Multicriteria Optimization of a Three-Conductor Modal Filter Using Mass-Dimensional Criterion

Anton O. Belousov
Tomsk State University of Control Systems and Radioelectronics
Tomsk, Russia

***Abstract* – The paper considers the problem of protecting electronic equipment against ultrashort pulses using modal filters (MF) and analyzes the structure of three-conductor microstrip MF. For the first time the mass-dimensional criterion was formulated for multicriteria optimization of the MF with any number of conductors. It was tested by optimizing the MF according to 5 criteria, including mass-dimensional criterion. As a result of the optimization, it was possible to improve not only the mass-dimensional parameters of the MF (which was previously optimized according to 4 criteria without taking into account the mass-dimensional criterion), but also the electrical (the attenuation of the ultrashort pulses at the output of the MF) and time (increase of the difference between the first and the last pulse delays) parameters.**

***Index Terms* – Protection devices, modal filters, microstrip lines, ultrashort pulse, optimization, mass-dimensional criterion, heuristic search, genetic algorithms.**

I. INTRODUCTION

CURRENTLY, THE PROBLEM of electromagnetic compatibility and protection against unintentional or intentional electromagnetic influences has become more relevant and socially significant due to the development of modern information and energy transmission technologies, remote monitoring and surveillance, various types of transport, as well as a number of technological processes [1].

The possibilities of modern ultrashort pulse generators are countless and they themselves pose a considerable danger to various equipment, especially critical [2]. In this regard, increasing attention is paid to the impacts of powerful ultrashort pulses and protection methods against them, one of which is the use of devices operating on the principle of modal filtration – modal filters (MF). They completely lack the negative aspects inherent in other protection devices [3, 4]: vulnerability to radiation, short service life, insufficient speed, the influence of parasitic inductances of leads, failure to operate at high voltages, etc. As an MF there can be employed microstrip structures on widely used metal-clad glass textolite [5].

II. PROBLEM STATEMENT

Initial simulation is an integral part of creating new technique. In addition, optimization methods by evolutionary algorithms are popular in this problem. They are widely used in power electronics [6] and applied electrodynamics [7]. Meanwhile, these steps are relevant when creating protective devices against ultrashort pulses. For example, the authors in [8] analyze the designs of multiconductor transmission lines (MCTL) based on microstrip MFs, formulate and test the main (electrical, time, matching) criteria for MF optimization, and form a hybrid model consisting of heuristic search and genetic algorithm (GA).

However, the reduction of the overall mass-dimensional characteristics of the final product through optimization, which is its logical continuation and addition, has not been considered. Therefore, the purpose of the work is to perform such research. To do this, it is necessary to formulate the mass-dimensional criterion in relation to the MF and check its performance through optimization. It is also useful to compare the results of such optimization with others.

III. THEORY

As noted earlier, to perform optimization with various analysis tasks it is preferable to use global optimization methods. Among them, evolutionary algorithms are most intensively developed and used, and consist of three main groups: evolutionary programming, evolutionary algorithms and GA. As the criteria for optimization or an objective function, a variety of conditions can be used. However, when optimizing protection devices are based on strip lines, the most significant are electric (attenuation of the ultrashort pulses, in the time domain), time (increase in difference delays i.e. τ_{max}–τ_{min}, as well as equalizing the time intervals between them to increase the total input pulse duration, which splitting completely at the same attenuation level), weight and size, as well as cost criteria. Since optimization by one criterion often degrades another, multicriteria optimization is preferable.

978-1-7281-6846-3/20/$31.00 ©2020 IEEE

This paper considers the formulation and verification of mass-dimensional criterion, the optimization of which is designed to reduce weight and size characteristics of an MF. Note that when testing the criterion, the location of the circuit ground and its mass were not taken into account.

