Multicriteria optimization of a meander line with broad-side coupling by genetic algorithms

K P Malygin, A V Nosov, R S Surovtsev, T T Gazizov and I Y Sagiyeva

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

E-mail: alexns2094@gmail.com

Abstract. Multicriteria quality functions for the dangerous pulse splitting into a sequence of pulses of smaller amplitude were formulated. The optimization was performed by simple genetic algorithm using these functions. As a result, 3 sets of optimal parameters providing the given criteria were obtained. Comparison of the results of the heuristic search and genetic algorithm showed their similarity. As a result of the genetic algorithm optimization in accordance with the formulated criteria, the attenuation (times) achieved 2.5 for the set of parameters one, 3.3 – for set two, and 3.42 – for set three.

1. Introduction

Today, electronic equipment (EE) is actively used in almost all fields of science and technology: military, nuclear, transport, space, etc. Uninterrupted operation of EE is very important. EE is developing rapidly: the size of components on printed circuit boards (PCBs) decreases and density of their packaging in EE increases, the operating voltages decrease and the operating signal frequencies increase. This leads to an increase in the sensitivity of EE components to natural (unintentional) and artificial (intentional) electromagnetic interferences. A particular danger for EE is created by ultrashort pulses (hereafter, a dangerous pulse (DP)), which can penetrate the EE through slots in the enclosure or shield and lead to malfunctions or complete failure of elements and devices [1, 2]. The most common means for protecting EE against such DPs are noise suppressors, electromagnetic shields, various filters, decoupling and gas-discharge devices. However, each of these devices has its own disadvantages [3, 4]: low power, low speed, and parasitic parameters. This makes it difficult to ensure the reliability and uninterrupted operation of the EE. Thus, it is necessary to find new ways of effective protection.

Various stripline devices for DP protection and signal filtering are noteworthy [5–10]. Modal filters (MF) [11] based on modal splitting technology [12] have been proposed, which are devoid of the noted disadvantages and also have a number of advantages (absence of semiconductor components, radiation resistance, long operation life, operation at high voltages and low cost). Another approach is splitting a DP into a sequence of lower amplitude pulses in a meander line turn with broad-side coupling (MLBSC) [13]. Conditions that ensure the splitting into four pulses (cross-talk, even mode (EM), additional pulse and odd mode (OM)) have been formulated:

\[ 2\tau_e \geq \tau_c, \]  
\[ l(\tau_o - \tau_e) \geq \tau_c, \]  
\[ \tau_{\text{max}} = 3\tau_{\text{min}}. \]
where \( \tau_0 \) and \( \tau_e \) are the per-unit-length delays (PULD) of the OM and EM of the line respectively, \( t_p \) is the total DP duration, \( l \) is the length of a meander half-turn, \( \tau_{\text{min}} \) and \( \tau_{\text{max}} \) are the minimum and maximum of the PULD of the EM and OM of the line, respectively. Condition (1) ensures the arrival of an EM pulse after of the cross-talk pulse, (2) – splitting of the main signal into pulses of EM and OM, and (3) – the arrival of all pulses with equal time intervals between each other. As a result of the study [13], the maximum DP attenuation by 3.3 times relative to half of the e.m.f. was shown. However, the parameters providing conditions (1)–(3) and such DP attenuation were obtained using a heuristic search, which did not take into account the matching of the line in a tract, and the real geometric parameters. In order to consider these criteria, one can use more efficient methods of global optimization, for example, genetic algorithms (GAs), which are provided by the TALGAT software available to the authors [14]. The aim of this paper is to perform multicriteria GA optimization of an MLBS by the criteria of complete DP splitting and minimization of its amplitude. For this, it is first necessary to formulate the criteria that provide DP splitting and minimize its amplitude at the end of the line, and then to perform the optimization.

2. Initial data for simulation

The cross-section of the line under investigation is shown in figure 1a, and has the following parameters: conductor A is active, conductor G is reference ground, \( w \) and \( t \) are the width and thickness of the conductors respectively, \( s \) is the space between conductors, \( h \) is the thickness of the dielectric substrate, \( \varepsilon_r \) is the relative permittivity of the substrate, \( d \) is the distance from the edge of the structure to the conductor \((d=3w)\). The equivalent circuit of the line is shown in figure 1b, where \( R_1=R_2=(Z_LZ_L)^{0.5} \). As an excitation, we selected a trapezoid pulse with the parameters: e.m.f. – 1 V, the duration of the flat top – 100 ps, the rise and fall times – 50 ps each.

