Multicriteria Optimization of Multiconductor Modal Filters by Genetic Algorithms

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***Abstract*— Multicriteria optimization by genetic algorithms is considered. We optimize novel devices for the protection against ultrashort pulses referred to as multiconductor modal filters (MF) by means of the decomposition of the pulses into a sequence of smaller pulses. A multicriteria objective function with amplitude and time criteria is formulated. Five amplitude criteria are proposed for the critical systems, as well as range-time and interval-time criteria. To test the theory, four-criterion optimization of four parameters for a three-conductor microstrip MF has been performed. The results have shown the importance of optimization of multiconductor MF with the simultaneous use of several criteria: the three-conductor microstrip MF with attenuation factor of 21.4 times for ultrashort pulse with the duration of less than 0.6 ns/m is obtained.**

Key words*— protection device, modal filtering, modal filters, multicriteria optimization, genetic algorithms.

I. INTRODUCTION

Contemporary radio electronic devices have wide functional capabilities but, at the same time, they are susceptible to electromagnetic interference. Conducted interference is considered to be the most harmful one, as it can penetrate into devices directly through conductors [1]. Modern generators of ultrashort pulses have very high capabilities [2]. As a result, there is a potential threat for the devices. Therefore, it is necessary to improve the protection of electronics against ultrashort pulses.

A technique of modal filtration [3] was proposed for the protection of electronic equipment against ultrashort pulses. This technique is based on modal decomposition of a pulse signal which occurs due to a difference between the modal delays in multiconductor transmission lines. A number of studies [4–9] on the use of multiconductor microstrip lines (MSL) as protective devices against ultrashort pulses have been performed. Results of simulation of MSL consisting of 3–5 conductors showed the decomposition of an input pulse at the end of a conductor into 3–5 pulses with the maximum amplitudes of 3, 3.6 and 4.5 times (correspondingly) less than a signal in the near end of a line [4]. Optimization showed that the equalization of the differences between delays of decomposition pulses allows increasing duration of a pulse which is going to be completely decomposed in these structures [5]. In addition, the formulation of the main criteria for optimizing a multiconductor modal filter (MF) has been performed and an example of its optimization has been given by criteria of the minimization of the maximum output amplitude and the maximization of a difference of time delays between the first and the last decomposition pulses [6]. Experimental confirmation of the modal filtering based on multiconductor MSL was performed. For two- and three-conductor MSL, the attenuation of 11.5 and 13.7 times was obtained [7], and for four- and five-conductor – 12.6 and 15.3 times [8]. In [4–8], a heuristic search for parameters was used, but it did not provide the best results. This disadvantage is eliminated in [9] based on optimization of the three-conductor MSL MF using a genetic algorithm (GA) providing the output MF amplitude 13% less than after the heuristic search.

Meanwhile, in [4–9] only one criteria was used for the optimization. Thus, it is expedient to formulate a general objective function for the optimization by several criteria and to formulate a basic optimization criteria. The aim of this paper is to perform such research.

II. GENERAL FORMULATION OF THE MULTICRITERIA OBJECTIVE FUNCTION

Formulation of a multicriteria objective function (F) implies combining separate criteria to a single problem of minimization or maximization:

$$F \to \min \text{ or } F \to \max. \quad (1)$$

For brevity, we will consider the minimization. For example, the sum or maximum of the weighted and normalized absolute values of the objective functions that formulate separate criteria can be minimized:

$$F = \sum_i F_i \text{ or } F = \max\{F_i\} \quad (2)$$

where

$$F_i = M_i \frac{f_i}{K_i} \quad (3)$$

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

Normalization coefficients K_i are chosen to be equal to the maximum possible value of the i-th objective function so that

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the value of f_i/K_i becomes dimensionless and takes values from 0 to 1 during optimization. Moreover, K_i must guarantee non-negative values of F_i. The significance of the i-th criterion is given by the weighting coefficients M_i. If the criteria are of equal value to the user, then these coefficients are the same and can be given as

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

Optimization can be performed according to various criteria. Amplitude and time criteria are relevant for multiconductor MFs. They are discussed in detail in the following sections.

