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Optimization of protective cables in the range of real geometric parameters

N O Vlasova and A O Belousov

Tomsk State University of Control Systems and Radioelectronics, 40, Lenina ave.,
Tomsk, 634050, Russia

E-mail: ostrolistaya97@mail.ru

Abstract. This work presents the results of simulation and optimization of multiconductor modal filters (MFs) with circular cross section in the range of real geometric parameters. Five MF structures with 2–4 conductors are considered in a protective shield and without it. Parametric optimization was performed by the amplitude and time criteria in order to obtain a complete ultrashort pulse (USP) decomposition. As a result, it was achieved in all structures with a maximum attenuation factor of 3.7 times.

1. Introduction

Various types of production areas have seen the emergence of more and more modern multi-purpose technical devices (TD) in recent years. The problem of ensuring electromagnetic compatibility is more often exacerbated by the fact that the devices appear simultaneously in the large number [1]. An important task in this case is to protect critical TD (the failure of which can lead to big problems) against intentional electromagnetic interference, which in practice can take various forms. Conducted emissions are particularly hazardous, for example, an ultrashort pulse (USP) with a high voltage level and a subnanosecond rise time. As such, USPs are able to localize in critical TD nodes, disrupting their operation and even completely disabling the TD. Therefore, the protection of the device is relevant, in particular, safety facilities and control systems for critical equipment.

We know that traditional protection devices installed at the TD input, unfortunately, have disadvantages, namely: low power, insufficient operation speed, parasitic parameters, and short service life. In order to eliminate these disadvantages and provide protection against powerful USP, the technology of modal filtration is used. The essence of this technology is to decompose the exciting USP into a pulse sequence because of the difference of modes delays [2–4] in multiconductor transmission lines (MCTL). This technology is effectively used in protective devices called modal filters (MF) [5]. Meanwhile, traditional MFs are implemented mainly on coupled and multiconductor strip structures. However, of interest are MFs based on structures with circular cross-section (CS) (protective cables), which have several significant advantages compared to MFs based on strip structures: design flexibility, greater length (without sacrificing overall dimensions), and the possibility to use ready-made cables. Nevertheless, not enough efforts have been devoted to the study of modal filtration with circular CS [6]. At the moment, an important task is to create a prototype of a protective cable; the first step towards the solution is optimization in the range of real parameters. Thus, it is relevant to study the possibility of complete decomposition (CD) of a USP at the output of 2-, 3-, and 4-conductor MFs with circular CS in the range of real geometrical parameters. To



provide versatility of the task, the modal filter is considered in a protective shield and without it. The purpose of this work is to conduct such research.

2. The main approaches to simulation and optimization

First of all, structures with a circular CS, consisting of 2–4 conductors were chosen. The choice of the range of parameters to optimize these structures is caused by the values of geometric parameters of real cables that are widespread and used both in industry and in household environment.

To begin with, the geometric models of the MF CS were built. Then, the matrices of per-unit-length coefficients of electrostatic (**C**) and electromagnetic (**L**) inductions were calculated. Losses were not taken into account. Next, equivalent circuits for simulation were drawn up and loads and excitations were set. Finally, the time response to the pulse excitation was computed. For the simulation, we chose MF configurations that had been previously studied in [7, 8]. Figure 1 shows CS of the structures after optimization by heuristic search (HS_{opt}), where ϵ_{ri} is the relative dielectric permittivity of the insulation and r_i is the radius of the CS element. We investigated MF 1 (with the number of conductors $N=2$), MF 2 (for $N=2$), MF 3 (for $N=3$), MF 4 (for $N=3$), and MF 5 (for $N=4$). MFs with a circular CS for the study were selected in the following configurations. MF 1 is a central reference conductor, which is covered with a dielectric with two conductors symmetrically located around it. The entire structure is covered with a dielectric. MF 2 is a shielded structure, in the center of which there is a dielectric core with two conductors in a dielectric filling symmetrically located at a short distance around it. MF 3 is a reference conductor covered with a dielectric with three conductors located around it and the entire structure is covered with a dielectric. MF 4 is a shielded structure, in the center of which there is a dielectric core with three conductors in a dielectric filling located at a short distance around it. MF 5 is a shielded structure with four conductors in a dielectric filling located inside it, at some distance from the center.