Optimization in the paper is performed by the simple GA. GAs are algorithms of the heuristic approach. They are used to solve search and optimization problems. GAs include both elements of deterministic and stochastic approaches. Therefore, GA cannot be attributed only to random search methods. The principle of GA is based on the evolution theory (the fittest survives). In the process of the algorithm, several branches of evolution are considered at once. Using the «fitness function», the GA «creates» new generations (a set of individuals (task parameters)) of objects whose genetic structure is most fitted to the current situation. Therefore, the GA simulates the adaptation process using the objects variability mechanisms. It was established that the use of GA in relation to the problems of electrodynamics, quasistatics, and radio wave propagation, in view of its advantages, popularized its use among scientists. In this paper, during optimization, GA parameters were selected as in [8].

Let us formulate a multicriteria objective function (F) [8]. Its formulation means the designation of a specific task: minimization or maximization:

$$F \to \min \text{ or } F \to \max. \tag{1}$$

Further consideration will be given to the minimization task. For example, one can minimize the sum of objective functions or the maximum of weighted and normalized absolute values of objective functions, each of which represents a separate criterion:

$$F = \sum_i F_i \text{ or } F = \max\{F_i\} \tag{2}$$

where

$$F_i = M_i \frac{f_i}{K_i} \tag{3}$$

where f_i is the objective function, K_i is the normalization constant, M_i is the weighting coefficient of the i-th criterion and i=1, 2, …, N_C, where N_C is the number of criteria.

K_i is chosen to be equal to the maximum value of the i-th objective function so that the f_i/K_i becomes dimensionless and takes values from 0 to 1 during optimization. In addition, K_i must guarantee the condition of $F_i \geq 0$. The importance of the i-th criterion is given by the M_i. If the significance of the criteria is the same, then M_i are also the same and are defined as

$$M_i = \frac{1}{N_C}. \tag{4}$$

Depending on the task, various criteria can be used during optimization. To improve the characteristics of the MFs including multiconductor structures, amplitude and time criteria are important, as well as matching criteria. They are discussed in detail in [8].

IV. CROSS SECTION AND SCHEMATIC DIAGRAM

A multiconductor microstrip line (MSL) was selected for the research with length of l=60 cm, and consisting of 3 conductors. Its cross section is generally shown in Fig. 1 where w is the width of conductors, s_i is separations between them, t is the thickness of conductors and h is the thickness of the dielectric, ε_r is the permittivity of the dielectric. Its schematic diagram is shown in Fig. 2.

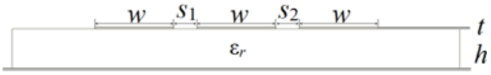

Fig. 1. Cross section of the three-conductor microstrip MF.

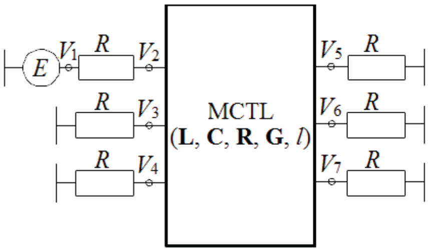

Fig. 2. Schematic diagram of the three-conductor microstrip MF.

First, the construction of a geometric model of the cross section of the MF is perfomed. Then, the matrix of per-unit-length coefficients of electrostatic **C** and electromagnetic **L** inductions are calculated. The matrix of per-unit-length resistances **R** [10] and conductivities **G** [9] is also calculated to take into account losses in conductors and dielectrics, respectively. Next, a schematic diagram for simulation is compiled, loads and excitation are set, the time response to the pulse excitation is calculated in the parameter range and, finally, the MF parameters are optimized for a given objective function.

In recognition of the quasistatic approach, it was assumed that the TEM wave propagates in the considered MF. Simulation and optimization were performed in the TALGAT software [11], which gives acceptable accuracy in solving such tasks. As the excitation pulse signal, we used a real digitized signal from a computational combined S9-11 oscilloscope with parameters: EMF amplitude 0.644 V (measured at a load of 50 Ω), rise duration of 56 ps, decay of 48 ps and flat top of 4 ps (total duration at levels of 0.1–0.9 was 108 ps).