III. AMPLITUDE CRITERIA

The most important criteria for optimization of MF are amplitude ones. They can be considered in the time and frequency domains. It is useful to analyze the waveform $U(t)$ at the output of the MF to provide protection against the ultrashort pulse of electromotive force $E(t)$. Therefore, let us consider the amplitude criteria in the time domain. On the basis of $U(t)$, five norms used to evaluate the effectiveness of ultrashort pulses impact on different (in relation of specifity of response to the impact) equipment are formulated [2]. Using these norms, we can formulate expressions for f_i and K_i.

1. For the circuit upset, as well as electric breakdown or arc-over effects, the maximum magnitude of the value of the $U(t)$ is important:

$$f_1 = \max|U(t)|, \;\; K_1 = \max|E(t)|. \tag{5}$$

2. For component arcing, as well as the circuit upset, the maximum magnitude of the $U(t)$ change rate is important:

$$f_2 = \max\left|\frac{\partial U(t)}{\partial t}\right|, \;\; K_2 = \max\left|\frac{\partial E(t)}{\partial t}\right|. \tag{6}$$

3. For dielectric puncture, the maximum magnitude of the integral of the $U(t)$ is important:

$$f_3 = \max\left|\int_0^t U(t)dt\right|, \;\; K_3 = \max\left|\int_0^t E(t)dt\right|. \tag{7}$$

4. For equipment damage, the integral of the $U(t)$ magnitude is important:

$$f_4 = \int_0^\infty |U(t)|dt, \;\; K_4 = \int_0^\infty |E(t)|dt. \tag{8}$$

5. For component burnout, the square root of the integral of the square of the $U(t)$ magnitude is important:

$$f_5 = \left\{\int_0^\infty |U(t)|^2 dt\right\}^{\frac{1}{2}}, \;\; K_5 = \left\{\int_0^\infty |E(t)|^2 dt\right\}^{\frac{1}{2}}. \tag{9}$$

IV. TIME CRITERIA

Time criteria are important for preventing impulses that increase the maximum voltage at the MF output with increasing duration of the exiting ultrashort pulse. Compared to amplitude ones, time criteria may not require costly computation of the response, since it is enough to calculate only the per-unit-length delays. We consider two types of time criteria: range-time and interval-time criteria.

One of them is associated with the expansion of the pulses time range at the MF output. The other is related to the alignment of time intervals. Note that in time criteria, the values of the per-unit-length delay are ordered in ascending order.

A. Range-time Criteria

Range-time criteria are associated with expansion of the time range of decomposition pulses at the MF output. These criteria are important for increasing the maximum duration of an exciting ultrashort pulse, which will be decomposed completely. The first one makes per-unit-length delay of the first pulse ($\tau_{\min}$) as short as possible, i.e. as determined by the light velocity in vacuum. The second one makes per-unit-length delay of the last impulse ($\tau_{\max}$) as long as possible, i.e. as determined by the light velocity in dielectric with the maximum value of the relative dielectric permittivity ($\varepsilon_{r\max}$).

1. For the first range-time criterion

$$f_6 = \tau_{\min} - \frac{1}{\mathrm{c}}, \;\; K_6 = \frac{\sqrt{\varepsilon_{r\max}} - 1}{\mathrm{c}}. \tag{10}$$

2. For the second range-time criterion

$$f_7 = \frac{\sqrt{\varepsilon_{r\max}}}{\mathrm{c}} - \tau_{\max}, \;\; K_7 = \frac{\sqrt{\varepsilon_{r\max}} - 1}{\mathrm{c}}. \tag{11}$$

To expand the time range in both directions these criteria must be used together. They are applicable to MF with any number of conductors (N).

