Conditions for ultrashort pulse decomposition in multi-cascade protection devices based on meander microstrip lines

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Abstract. The research presents universal conditions which allow the complete splitting of a dangerous pulse (DP) in a meander microstrip line (MMSL) of any number of cascades. The verification of the conditions was performed on the example of an MMSL of two, three, four and five cascades. Attenuation (times) of a DP in the MMSL of three turns was 8.1, of four turns – 19.9 and of five turns – 33.16.

1. Introduction

With the steady development of technologies, there is a decrease in the size of components on printed circuit boards (PCBs) and density of their packaging in radio equipment (RE). Herewith, the operating voltages decrease and the operating signal frequencies increase. All of these lead to an increase in the RE susceptibility to various electromagnetic interferences (EMI). Also, there is a the risk of RE damage from pulsed [1] and continuous [2] excitations, even with small amplitudes of the field density. A powerful ultrashort pulse (hereafter, a dangerous pulse (DP)), which can penetrate into the RE and disable it due to its wide spectrum and high power, is particularly dangerous [3, 4]. Traditional protection means (for example, voltage suppressors, varistors, passive RC and LC filters) often cannot provide adequate protection because of their disadvantages [5, 6]. Thus, it is necessary to find new ways of effective protection.

There are various devices based on strip lines utilized for protecting against DPs and filtering the signal [7–12]. To protect against DPs, modal filters (MF) [13], that are based on the modal splitting technology [14]. The proposed MFs are devoid of the indicated disadvantages and have a number of advantages (absence of semiconductor components, long operating life, operation at high voltages and low cost). Another approach is DP splitting into a sequence of lower amplitude pulses in a meander microstrip line (MMSL) [15, 16]. For this, the conditions have been formulated to ensure such splitting. The fulfillment of these conditions allowed attenuation of the DP (relative to half the e.m.f.) in the MMSL of one cascade by 2.42 times and in the MMSL of two cascade-connected turns - 5.2 times. Thus, the more cascades in the MMSL, the greater the DP attenuation. However, an increase in the number of cascades increases the number and complexity of conditions, and it is necessary to splitting formulate the conditions for the DP splitting. This considerably complicates the synthesis of multi-cascade protection devices. Therefore, the aim of this paper is to formulate universal conditions for the DP splitting in the MMSL for an arbitrary number of cascades.
2. Conditions for the DP splitting in an MMSL of 1 and 2 cascades

The signal at the end of the MMSL of 1 turn consists of 3 pulses (pulses of crosstalk at the near end of the line, odd (OM) and even modes (EM)). There will be no superposition of these pulses, if the following conditions are satisfied [15]

\[2l_1 \tau_o \geq \tau_c,\]
\[2l_2 \geq 2l_0 + \tau_c\]  

where \(\tau_o\) and \(\tau_c\) are the per-unit-length delays (PULD) of the OM and EM, \(l\) is the half-turn length, \(\tau_c\) is the total DP duration. When conditions (1) and (2) are fulfilled in the MMSL of one turn, the DP can be split into three main pulses.

In the MMSL of 2 turns connected in cascade, the DP is split into nine pulses. First, the DP is split into three pulses in the first turn, and then each of the pulses is split into three pulses in the second turn. For such splitting, it is necessary to fulfill the conditions [16]:

\[2l_1 \tau_o \geq \tau_c,\]
\[2l_2 \tau_o \geq 2l_0 + \tau_c,\]
\[2l_1 \tau_o \geq 2l_2 \tau_o + \tau_c,\]
\[2l_1 \tau_o \geq 2l_1 \tau_o + 2l_2 \tau_o + \tau_c\]

where \(\tau_{o1,2}\) and \(\tau_{o1,3}\) are the PULD of the EM and OM of the first and second turns, respectively, and \(l_1\) and \(l_2\) are the lengths of their half turns. Further, the indices 1, 2, ..., \(N\) of the variables \(\tau_o,\tau_0\) and \(l\) will mean the number of the turn which they correspond to.

3. Conditions for the DP splitting in an MMSL of three cascades

In the case of three turns, the DP can be split into twenty-seven pulses of lower amplitude. For this, in the line of two turns, it is necessary that the delay of each of the main pulses (except the first) be greater than the delay of the previous pulse summed up with the DP duration.