3. Simulation results

The simulation was performed in the TALGAT software [9]. The values of the conductor loads (R) are taken equal to 50Ω . As excitation, we used a source of trapezoidal pulse signals with an EMF equal to 5 V and a total duration of 150 ps. Figures 1f–h show equivalent circuits of MFs, which are 1 m in length. Figure 2 presents the voltage waveforms at the MF 1–5 output after HS_{opt} .

It is important to show the ranges of real geometrical parameter values (mm) of typical wires and cables, which are close to the CS structure of the MFs. The most widespread in industrial use is the wire with an aluminum core with polyvinylchloride insulation of 3x2.5. It is used for electrical installations, i.e., for stationary laying in lighting and power networks, as well as for deploying electrical equipment, machines, and mechanisms. The wire has the following characteristics: the radius of the conductors varies in the range of 1.15–1.45, the thickness of the insulation is 0.5–1.1, the length of the separation base is 0.8–1, and the thickness of the separation base is 0.6–0.8. Vinyl-insulated flexible aluminum power cable in vinyl sheathing-P 3x6 (single core)–0.66 is also widely used in enterprises and is designed for power transmission and distribution in stationary electrical installations. The cable has the following characteristics: conductor radius varies in the range 1.3–1.5, the thickness of insulation around the conductors is 0.5–1.1, and the thickness of the external insulation is 0.7–1.5. The distance between the insulation around the conductors, the conductors and the external insulation is 0.15. To supply power to electrical appliances, the most common are cables NYM 4x10-0.66 that has the following parameters: the radius of conductors range from 1.7–2.15, the thickness of insulation around the conductors is 0.8–1.1, thickness of the internal insulation is 1.3–1.6, and thickness of external insulation is 1.5–1.75.

As a result of parametric optimization of MF 1–5, the following values (mm) were obtained. For MF 1: $r_1=0.9$, $r_2=1.6$, $r_3=3.45$, at $\epsilon_{r1}=1$, $\epsilon_{r2}=6$, $\epsilon_{r3}=3$. For MF 2: $r_1=0.9$, $r_2=0.7$, $r_3=3.5$, $r_4=3.7$ at $\epsilon_{r1}=1$, $\epsilon_{r2}=10$, $\epsilon_{r3}=3$. For MF 3: r_1 (the reference conductor and conductor 1)=0.9, r_1 (conductor 2)=0.88, r_1 (conductor 3)=0.89, $r_2=1.6$, $r_3=3.45$ at $\epsilon_{r1}=1$, $\epsilon_{r2}=10$, $\epsilon_{r3}=3$. For MF 4: r_1 (conductor 1)=0.5, r_1 (conductor 2)=0.35, r_1 (conductor 3)=0.52, $r_2=1.35$, $r_3=2.7$, $r_4=3.5$ at $\epsilon_{r1}=1$, $\epsilon_{r2}=5$, $\epsilon_{r3}=10$. For MF 5:

r_1 (conductor 1)=0.9, r_1 (conductor 2)=0.5, r_1 (conductor 3 and 4)=0.7, $r_3=3$, $r_4=4$, r_5 (conductor 1)=0.97, r_5 (conductor 2)=0.55, r_5 (conductor 3 and 4)=0.85 at $\epsilon_{r1}=1$, $\epsilon_{r3}=3$, ϵ_{r4} (conductor 1)=20, ϵ_{r4} (conductor 2)=17, ϵ_{r4} (conductor 3)=10, ϵ_{r4} (conductor 4)=5. As a result, the obtained values lie in the range of real parameters of well-known cables. Table 1 presents the main characteristics of the MF 1–5 after HS_{opt}.