V. MASS-DIMENSIONAL CRITERION

Let us formulate the mass-dimensional criterion as applied to printed circuit boards (Fig. 3). For example, let us consider a printed circuit board based on a coupled line.

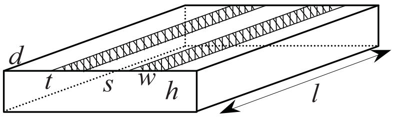

Fig. 3. Standard form of printed circuit board.

The formula for mass calculation is written as

$$m = \rho_m V \tag{5}$$

where ρ_m is the density of the material and V is the volume of the product. It is advisable to apply the formula to the entire structure under consideration, for example, for a conventional coupled MSL, to calculate the mass of all conductors and the dielectric substrate (as well as the covering layer, if any).

Let us consider the conductor (Fig. 4).

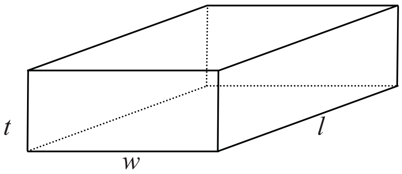

Fig. 4. Basic geometric parameters of the conductor.

The volume of the conductor will be calculated as

$$V = lwt \tag{6}$$

where l is the length of the conductor, w is the width of the conductor and t is the height of the conductor.

Then, the mass of N identical conductors will be

$$m = N\rho_c lwt. \tag{7}$$

And for the more general case of N different conductors, the criterion takes the form

$$f_i = l\rho_c \sum_{j=1}^{N} w_j t_j. \tag{8}$$

The volume of dielectric(s) will be calculated as

$$V = lh\left(2d + \sum_{j=1}^{N} w_j + \sum_{j=1}^{N-1} s_j\right) \tag{9}$$

where w_i and s_i are the width and spacing of the i-th conductor.

The criterion for the dielectric takes the form

$$f_i = hl\rho_d\left(2d + \sum_{j=1}^{N} w_j + \sum_{j=1}^{N-1} s_j\right). \tag{10}$$

Thus, the general form of the mass-dimensional criterion is

$$F_i = M_i \frac{f_1 + f_2}{K_1 + K_2} \tag{11}$$

where

$$f_1 = \rho_c \sum_{j=1}^{N} w_j t_j, \quad f_2 = h\rho_d\left(2d + \sum_{j=1}^{N} w_j + \sum_{j=1}^{N-1} s_j\right). \tag{12}$$

$$K_1 = N\rho_c w_{\max} t_{\max}, \quad K_2 = N\rho_d h_{\max}\left(2d_{\max} + w_{\max}\right). \tag{13}$$

Let us calculate, for example, the mass and volume of the structure obtained by 4-criterion optimization of a 3-conductor microstrip MF [8]. Suppose that the conductors are made of copper and the dielectric material is FR-4 fiberglass (ε_r=5).

The mass of conductors will be calculated as

$$\begin{aligned} m &= N\rho_c lwt \\ &= 3\cdot 8960\ \text{kg/m}^3 \cdot 0.6\ \text{m}\cdot 0.001\ \text{m}\cdot 0.000174\ \text{m}. \end{aligned} \tag{14}$$

The mass of conductors is 0.002806 kg with a volume of $3.132\cdot 10^{-7}$ m^3.

The dielectric mass will be calculated as

$$\begin{aligned} m &= \rho_d lh\left(2d + 3w + s_1 + s_2\right) \\ &= 2000\ \text{kg/m}^3 \cdot 0.6\ \text{m}\cdot 0.000995\ \text{m} \\ &\cdot\left(2\cdot 0.009\ \text{m} + 0.003\ \text{m} + 0.000115\ \text{m} + 0.00001\ \text{m}\right). \end{aligned} \tag{15}$$

The dielectric mass is 0.025 kg with a volume of $1.261\cdot 10^{-5}$ m^3. Thus, the total mass of the structure is 0.028 kg with a total volume of $1.292\cdot 10^{-5}$ m^3.