First, we determine the delays of each of the twenty seven main splitting pulses similarly to [16]:

\(t_{p1}=0\) ns, \(t_{p2}=2l_1 \tau_o, t_{p3}=2l_1 \tau_o, t_{p4}=2l_1 \tau_o, t_{p5}=2l_2 \tau_o + 2l_1 \tau_o, t_{p6}=2l_2 \tau_o + 2l_1 \tau_o, t_{p7}=2l_2 \tau_o, t_{p8}=2l_2 \tau_o + 2l_1 \tau_o, t_{p9}=2l_2 \tau_o + 2l_1 \tau_o, t_{p10}=2l_1 \tau_o, t_{p11}=2l_1 \tau_o + 2l_2 \tau_o, t_{p12}=2l_1 \tau_o + 2l_2 \tau_o, t_{p13}=2l_1 \tau_o + 2l_2 \tau_o, t_{p14}=2l_1 \tau_o + 2l_2 \tau_o, t_{p15}=2l_1 \tau_o + 2l_2 \tau_o, t_{p16}=2l_1 \tau_o + 2l_2 \tau_o, t_{p17}=2l_1 \tau_o + 2l_2 \tau_o, t_{p18}=2l_1 \tau_o + 2l_2 \tau_o, t_{p19}=2l_1 \tau_o + 2l_2 \tau_o, t_{p20}=2l_1 \tau_o + 2l_2 \tau_o, t_{p21}=2l_1 \tau_o + 2l_2 \tau_o, t_{p22}=2l_1 \tau_o + 2l_2 \tau_o, t_{p23}=2l_1 \tau_o + 2l_2 \tau_o, t_{p24}=2l_1 \tau_o + 2l_2 \tau_o, t_{p25}=2l_1 \tau_o + 2l_2 \tau_o, t_{p26}=2l_1 \tau_o + 2l_2 \tau_o, t_{p27}=2l_1 \tau_o + 2l_2 \tau_o.

Knowing how to determine the delays of each of the twenty seven main pulses, we will formulate the conditions for the complete DP splitting in a MMSL of three turns, based on a detailed analysis in [16]:

\[2l_1 \tau_o \geq \tau_c,\]
\[2l_2 \tau_o \geq 2l_1 \tau_o + \tau_c,\]
\[2l_2 \tau_o \geq 2l_2 \tau_o + \tau_c,\]
\[2l_2 \tau_o \geq 2l_2 \tau_o + 2l_3 \tau_o + \tau_c,\]
\[2l_2 \tau_o \geq 2l_2 \tau_o + 2l_3 \tau_o + \tau_c,\]
\[2l_2 \tau_o \geq 2l_2 \tau_o + 2l_3 \tau_o + 2l_4 \tau_o + \tau_c,\]
\[2l_2 \tau_o \geq 2l_2 \tau_o + 2l_3 \tau_o + 2l_4 \tau_o + \tau_c.\]

Let us check conditions (7)–(12) based on a quasi-static simulation performed in the TALGAT software [17]. The 1, 2 and 3 turns have similar cross-sections (figure 1a). The equivalent circuit of a 3-turn MMSL is shown in figure 1b. \(R1\) is taken to be equal to the geometric mean of the EM and OM.
impedances of the first turn, and the $R2$ – of the third turn. As an excitation, we selected a trapezoid pulse with 1 V e.m.f. and the duration of the flat top equal to 100 ps, and the rise and fall times - 50 ps.

To fulfill conditions (7)–(12), the geometric parameters of the turns were optimized by a heuristic search. The following optimal values of the parameters of turns 1, 2 and 3 were obtained: $w_1=100 \, \mu m$, $t_1=160 \, \mu m$, $s_1=20 \, \mu m$, $h_1=200 \, \mu m$, $e_1=480$, $l_1=100 \, mm$; $w_2=400 \, \mu m$, $t_2=600 \, \mu m$, $s_2=20.3 \, \mu m$, $h_2=200 \, \mu m$, $e_2=120$, $l_2=60 \, mm$; $w_3=w_2$, $t_3=t_2$, $s_3=s_2$, $h_3=h_2$, $e_3=e_2$, $l_3=15 \, mm$.