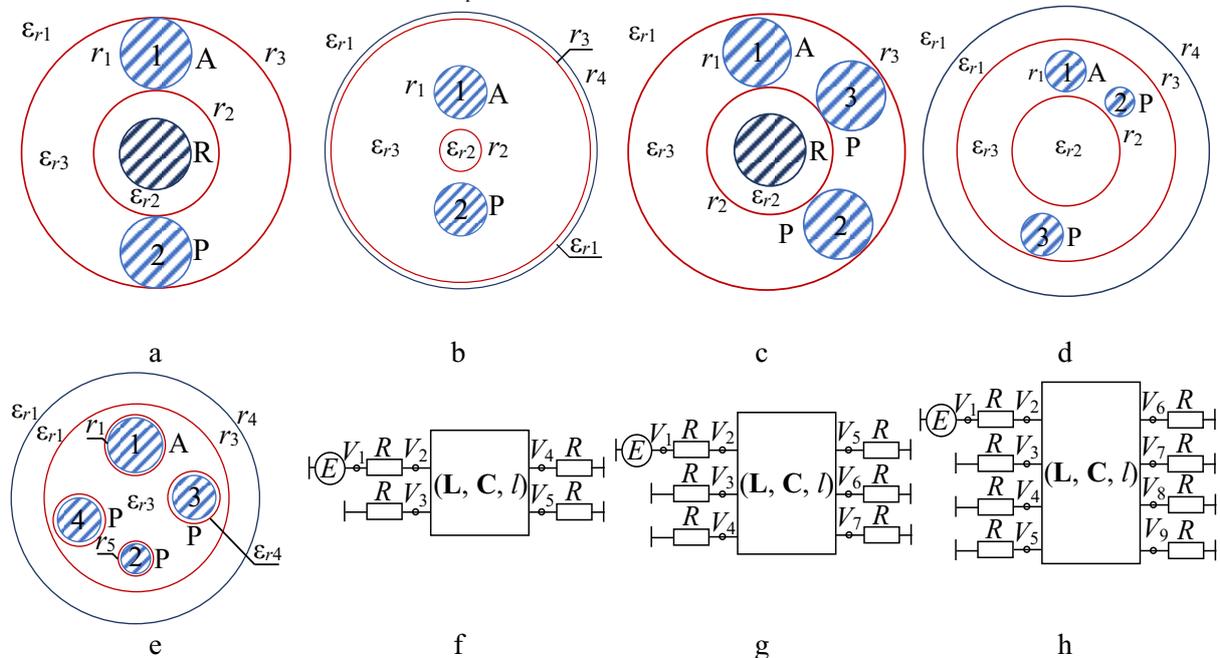


Figure 1. CS of MF 1 (a), 2 (b), 3 (c), 4 (d), and 5 (e) after HS_{opt} and their equivalent circuits (f–h)