VI. OPTIMIZATION RESULTS

To test the new mass-dimensional criterion, multicriteria optimization of the 3-conductor MSL was performed using the objective function that combines 1 amplitude and 3 time criteria, as well as the mass-dimensional criterion at $M_{1\text{–}5}$=0.2:

$$\begin{aligned} F &= M_1 \frac{\max\left(U(t)\right)}{\max\left(E(t)\right)} + M_2 \frac{\tau_1 - \frac{1}{c}}{\frac{\sqrt{\varepsilon_{r\max}} - 1}{c}} \\ &+ M_3 \frac{\frac{\sqrt{\varepsilon_{r\max}}}{c} - \tau_3}{\frac{\sqrt{\varepsilon_{r\max}} - 1}{c}} + M_4 \frac{\left|2\tau_2 - \tau_1 - \tau_3\right|}{\frac{\sqrt{\varepsilon_{r\max}} - 1}{c}} \\ &+ M_5 \frac{\rho_c \sum_{j=1}^{N} w_j t_j + h\rho_d\left(2d + \sum_{j=1}^{N} w_j + \sum_{j=1}^{N-1} s_j\right)}{N\rho_c w_{\max} t_{\max} + N\rho_d h_{\max}\left(2d_{\max} + w_{\max}\right)}. \end{aligned} \tag{16}$$

As a result of optimization with the help of GA, the following values were obtained: w=1000 µm, t=178 µm, h=323 µm, s_1=11 µm and s_2=90 µm at d=3w and a length of MSL of 60 cm. The voltage amplitude at the output of the line (Fig. 5) amounted to 0.0208522 V (which is 1.5 times less than the value obtained from 4-criterion optimization), the per-unit-length modal delays were 4.13699, 5.52708, 6.85083 ns/m, therefore their differences were 1.39006 and 1.32375 ns/m, i.e coincide with an accuracy of 10 ps/m. In this case, the maximum difference in the per-unit-length modal delays was 2.71384 ns/m (while 2.48689 ns/m was obtained from the optimization results of [8]).

Let us calculate the mass of the structure. Similarly, the conductors are assumed to be made of copper, and the dielectric material (ε_r=5) is FR-4 fiberglass.

The mass of conductors is given as

$$\begin{aligned} m &= N\rho_c lwt \\ &= 3\cdot 8960\ \text{kg/m}^3\cdot 0.6\ \text{m}\cdot 0.001\ \text{m}\cdot 0.000178\ \text{m}. \end{aligned} \tag{17}$$

The mass of conductors is 0.002871 kg with a volume of $3.204\cdot 10^{-7}$ m^3.

The dielectric mass is calculated as

$$\begin{aligned} m &= \rho_d lh\left(2d+3w+s_1+s_2\right) \\ &= 2000\ \text{kg/m}^3\cdot 0.6\ \text{m}\cdot 0.000323\ \text{m} \\ &\cdot\left(2\cdot 0.009\ \text{m}+0.003\ \text{m}+0.00009\ \text{m}+0.000011\ \text{m}\right). \end{aligned} \tag{18}$$

Thus, the dielectric mass is $8.179\cdot 10^{-3}$ kg with a total volume of $4.089\cdot 10^{-6}$ m^3, and the total mass of the structure is 0,011 kg with a total volume of $4.409\cdot 10^{-6}$ m^3, (Table I) which is 2.5 times by weight and 3 times by the volume less than the values obtained during optimization without taking into account the mass-dimensional criterion.