![Cross-section of one cascade of the line (a) and equivalent circuit of three turns (b).](image)

Figure 1. Cross-section of one cascade of the line (a) and equivalent circuit of three turns (b).

Simulation was carried out in the TALGAT software [9]. Calculated PULD of the EM and OM of each turns: $\tau_o=47.88 \, ns/m$, $\tau_c=\tau_0=27.88 \, ns/m$, $\tau_0=23.94 \, ns/m$, $\tau_0=\tau_0=9.29 \, ns/m$. When substituting PULD of the turn modes into $f_{p1}$, $f_{p2}$, ..., $f_{p27}$ we obtain: $f_{p1}=0 \, ns$, $f_{p2}=0.27 \, ns$, $f_{p3}=0.83 \, ns$, $f_{p4}=1.12 \, ns$, $f_{p5}=1.39 \, ns$, $f_{p6}=1.95 \, ns$, $f_{p7}=3.35 \, ns$, $f_{p8}=3.62 \, ns$, $f_{p9}=4.18 \, ns$, $f_{p10}=4.79 \, ns$, $f_{p11}=5.07 \, ns$, $f_{p12}=5.62 \, ns$, $f_{p13}=5.9 \, ns$, $f_{p14}=6.18 \, ns$, $f_{p15}=6.74 \, ns$, $f_{p16}=8.13 \, ns$, $f_{p17}=8.41 \, ns$, $f_{p18}=8.97 \, ns$, $f_{p19}=9.58 \, ns$, $f_{p20}=9.85 \, ns$, $f_{p21}=10.41 \, ns$, $f_{p22}=10.69 \, ns$, $f_{p23}=10.97 \, ns$, $f_{p24}=11.53 \, ns$, $f_{p25}=12.92 \, ns$, $f_{p26}=13.2 \, ns$, $f_{p27}=13.76 \, ns$. We also note that when the known variables are substituted into conditions (7)–(12), they are satisfied. The calculated waveform at the end of the MMSL of 3 turns with optimal parameters is shown in figure 2.

![Signal waveform at the end of the MMSL of three turns.](image)

Figure 2. Signal waveform at the end of the MMSL of three turns.

The figure shows that the DP is represented by twenty-seven main pulses. Signal amplitude does not exceed 0.062 V. Also, the end of the line contains pulses caused by reflections from the connections between the half-turns and the ends of the line. As a result, the DP attenuation in the MMSL of 3 turns was 8.1 times (relative to $E/2$).

4. Conditions for the DP splitting in an MMSL of any number of cascades

We note that the conditions for one, two and three turns of the MMSL have a number of similarities: in (1), (3) and (7) the OM delay in the last turn of the device must be no less than the DP total duration; in (2), (4) and (8) the EM delay of the last turn must be no less than the sum of the OM delay of the same turn and the DP total duration; in (5) and (9) the OM delay of the penultimate turn must be no less than the sum of the EM delay of the last turn and the DP total duration; in (6) and (10) the EM delay of the penultimate turn must not be less than the sum of the delays of the OM of the penultimate turn, the EM...
of the last turn and the DP total duration; in (11) the OM delay of the first turn must be no less than the sum of the EM delays of all subsequent turns and the DP total duration; in (12) the EM delay of the first turn must be no less than the sum of the delays of the OM of the first turn, the EM of all subsequent turns and the DP total duration. Thus, conditions (1), (3), (7), (5), (9), (11) limit OM delays and conditions (2), (4), (8), (6), (10), (12) - EM.

Finally, for a complete DP splitting in an MMSL of an arbitrary number of cascades, the OM delay of each turn must be no less than the sum of the EM delays of all subsequent turns and the DP total duration, and the EM delay of each turn must be no less than the sum of the delays of the OM of each turn, EM of all subsequent turns and the total duration of the input pulse. Based on the abovementioned, we formulate the conditions for the DP splitting in the MMSL of an arbitrary number of cascades:

\[ 2l_n \tau_{on} \geq \sum_{i=n+1}^{N} 2l_i \tau_{en} + t_{\Sigma}, \quad n = 1...N \]  \hspace{1cm} (13)

\[ 2l_n \tau_{om} \geq 2l_n \tau_{em} + \sum_{i=n+1}^{N} 2l_i \tau_{en} + t_{\Sigma}, \quad n = 1...N \]  \hspace{1cm} (14)

where \( N \) is the number of the line turns. Thus, when sequentially substituting \( n \) with the number of cascades from 1 to \( N \), we obtain the conditions for the DP splitting in a MMSL consisting of \( N \) cascades. We note that for \( N=2 \) and algebraic transformations (13) and (14), we obtained expressions (3)–(6), and for \( N=3 \) – (7)–(12).