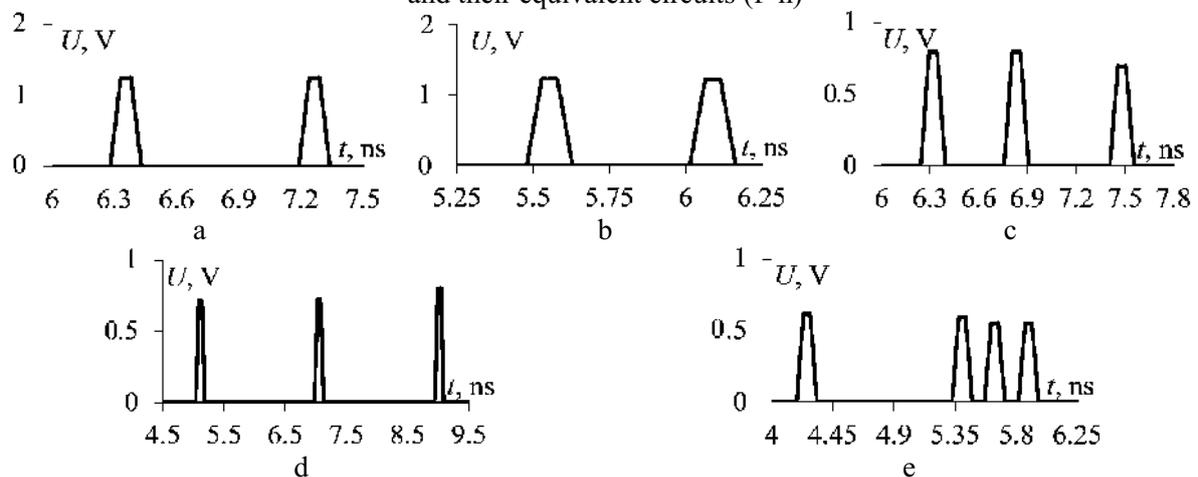


Figure 2. Voltage waveforms at the output of MF 1 (a), 2 (b), 3 (c), 4 (d), and 5 (e) after HS_{opt}

Table 1. Amplitudes of decomposition pulses (U_i) at the output of MF 1–5 and the differences of the modal delay ($\Delta\tau_i$) values

MF	U_{in}, V	U_i, V				$\Delta\tau_i, ns/m$		
		U_1	U_2	U_3	U_4	$\Delta\tau_1$	$\Delta\tau_2$	$\Delta\tau_3$
1	2.49	1.25	1.24			0.77		
2	2.45	1.23	1.22			0.38		
3	2.3	0.8	0.8	0.7		0.31	0.5	
4	2.3	0.71	0.72	0.8		1.74	1.81	
5	2.3	0.62	0.59	0.55	0.55	1	0.03	0.11

Since MF 1 has only the active and passive conductor, a CD is obtained without changing the conductor coordinate arrangement (regarding to [7, 8]). Figure 2a shows that 2 pulses of half the amplitude (with respect to U_{in}) come to the end of the MF 1. In this case, the decomposition pulses do not overlap, thereby reducing the maximum value of the output voltage U_{max} . It follows from Table 1 that the $\Delta\tau_1$ value is 0.77 ns/m, which allows increasing the total duration of the exciting pulse to 0.9 ns (according to the time response) with the same attenuation coefficient.

After HS_{opt} of MF 2 in the range of real geometrical parameters, the conductor coordinate arrangement also remained unchanged (regarding to [7, 8]). To improve the device performance, the size of the internal dielectric was reduced and the size of the external dielectric was increased. Thus, the distance from the conductors to the external shield has increased, which improved the MF 2 performance. Figure 2b demonstrates that two pulses arrive at the end of MF 2, the voltage level of which is also 2 times less than U_{in} . The decomposition pulses do not overlap. The $\Delta\tau_1$ value is 0.38 ns/m, which allows increasing the total duration of the exciting pulse to 0.5 ns with the same attenuation coefficient.

After HS_{opt} of MF 3 shown in Figure 1c, analogous to MF 1, we did not require to change conductor coordinate arrangement (regarding to [7, 8]). Since preliminary optimization was performed in [7, 8], a different coupling between the active and two passive conductors was achieved in advance. Because of the shield, CD could only be obtained by distancing it far enough from the external dielectric. It can be seen from the obtained parameters that the dielectric permittivity of the external and internal dielectrics differs insignificantly. However, this allows to bring the 1 and 2 decomposition pulses closer to each other. It was necessary to reduce the dimensions of the conductor radius to equalize the amplitudes of the decomposition pulses. As shown in Figure 2c, three pulses come to the end of MF 3. At that, the voltages of pulses 1 and 2 are 2.88 times less than the U_{in} value, and the pulse 3 voltage is less by 3.33 times. We can also see that the decomposition pulses do not overlap. The U_{max} value is 0.8 V, which is 2.88 times less than the U_{in} value. The $\Delta\tau_1$ value is 0.31 ns/m, and the $\Delta\tau_2$ value is 0.5 ns/m. Since the minimum $\Delta\tau$ value is 0.31 ns/m, it is possible to increase the total duration of the exciting pulse to 0.46 ns at the same attenuation coefficient.