TABLE I

THE MASS VALUES OF CONDUCTOR (C), DIELECTRIC (D) AND TOTAL (T) MASS AND VOLUME OF 3-CONDUCTOR MSL'S BEFORE AND AFTER OPTIMIZATION

Structure	Mass, kg			Volume, m^3
	C	D	T	
Before opt.	$2.806\cdot 10^{-3}$	0.025	0.028	$1.292\cdot 10^{-5}$
After opt.	$2.871\cdot 10^{-3}$	$8.179\cdot 10^{-3}$	0.011	$4.409\cdot 10^{-6}$

VII. CONCLUSION

When optimizing a 3-conductor structure using a 5-criterion objective function, it was possible to improve its characteristics not only in terms of mass and size parameters, but also in amplitude and time criteria (with the exception of the interval-time criterion, where the results were slightly worse). For instance, the amplitude level at the output of the MF after 5-criterion optimization, taking into account the mass-dimensional criterion, was 47% less than in [8].

The methodological significance of this work lies in the general presentation of the mass-dimensional criterion and its testing through optimization according to a very general 5-criterion objective function which takes into account the mass-dimensional criterion suitable for optimizing any multiconductor MF.

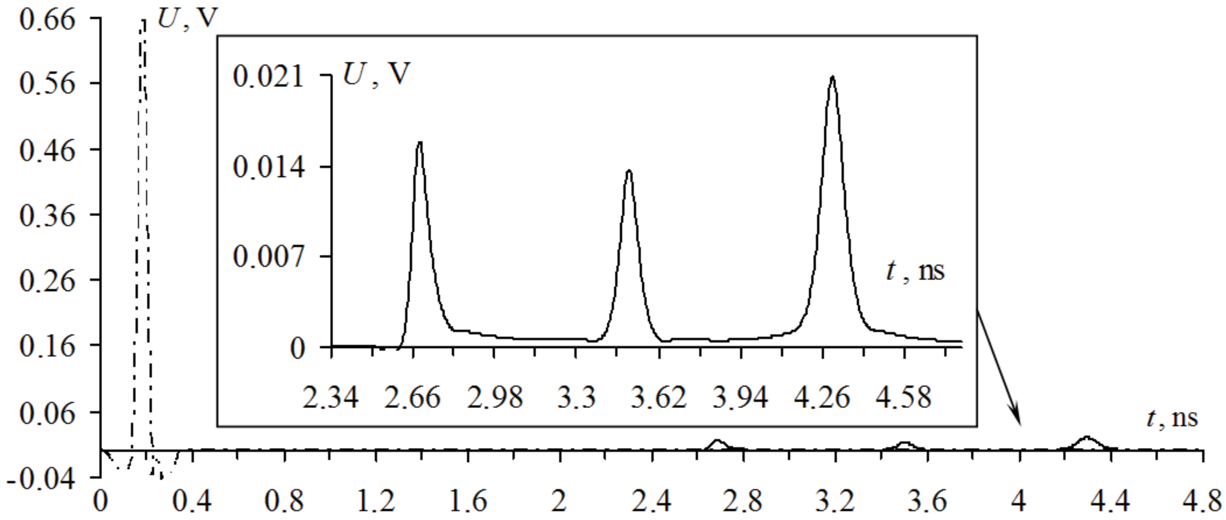

Fig. 5. EMF (–·–) and output voltage (—) waveforms of a 3-conductor microstrip MF with parameters obtained as a result of 5-criteria GA optimization taking into account the mass-dimension criterion.

Thus, the paper for the first time formulated the mass-dimensional criterion. It was tested by optimizing a three-conductor MF according to 5 criteria, including mass-dimensional criterion. As a result of the optimization, it was possible to improve not only the mass and size parameters of the MF (which was previously optimized according to 4 criteria without taking into account the mass-dimensional criterion), but also the electrical (the attenuation of the ultrashort pulses at the output of the MF) and time (the increase of the per-unit-length modal delays differences of the decomposition pulses) parameters. An interesting fact is that it was possible to do this by adding a mass-dimensional criterion to the multicriteria objective function, which is clearly not correlate with the electrical and time MF parameters. However, the parameter s_i has a strong effect on the electrical and time characteristics. Its change affects the couple between the conductors, and its optimum (for the best values of electric and time characteristics) is close to the lower boundary of the optimization range, where the parameter values tend to with additional optimization, taking into account the mass-dimensional criterion. Therefore, there is a correlation of the additional criterion with the main ones.