B. Interval-time Criteria

This criterion is important when $N>2$. It is used to equalize time intervals between the pulses at the MF output. It allows increasing the duration of the exciting ultrashort pulse, which will be decomposed at the MF output completely. For arranged by increasing values of the per-unit-length delays, based on the deviation of the current values of the per-unit-length delay of the intermediate modes from the values according to uniform time intervals between the pulses, we obtain

$$f_8 = \max\left|\tau_i - \left(\tau_{\min} + (i-1)\cdot\Delta\right)\right|, \; i = 2, ..., N-1, \; K_8 = \frac{\sqrt{\varepsilon_{r\max}} - 1}{\mathrm{c}} \tag{12}$$

where

$$\Delta = \frac{\tau_{\max} - \tau_{\min}}{N-1} \tag{13}$$

where τ_i – value of per-unit-length delay of the i-th pulse.

V. OPTIMIZATION OF THE THREE-CONDUCTOR MF

To test the theory, the three-conductor microstrip MF was optimized with the help of a GA. We use the multicriteria objective function that combines one amplitude (5) and three (10–12) time criteria for N=3

$$F = \frac{\max(U(t))}{\max(E(t))} + \frac{\tau_1 - \frac{1}{\mathrm{c}}}{\frac{\sqrt{\varepsilon_{r\max}} - 1}{\mathrm{c}}} + \frac{\frac{\sqrt{\varepsilon_{r\max}}}{\mathrm{c}} - \tau_3}{\frac{\sqrt{\varepsilon_{r\max}} - 1}{\mathrm{c}}} + \frac{|2\tau_2 - \tau_1 - \tau_3|}{\frac{\sqrt{\varepsilon_{r\max}} - 1}{\mathrm{c}}}. \tag{14}$$

GA is an evolutionary algorithm, with the main idea of using the ideas of evolution theory to solve optimization problems. The algorithm is divided into three main stages: crossing (the formation of the population), selection and mutation. GA works until the result is acceptable or the number of generations (cycles) reach a predetermined value. In general, the use of GA eliminates the task of exhaustive search. Therefore, GA is widely used in solving a wide variety of tasks. In this paper, we used simple GA. The GA parameters were chosen as follows: number of individuals – 50; number of generations – 100; mutation coefficient of 0.1; crossover coefficient of 0.5.

Parameters and forms of the signal were calculated in TALGAT software [10]. It was assumed that a T-wave is propagating along the MF. Losses in conductors and dielectrics were considered. A digitized signal of the oscilloscope C9-11 was used as an exciting pulse, it was measured at 50 Ω load, with an amplitude of 0.657 V. Durations of rise – 27 ps, fall – 29 ps and flat top – 9 ps, so that the overall duration – 65 ps. (Durations were measured at levels of 0.1–0.9). Schematic diagram of the MF is shown in Fig. 1, and the cross section with parameters after optimization in Fig. 2.

