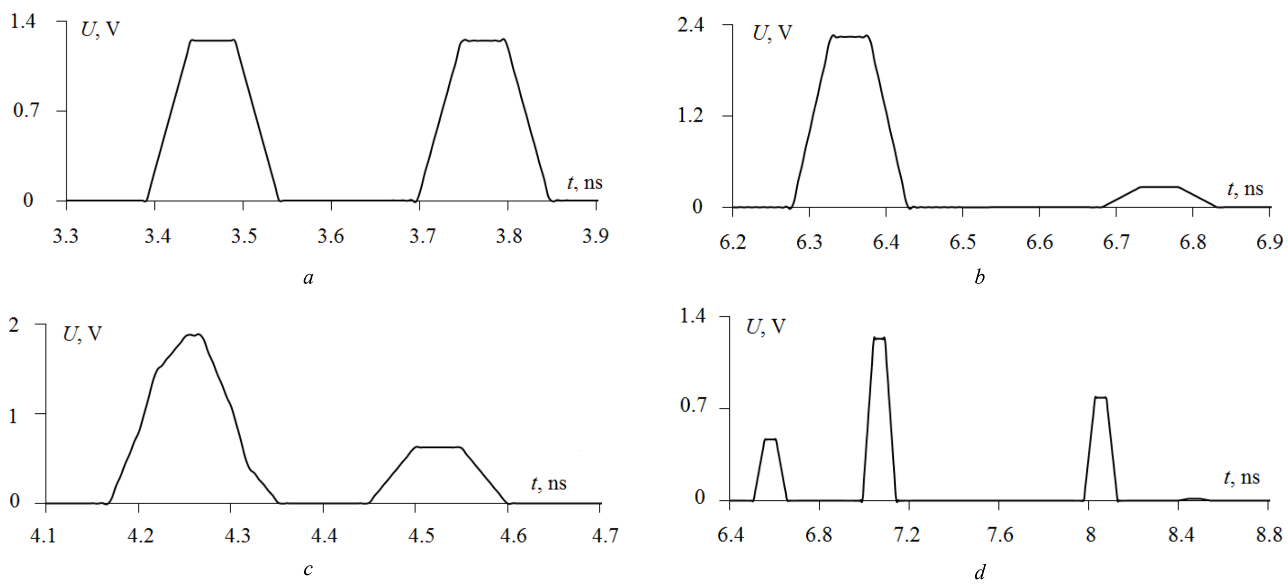

Fig. 3. Voltage waveforms at the MF 1 (*a*), MF 2 (*b*), MF 3 (*c*) and MF 4 (*d*) outputs before optimization.

TABLE I. MAIN CHARACTERISTICS OF MFS 1–4 BEFORE OPTIMIZATION

MF	U_{in}, V	Decomposition pulses 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	1.248	1.249				0.16			
2	2.48	2.2	0.28				0.37			
3	2.5	1.87	0.64				0.1			
4	2.4	0.46	1.23	0.78	0.015		0.34	0.83	0.27	

Fig. 3 shows the overlapping of pulses arriving at the output of MFs 2–4. As a result, these MFs increase the resulting maximum output amplitudes. We know that in the general case in multiconductor MFs, there are *N* decomposition pulses. Meanwhile, it can be seen that in MFs 2–4, 2, 2, and 4 pulses arrive at the output, rather than 3, 4, and 5 pulses, respectively, as it should be. This suggests superposition of some decomposition pulses coming at the same time. This fact results from similar couplings between the active and passive conductors in MFs 2–4. It is also noteworthy that in Fig. 3*c* pulse 1 has a different trapezoidal shape. This fact indicates that the values of the per-unit-length time delays (τ) of some pulses (corresponding to pulse 1 in Fig. 3*c*) were different, but their difference was insufficient for their CD. Incomplete USP decomposition at the output of MFs 2–4 can also be seen from the data in Table I, where the coincidence of certain τ values is observed. Obviously, for CD of the exciting USP in all MFs, it is advisable to perform parametric optimization.

IV. OPTIMIZATION RESULTS

Optimization was performed by heuristic search (HS_{opt}) according to several criteria, the amplitude, the time-interval, and the minimum- and maximum-time. The main focus was on establishing different couplings between the active and passive conductors. It is known from practical simulation and optimization experience that changing the ε_r value of the central dielectric allows increasing the time intervals between decomposition pulses. In addition, it was found that changing the ε_r value of the internal dielectric changes the amplitudes of pulses 2 and 3. The cross-sections of the MFs with the optimal parameters are shown in Fig. 4 and the voltage waveforms at the output of MFs 1–4 after HS_{opt} are shown in Fig. 5. Table II shows the main characteristics of MFs 1–4 after simulation with the optimal parameters.