Meanwhile, the formulated mass-dimensional criterion, as well as the amplitude and time ones, is applicable for optimizing an MF with any number of conductors. The most promising in this direction seems to be a further study of optimizing an MF which takes into account the cost criterion.

ACKNOWLEDGMENT

The criteria formulation was funded by RFBR, project number 19-37-90075. The optimization were carried out at the expense of the Russian Federation President grant MD-2652.2019.9.

REFERENCES

[1] Z.M. Gizatullin, R.M. Gizatullin, “Investigation of the immunity of computer equipment to the power-line electromagnetic interference,” Journal of Communications Technology and Electronics, no. 5, pp. 546–550, 2016.

[2] N. Mora, F. Vega, G. Lugrin, F. Rachidi, M. Rubinstein, “Study and classification of potential IEMI sources,” System and assessment notes. – Note 41. – 8 July, 2014.

[3] M.A. Messier [et al.], “Response of telecom protection to three IEC waveforms,” Proc. of the 15th Int. Zurich Symp. on EMC, Zurich, Switzerland, Feb. 18–20, pp. 127–132, 2003.

[4] IEC 61000-4-x Tests for TI’s Protection Devices (IEC 61000-4-4, IEC 61000-4-5).

[5] 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, pp. 1136–1142, 2016. DOI: 10.1109/TEMC.2016.2548783.

[6] M. Reformat, E. Kuffel, D. Woodford, W. Pedrycz, “Application of genetic algorithms for control design in power systems,” IEE Proceedings – Generation, Transmission and Distribution, vol. 145, no. 4, pp. 345–354, Jul 1998. DOI: 10.1049/ip-gtd:19982003.

[7] K. Goudos, C. Kalialakis, R. Mittra, “Evolutionary algorithms applied to antennas and propagation: A review of state of the art,” Hindawi Publishing Corporation Int. J. of Antennas and Propagation Volume, pp. 1–12, 2016, article ID 1010459.

[8] A.O. Belousov, T.R. Gazizov “Systematic approach to optimization for protection against intentional ultrashort pulses based on multiconductor modal filters,” Complexity [URL: http://downloads.hindawi.com/journals/complexity/2018/5676504.pdf], vol. 2018, pp. 1–15, 2018.

[9] A.R. Djordjevich, R.M. Biljic, V.D. Likar-Smiljanic, T.K. Sarkar “Wideband frequency-domain characterization of FR-4 and time-domain causality,” IEEE Trans. on Electromagnetic Compatibility, vol. 43, no. 4, Nov., pp. 662–666, 2001.

[10] Matthaei G.L., Chinn G.C, “Approximate calculation of the high-frequency resistance matrix for multiple coupled lines,” Microwave Symposium Digest, pp. 1353–1354, 1992.

[11] S.P. Kuksenko, T.R. Gazizov, A.M. Zabolotsky, R.R. Ahunov, R.S. Surovtsev, V.K. Salov, Eg.V Lezhnin, “New developments for improved simulation of interconnects based on method of moments,” Advances in Intelligent Systems Research (ISSN 1951-6851). Proc. of the 2015 Int. Conf. on Modeling, Simulation and Applied Mathematics (MSAM2015). – Phuket, Thailand, pp. 293–301, August 23–24, 2015.

Belousov Anton Olegovich was born in 1994. He received the B.Sc. degree of TUSUR in 2015 and M.Sc. degree in 2017. Currently, he is a third year postgraduate student and is working as a Junior Researcher at TUSUR. He is the author of 56 scientific papers.

E-mail: ant1lafleur@gmail.com