For MF 4, it was necessary to change the conductor coordinate arrangement during HS_{opt} , to ensure a different coupling between the active and the two passive conductors. However, in order to equalize the decomposition pulse amplitudes and to improve the MF 4 characteristics, the size of conductor radius was insignificantly reduced (but still remained in the range of real parameters). Thus, the amplitude of pulse 2 decreased, and the time intervals between decomposition pulses slightly increased. Thus, it was possible to equalize the time intervals between the decomposition pulses, as well as their amplitudes. As we can see in Figure 2d, three pulses come to the end of MF 4. In this case, the voltages of pulses 1 and 2 are 3.2 times less than the U_{in} value, and the pulse 3 voltage is 2.87 times less. It can also be seen that the decomposition pulses do not overlap. The U_{max} value is 0.8 V, which is 2.87 times less than the U_{in} value. The $\Delta\tau_1$ value is 1.74 ns/m, and the $\Delta\tau_2$ value is 1.81 ns/m. Since the minimum $\Delta\tau$ value is 1.74 ns/m, it is possible to increase the total duration of the exciting pulse to 1.89 ns with the same attenuation coefficient.

It was necessary to change the symmetrical arrangement of conductors in MF 5 during HS_{opt} by changing their coordinate arrangement. Since each conductor is insulated with a dielectric, it was possible to improve the MF characteristics by setting a different ϵ_r value around each conductor. Conductors 3 and 4 have the same radius as the dielectric radius around them. However, they are located at different distances from the active conductor, it was possible to avoid pulse overlap at the MF 5 output. The CD of the exciting USP is obtained, and the amplitudes of the decomposition pulses are relatively equal. Figure 2e demonstrates that there are 4 pulses coming to the end of MF 5. The voltage of pulse 1 is 3.7 times less than the U_{in} value, the pulse 2 voltage is 3.9 times less, and the voltages of pulses 3 and 4 are 4.18 times less. The U_{max} value is 0.62 V, which is 3.7 times less than the U_{in} value. The $\Delta\tau_1$ value is 1 ns/m, the $\Delta\tau_2$ value is 0.03 ns/m, and the $\Delta\tau_3$ value is 0.11 ns/m, therefore, there is no pulses overlapping. Since the minimum $\Delta\tau$ value is 0.03 ns/m, it is possible to increase the total duration of the exciting pulse to 0.18 ns at the same attenuation coefficient.

From Table 1, we can see that the optimization that considered the real parameters succeeded in achieving a CD of the exciting USP in MFs 1–5. During HS_{opt} of MF 3 and MF 4, it was possible to equalize the amplitudes of pulses 1 and 2, and for MF 4, it was possible to equalize the time intervals between all the decomposition pulses. The optimization of MF 5 managed to equalize the amplitudes of pulses 1 and 2, and pulses 3 and 4 in pairs, but failed to achieve the interval-time criterion (alignment of the time intervals between the decomposition pulses). Meanwhile, the parameters obtained during HS_{opt} allow us to approach the matching of the structures with the path (because the obtained value of U_{in} is close to half the EMF).

4. Conclusion

We performed the simulation and optimization of multiconductor MFs with circular CS in the range of real geometrical parameters for the first time. We considered the MFs in a protective shield and without it. It is generally known that the shield reduces the MF protective characteristics. Nevertheless, we performed HS_{opt} according to the amplitude and time criteria and achieved a CD of the exciting USP in all MFs by providing a different coupling between the active and passive conductors. As a result of HS_{opt} , a CD of the exciting USP was achieved in all MFs with a maximum attenuation coefficient of 3.7 (MF 5). In addition, relatively equal time intervals were achieved between the decomposition pulses in MFs 1–4.

Acknowledgments

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