The CD of the exciting USP at the output of MF 1 was achieved at the initial parameters, but there is a possibility to improve its characteristics by increasing the time intervals between the decomposition pulses. To achieve this, the size of the internal dielectric was reduced during optimization. As a result, the following parameter values were obtained: ε_{r1}=1; ε_{r3}=10; r_1=0.9 mm; r_2=0.9 mm; r_3=2.8 mm. The *R* values were taken equal to 18 Ω. Fig. 5*a* shows that two pulses of half the amplitude (relative to the input voltage (U_{in})) come to the end of the line. Table II also shows that $\Delta\tau$ between pulses 1 and 2 is 0.25 ns/m, which allows increasing the duration of the exciting USP to 0.42 ns in MF 1 with the same attenuation coefficient.

Fig 4*b* shows the CS of MF 2 after optimization. As a result, the dielectric size was reduced, which led to an increase in the time intervals between decomposition pulses. The CD of the exciting USP is achieved by changing the coordinate arrangement of the passive conductors relative to the active one, as well as by changing the ε_r value. In addition, it was possible to equalize the amplitudes of all decomposition pulses. The following parameter values were obtained: ε_{r1}=1; ε_{r2}=5; ε_{r3}=23; r_1 (cond. 1 and 3)=0.9 mm; r_1 (cond. 2)=0.73 mm; r_3=3.7 mm; r_4=3.3 mm. The *R* values were taken equal to 20 Ω. Fig. 5*b* shows that the end of the line sees 3 pulses, each of which is 3.1 times less than the U_{in} value. Table II demonstrates that $\Delta\tau_1$ is 2.55 ns/m, and $\Delta\tau_2$ is 2.73 ns/m. Therefore, it is possible to increase the duration of the exciting USP up to 2.7 ns in MF 2 with the same attenuation coefficient.

Fig. 4*c* shows the CS of MF 3 after optimization. As a result, the ε_r value of all dielectrics changed, as well as the *r* values of the conductors and their coordinate arrangement, to break the symmetry and establish different couplings between the active and passive conductors. As a result of optimization, it was possible to achieve the CD of the exciting USP into 4 pulses of lower amplitudes. The following parameter values were obtained: ε_{r1}=1; ε_{r2}=60; ε_{r4} (cond. 1)=24; ε_{r4} (cond. 2)=11; ε_{r4} (cond. 3)=15; ε_{r4} (cond. 4)=5; r_1 (cond. 1)=0.9 mm; r_1 (cond. 2 and 4)=0.8 mm; r_1 (cond. 3)=0.7 mm; r_2=1.3 mm; r_5=0.95 mm. The *R* values were taken equal to 31 Ω. From Fig. 5*c* we can see that four pulses come to the end of the line; all of them are less than the U_{in} value: pulses 1 and 2 by 3.2 times, pulse 3 by 3.25 times, and 4 by 13 times. Table II shows that $\Delta\tau_1$ is 0.25 ns/m, $\Delta\tau_2$ is 0.18 ns/m, and $\Delta\tau_3$ is 0.36 ns/m. Therefore, it is possible to increase the duration of the exciting USP up to 0.33 ns in MF 3 with the same attenuation coefficient.

Fig. 4*d* shows the CS of MF 4 after optimization. As a result, the ε_r value of dielectrics around conductors changed, as well as the *r* value of 2–5 conductors and their coordinate arrangement, to establish different couplings between the active and passive conductors. The following parameter values were obtained: ε_{r1}=1; ε_{r2}=120; ε_{r3}=5; ε_{r4} (cond. 1)=4; ε_{r4} (cond. 2)=20; ε_{r4} (cond. 3)=3; ε_{r4} (cond. 4)=55; ε_{r4} (cond. 5)=42; r_1 (cond. 1)=0.9 mm; r_1 (cond. 2)=0.5 mm; r_1 (cond. 3)=0.8 mm r_1 (cond. 4)=0.82 mm; r_1 (cond. 5)=0.5 mm r_2=1.55 mm; r_3=5.1 mm; r_4=4.6 mm r_5=0.95 mm. The *R* values were taken equal to 29 Ω. Fig. 5*d* shows that five pulses come to the end of the line; all of them less than the U_{in} value: pulses 1 and 3 by 4.3 times, pulse 2 by 4.47 times, pulse 4 by 4.39 times, and pulse 5 by 20.5 times. Table II shows that $\Delta\tau_1$ is 1.86 ns/m, $\Delta\tau_2$ is 1.52 ns/m, $\Delta\tau_3$ is 0.75 ns/m, and $\Delta\tau_4$ is 2.51 ns/m. Therefore, it is possible to increase the duration of the exciting USP up to 0.9 ns in MF 4 with the same attenuation coefficient.