5 Approbation of the obtained conditions on the example of a line of four and five turns

We now check conditions (13)–(14) using the example of the quasi-static simulation of the MMSL of four and five turns, the lengths of which are summarized in table 1. \( R1 \) is taken to be equal to the geometric mean of the EM and OM impedances of the first turn, and the \( R2 \) – of the last turn.

| Table 1. The length (mm) of each turn of the MMSL of 4 and 5 turns. |
|------------------|------------------|------------------|------------------|------------------|------------------|------------------|
|                  | MMSL of four turns |                  | MMSL of five turns |                  |                  |                  |
| \( l_1 \)        | 728               | \( l_2 \)        | 320               | \( l_3 \)        | 152               | \( l_4 \)        | 50               |
| \( l_5 \)        | 2450              | \( l_6 \)        | 1080              | \( l_7 \)        | 510               | \( l_8 \)        | 140              |
| \( l_{9} \)     | 728               | \( l_{10} \)     | 320               | \( l_{11} \)     | 152               | \( l_{12} \)     | 50               |

The cross-sections of the turns of the lines are the same as in figure 1a. Their parameters were obtained by a heuristic search according to the criterion of the fulfillment of conditions (13)–(14). The optimal values of parameters for the MMSL of four cascades were: \( w_1=100 \, \mu m, \, w_2=w_3=w_4=400 \, \mu m, \, t_1=160 \, \mu m, \, t_2-t_4=600 \, \mu m, \, s_1=s_2=80 \, \mu m, \, h_1=h_2=h_3=h_4=200 \, \mu m, \, e_1=800, \, e_2=440, \, e_3=110, \, e_4=50. \) The optimal values of parameters for the MSL of five cascades were: \( w_1=100 \, \mu m, \, w_2=w_3=w_4=w_5=400 \, \mu m, \, t_1=160 \, \mu m, \, t_2-t_4-t_5=600 \, \mu m, \, s_1=s_2=s_3=s_4=s_5=20 \, \mu m, \, h_1=h_2=h_3=h_4=h_5=200 \, \mu m, \, e_1=800, \, e_2=440, \, e_3=110, \, e_4=e_5=50. \) The PULD of the even and OM of the MMSL of four turns were: \( \tau_{sd}=61.77 \, ns/m, \, \tau_{s}=53.24 \, ns/m, \, \tau_{d}=26.69 \, ns/m, \, \tau_{d}=24.97 \, ns/m, \, \tau_{sd}=30.89 \, ns/m, \, \tau_{sd}=16.91 \, ns/m, \, \tau_{sd}=8.91 \, ns/m, \, \tau_{sd}=7.27 \, ns/m. \) The signal waveforms at the end of the MMSL of 4 and 5 turns are shown in figure 3.
Figure 3. Signal waveforms at the end of the MMSL of four (a) and five (b) turns.

The DP voltage at the end of the line of four turns does not exceed 0.025 V, and of five turns – 0.015 V. Also, at the end of the lines there are many pulses caused by reflections from the ends of the lines and connections between half-turns. As a result, the maximum DP attenuation (relative to $E/2$) at the end of the MMSL of four turns was 19.9 times, and five – 33.16 times.

6. Conclusion
The research presents universal conditions which allow the complete splitting of a dangerous pulse (DP) in a MMSL of any number of cascades. The verification of the conditions was performed on the example of the MMSL of two, three, four and five cascades. Attenuation (times) of a DP in the MMSL of three turns was 8.1, of four turns – 19.9 and of five turns – 33.16. Note that the values of the parameters of the MMSL cross-sections were obtained by a heuristic search according to the criterion for fulfilling the formulated conditions without taking into account the real geometric parameters. Therefore, in practical implementation of such devices, it is necessary to take into account the real parameters. Since the structures under investigation are linear this can be achieved through scaling and optimization with genetic algorithms.

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