![Cross-section and equivalent circuit of the MLBS.](image)

Note that in [13], we have found 3 sets of parameters using a heuristic search: sets 1 and 2 provide the conditions (1) and (2) and DP attenuation (times) by 2.5 and 3.3, respectively (relative to \( E/2 \)), and set 3 provides the condition (3) and DP attenuation by 3.4 times (relative to \( E/2 \)). For clarity, Table 1 summarizes the sets of obtained parameters and the corresponding amplitudes at node \( V_3 \) from [13].

| № | \( w, \mu m \) | \( t, \mu m \) | \( s, \mu m \) | \( \varepsilon_r \) | \( h, \mu m \) | \( l, \mu m \) | \( U, V \) |
|---|---|---|---|---|---|---|---|
| 1 | 1000 | 18 | 200 | 5 | 540 | 150 | 0.202 |
| 2 | 380 | 18 | 200 | 20 | 940 | 150 | 0.151 |
| 3 | 1000 | 136 | 5 | 500 | 1200 | 80 | 0.146 |

When optimizing the line under investigation, we will use 3 sets of parameters from Table 1, relative to which the ranges were selected: for the first set – \( 900 \mu m \leq w \leq 1100 \mu m, \ 10 \mu m \leq t \leq 26 \mu m, \ 150 \mu m \leq s \leq 250 \mu m \); for the second – \( 250 \mu m \leq w \leq 450 \mu m, \ 10 \mu m \leq t \leq 26 \mu m, \ 150 \mu m \leq s \leq 250 \mu m \); for the third – \( 900 \mu m \leq w \leq 1100 \mu m, \ 106 \mu m \leq s \leq 166 \mu m, \ 2 \mu m \leq l \leq 15 \mu m \).
3. Formulation of a multicriteria quality function

When formulating a multicriteria quality function \( F \), it is necessary to bring individual criteria to one of the minimization or maximization tasks. We will do this following the paper [11]. For definiteness, we will consider minimization of the sum

\[
F = \sum_i F_i
\]

(4)

where

\[
F_i = M_i \frac{f_i}{K_i}
\]

(5)

where for each \( i \) criterion: \( f_i \) is the quality function; \( K_i \) is the normalization coefficient; \( M_i \) is the weighting factor; \( i = 0, 1, 2, \ldots, N_C \), where \( N_C \) is the number of optimization criteria. Coefficient \( K_i \) is chosen to be equal to the maximum of the possible values of the \( i \)-th quality function so that the value \( f_i/K_i \) becomes dimensionless and takes values from 0 to 1 in the optimization. Coefficient \( M_i \) sets the significance of the \( i \)-th criterion. If the criteria are equivalent for the user, then these coefficients are the same and can be set in units or as

\[
M_i = \frac{1}{N_C}.
\]

(6)

We now formulate 2 multicriteria quality functions: \( F_1 \) based on (1) and (2) and \( F_2 \) based on (3). Sets 1 and 2 will be used when optimizing the line under investigation using \( F_1 \), and sets 3 – using \( F_2 \).

First, we formulate the criteria based on conditions (1) and (2). Instead of unstrict inequality in the conditions, we consider the case of ordinary equality (the fulfillment of which will also allow us to fully split the DP). Then criterion \( f_1 \) providing (1) is

\[
f_1 = t_\Sigma - 2l \tau_e
\]

(7)

and the criterion \( f_2 \), which provides (2), is

\[
f_2 = t_\Sigma - l(\tau_o - \tau_e).
\]

(8)

Coefficients \( K_1 \) and \( K_2 \) are taken to be equal to the maximum values of \( f_1 \) and \( f_2 \), respectively, which are found from the extreme points of the range of values of the optimized parameters.

The third optimization criterion, \( f_3 \), is the criterion for amplitude minimization. To protect against a DP, it is relevant to analyze the signal voltage \( U(t) \) at node \( V3 \). If the danger is created by the maximum level of \( U(t) \), then

\[
f_3 = \max |U(t)|.
\]

(9)

Then, the normalization coefficient for \( f_3 \) is \( K_3 = \max |E(t)| \), where \( E(t) \) is the e.m.f. of the source. Thus, \( F_1 \) takes the form

\[
F_1 = M_1 \frac{f_1}{K_1} + M_2 \frac{f_2}{K_2} + M_3 \frac{f_3}{K_3}
\]

(10)

where \( M_1 = M_2 = M_3 \) in the optimization with the first set of parameters of the line, and \( M_1 = M_2 = 0.2, M_3 = 0.6 \) - with the second.

The quality function \( F_2 \) is formulated similarly but its first criterion \( f_1 \) is chosen based on the condition (3). Then \( f_1 \) for \( F_2 \) takes the form

\[
f_1 = 3 \tau_{\min} - \tau_{\max}.
\]

(11)
Coefficient $K_1$ is taken to be equal to the maximum value of $f_1$, which was found from the extreme values of the range of the optimized parameters. We note that $f_2$ and $K_2$ for $F_2$ are the same as $f_3$ and $K_3$ for $F_1$ respectively. Thus, $F_2$ will take the form

$$F_2 = M_1 \frac{f_1}{K_1} + M_2 \frac{f_2}{K_2}$$

(12)

where $M_1=M_2$.