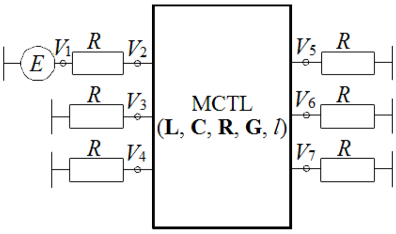

Fig. 1. Schematic diagram for research

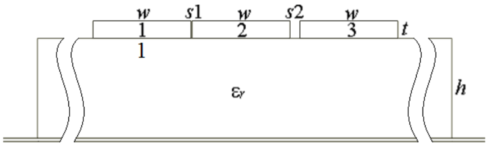

Fig. 2. Cross sections of three-conductor MSL

MF was optimized for the following parameters: width of conductors (w) is 1000 µm, relative permittivity (ε_r) is 5, length of line (l) is 60 cm, R=50 Ω. The value of w was optimized in order to assure 50 Ω characteristic impedance of a single line and it was unchanged, as well as the value of ε_r. The thickness of conductors t, thickness of dielectric h and values of conductors separations $s1$ and $s2$ were optimized for the multicriteria objective function (14). Optimization of t was performed in a range of 10–200 µm, optimization of h – in a range of 200–2000 µm, and $s1$ and $s2$ – 1–1000 µm. As a result of the optimization with the help of GA, the values of t = 174 µm, h = 995 µm, $s1$ = 10 µm and $s2$ = 115 µm were obtained. The amplitude of the signal at the output of the line was 0.03067 V, the per-unit-length delays are equal to 3.96396, 5.20713, 6.45085 ns/m, so that the differences in the per-unit-length delays of adjacent pulses are equal to 1.24317 and 1.24372 ns/m, i.e. coincide up to 1 ps/m. The waveforms at the input and output of the three-conductor MF with parameters after the optimization using GA are presented in Fig. 3.

VI. CONCLUSION

A general multicriteria objective function is obtained. The amplitude and time criteria for optimizing MF are formulated. The optimization of four parameters of a three-conductor microstrip MF by four criteria has been performed. At the MF output, a signal with an amplitude of 0.03067 V and the same difference in the delay values of adjacent pulses is obtained. Thus, the attenuation factor of 21.4 times is possible for ultrashort pulse with the duration of less than 0.6 ns/m.

In [9], a three-conductor MF was obtained for $s1$=330 µm and $s2$=675 µm with a maximum amplitude at the output of 0.03619 V. In this case, optimization was carried out only with respect to the parameters $s1$ and $s2$ in the range 200–885 µm, for further experimental realization of the structures. The amplitude level at the output of the MF of this paper is 18% less than in [9].

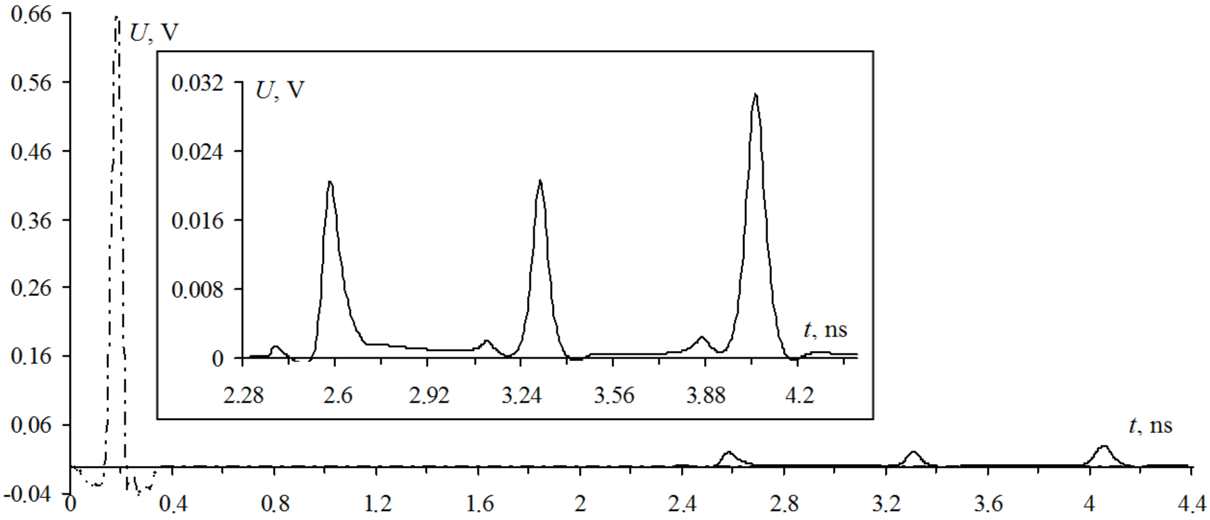

Fig. 3. Waveforms at the input (–·–·–) and output (——) (with enlarged fragment of the signal at the output) of three-conductor microstrip line MF after optimization of four-criteria optimization using GA

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