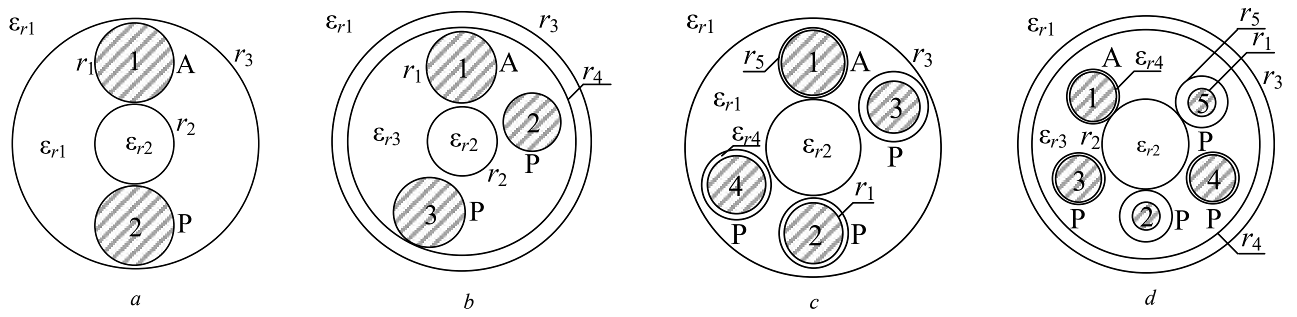

Fig. 4. Cross sections of MF 1 (*a*), MF 2 (*b*), MF 3 (*c*) and MF 4 (*d*) after HS_{opt}.

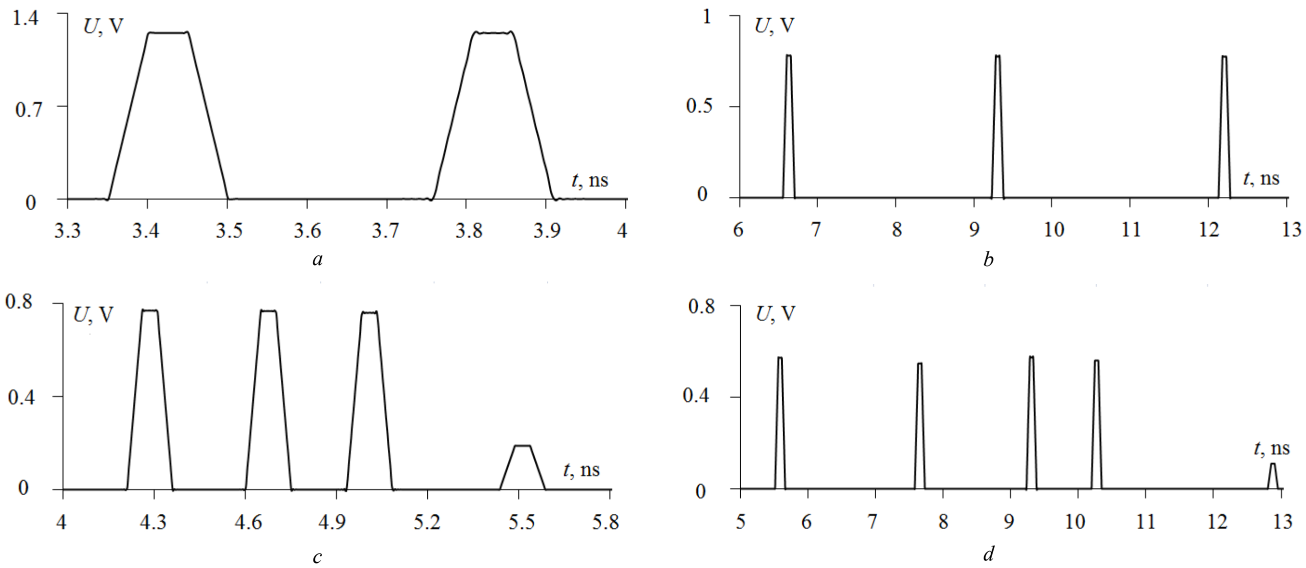

Fig. 5. Voltage waveforms at the MF 1 (*a*), MF 2 (*b*), MF 3 (*c*) and MF 4 (*d*) outputs after HS_{opt}.