4. Multicriteria optimization of an MLBSC

Simulation of the line under investigation was performed in the TALGAT software [14]. Table 2 summarizes the results of optimization by simple GA for the line under investigation using $F_1$ and $F_2$: 3 sets of optimal line parameters, PULD and the maximum amplitudes at node $V3$. The signal waveforms at node $V3$ for sets of optimal parameters are shown in figure 2. The optimal number of individuals in the population and the number of generations for which the formulated criteria are fulfilled are the following: 5 and 10 for set 1; 20 and 100 for set 2, 10 and 15 for set 3.

Table 2. Optimization results for the line under investigation using $F_1$ and $F_2$.

| №  | $w$, µm | $t$, µm | $s$, µm | $\varepsilon_r$ | $l$, mm | $\tau_{\max}$, ns/m | $\tau_{\min}$, ns/m | $U$, V |
|----|---------|---------|---------|-----------------|--------|----------------------|----------------------|-------|
| 1  | 903.507 | 25.908  | 155.196 | 5               | 150    | 6.54487              | 5.2058               | 0.198 |
| 2  | 283.527 | 10.8679 | 167.636 | 20              | 940    | 11.6206              | 10.2814              | 0.151 |
| 3  | 1070.79 | 161.423 | 2.00476 | 500             | 1200   | 58.3685              | 19.4275              | 0.146 |

Figure 2. Voltage waveforms at the end of the line under investigation with optimal sets: 1 (a), 2 (b), 3 (c)

The results show that the formulated criteria are satisfied: the DP at node $V3$ with three sets of parameters is represented by a sequence of pulses of smaller amplitude, and conditions (1)–(3) are provided when substituting the corresponding PULD from Table 2. The results of GA optimization and the heuristic search from [13] were found to be similar.

6. Conclusion

Multicriteria quality functions for the DP splitting into a sequence of pulses of smaller amplitude were formulated. The optimization was performed by a simple GA using these functions. As a result, 3 sets of optimal parameters providing the given criteria were obtained. Comparison of the results of the heuristic search and GA showed their similarity. As a result of the GA optimization in accordance with the formulated criteria, the attenuation (times) achieved 2.5 for the set of parameters one, 3.3 – for set two, and 3.42 – for set three. The formulated criteria will be used in the further practical implementation of the device, at the stage of optimizing its real geometric parameters (in accordance with the technological capabilities of PCB manufacturers).
Acknowledgments
The research was supported by the Russian Federation President grant MD-2652.2019.9 and Ministry of Science and Higher Education of the Russian Federation (Project FEWM-2020-0039) in TUSUR.

References
[1] Mora N, Vega F, Lugrin G, Rachidi F and Rubinstein M 2014 Study and classification of potential IEMI sources System and assessment notes 41 1-48
[2] Gizzatullin Z M and Gizatullin R M 2014 Journal of Communications Technology and Electronics 59(5) 424-6
[3] Messier M A, Smith K S, Radasky W A and Madrid M J 2003 Response of telecom protection to three IEC waveforms Proc. of the 15th Int. Zurich Symp on EMC (Zurich) 127-32
[4] Gizatullin Z M and Gizatullin R M 2016 Journal of Communications Technology and Electronics 61(5) 546-50
[5] Krzikalla R, Luikenter J, ter Haseborg L and Sabath F 2007 Systematic description of the protection capability of protection elements Proc. of IEEE Int. Symp. on EMC (Honolulu) 1-4
[6] Krzikalla R, Weber T and Haseborg J L 2003 Proc. of IEEE Int. Symp. on EMC (Istanbul) 1313-6
[7] Krzikalla R and Haseborg J L 2005 Proc. of IEEE Int. Symp. on EMC (Chicago) 977-81
[8] Weber T, Krzikalla R and Haseborg J L 2004 IEEE Trans. on EMC 46(3) 423-30
[9] Cui Q, Dong S and Han Y 2012 Investigation of waffle structure SCR for electrostatic discharge (ESD) protection IEEE Int. Conf. on Electron Devices and Solid State Circuit (Bangkok)1-4
[10] Hayashi H, Kuroda T, Kato K, Fukuda K, Baba S and Fukuda Y 2005 Int. Conf. On Simulation of Semiconductor Processes and Devices (Tokyo) 99-102
[11] Belousov A O and Gazizov T R 2018 Complexity 15
[12] Gazizov A T, Zabolotsky A M and Gazizov T R 2016 IEEE Trans. on EMC 58(4) 1136-42
[13] Belousov A O, Chernikova E B, Samoylichenko M A, Medvedev A V, Nosov A V, Gazizov T R and Zabolotsky A M 2020 Symmetry 12(1117) 1-39
[14] Kuksenko S P 2019 IOP Conf. Series: Materials Science and Engineering 560 1-7