TABLE II. MAIN CHARACTERISTICS OF MFS 1–4 AFTER OPTIMIZATION

MF	U_{in}, V	Decomposition pulses 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	1.248	1.248				0.25			
2	2.46	0.78	0.78	0.78			2.55	2.73		
3	2.47	0.77	0.77	0.76	0.19		0.25	0.18	0.36	
4	2.46	0.57	0.55	0.57	0.56	0.12	1.86	1.52	0.75	2.51

Fig. 5 demonstrates the CD of the exciting USP in all MFs. The data in Table II confirm this fact. The matching of MFs 1–4 with the path is also achieved (because the U_{in} value is half the EMF amplitude in all MFs). In addition, Table II shows that the optimization of MF 2 allowed equalizing the amplitudes of all pulses. Finally, Table II demonstrates the possibility to attenuate the exciting USP by 2, 3.1, 3.21 and 4.3 times with increasing its total duration up to 0.42, 2.7, 0.33 and 0.9 ns/m for MFs 1–4, respectively.

V. CONCLUSION

Thus, we performed simulation and parametric optimization of shielded protective structures with circular CS and with N=2, 3, 4, 5. The CD of the exciting USP in all MFs was achieved by establishing different couplings between the active and passive conductors. Optimization was performed according to the amplitude and time criteria. As a result of the optimization, the CD of the exciting USP in all MFs with a maximum attenuation of 4.3 times was achieved. In addition, relatively equal time intervals between decomposition pulses were achieved.

REFERENCES

[1] M. Kučera and M. Šebök, "Electromagnetic compatibility analysing of electrical equipment," 2016 Diagnostic of Electrical Machines and Insulating Systems in Electrical Engineering (DEMISEE), Papradno, 2016, pp. 104–109, doi: 10.1109/DEMISEE.2016.7530476.

[2] Er-Ping Li, Xing-Chang Wei, Andreas C. Cangellaris, En-Xiao Liu, Yao-Jiang Zhang, Marcello D'Amore, Joungho Kim, and Toshio Sudo, "Progress review of electromagnetic compatibility analysis technologies for packages, printed circuit boards, and novel interconnects," IEEE Transactions on Electromagnetic Compatibility, vol. 52, no. 2, May 2010, pp. 248–265, doi: 10.1109/TEMC.2010.2048755.

[3] Y.S. Zhechev, E.B. Chernikova, A.O. Belousov, T.R. Gazizov, "Experimental research of a reflection symmetric modal filter in the time and frequency domains," Systems of Control, Communication and Security, no. 2, 2019, pp. 162–179 (In Russian).

[4] A.O. Belousov, "Complete ultrashort pulse decomposition in modal filters with circular symmetry," IOP Conf. Series: Materials Science and Engineering, vol. 862, no. 5, pp. 1–7, 2020, doi: 10.1088/1757-899X/862/5/052050.

[5] H. Rong, Z. Mohammadi, Y.K. Sharma, F. Li, M.R. Jennings and P.A. Mawby, "Study of breakdown characteristics of 4H-SiC Schottky diode with improved 2-step mesa junction termination extension," 2014 16th European Conference on Power Electronics and

Applications, Lappeenranta, 2014, pp. 1–10, doi: 10.1109/EPE.2014.6910747.

[6] S. Brown, "High-frequency gas-discharge breakdown," Proceedings of the IRE, vol. 39, no. 12, 1951, pp. 1493–1501.

[7] A.T. Gazizov, A.M. Zabolotsky, T.R. Gazizov, "UWB pulse decomposition in simple printed structures," IEEE Transactions on Electromagnetic Compatibility, vol. 58, no. 4, 2016, pp. 1136–1142, doi: 10.1109/TEMC.2016.2548783.

[8] T.R. Gazizov, A.M. Zabolotsky, "New approach to EMC protection," 18th International Zurich Symposium on Electromagnetic Compatibility, 2007, pp. 273–276, doi: 10.1109/ EMCZUR.2007.4388248.

[9] N.O. Vlasova, A.O. Belousov, "Parametric optimization of protective structures with a circular cross-section," International scientific conference on electronic devices and control systems, 2020, pp. 254–257.

[10] E.B. Chernikova, "Analysis of the effect of the shielding enclosure on the characteristics of the reflection symmetric modal filter," Materials of the XIV International Youth Scientific Conference «Gagarin Readings – 2019», 2020, pp. 529–530.

[11] S.P. Kuksenko, "Preliminary results of TUSUR University project for design of spacecraft power distribution network: EMC simulation," IOP Conference Series: Materials Science and Engineering, pp. 1–7, 2019, doi: 10.1088/1757-899X/560/1/012110.