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Energy distribution on surge arrester elements selected by genetic algorithm in railway systems

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***Abstract* – Communication lines play very important role in railway industry. They enable to exchange data between signalling devices such as wheel detectors, evaluators, signals etc. All of them make it possible to manage rail traffic in a safe and efficient way. Availability which depends on robustness of the communication lines is one of the most important features of the system during its use. In this paper the verification of a surge protection module is presented at two stages, i.e. when the voltage has reached the threshold for a gas discharge tube (GDT) and when it is too low. These two cases have different characteristics and create new challenges during the design process.**

Keywords – railway, genetic algorithm, Matlab, protection module.

I. INTRODUCTION

Electromagnetic compatibility is very important in the railway environment as it has an impact on passenger safety and the availability of railway lines for train passages. It is required to deliver products with high EMC immunity and compact sizes.

Due to such constraints it is necessary to design a protection module and perform modelling [1] especially for digital interfaces, using a modern methodology [2] (e.g. a genetic algorithm) to improve the robustness, because they are inherently vulnerable.

In standard operating conditions the communication lines work at low voltage and low power. This can be observed in wayside equipment (e.g. wheel detectors), where CAN transmission is used to transfer data about the number of axles that have passed over the counting point, which is then used by the evaluator to report that a section is unoccupied. A *Free* state of the section means that the same number of wheels have entered and left the section. It allows the next vehicle to enter the section.

CAN communication line architecture is valuable because it allows you to minimize the length of wires used to create a network (bus topology). It contributes to the reduction of system installation and maintenance costs. It however also has some cons as a long network line is exposed to huge interferences present in the railway environment, like e.g. current of the value amounting to a few kA, high voltages up to 25kV and electromagnetic field connected with the above. These aspects pose new challenges that need to be faced by engineers in order to design a module that will be immune to disturbances of such kind.

II. RELATED RESULTS IN THE LITERATURE

Surge immunity is widely described in the related literature [3–5], but mostly in the form of analysis of power lines which are much more robust than communication interfaces. Some of the papers present analysis of communication lines [6] but they focus on the results of testing, not on the analysis of the margins, which provide much more information about the circuit.

Many artificial algorithms could be used to find the most efficient solution to the issue presented, but due to specific constraints only one of them was selected, for example since the domain of the problem is finite, the evolutionary algorithms were rejected because they operated based on continuous infinite sets. Use of simulated annealing is optimal only for one suboptimal solution, where's in the case of the issue concerned many of the suboptimal solutions could result in the similar goal function value, so SA was omitted. Ant colony optimalisation was rejected, because it easily fell into the trap of reaching the local optimum. Therefore, the genetic algorithm is probably the most flexible and universal way to find suboptimized solution for the described circuit.

As a result of the development of science and technology [7] it is possible to evaluate protection modules with the use of a genetic algorithm. It could be used in different ways to optimize the design of circuits. In paper [8] GA is used to optimize component location and routing. Paper [9] describes decreasing peak voltage in an autonomous navigation system to improve device immunity to interferences thereby significantly increasing the safety of passengers. Moreover, there is an example of using GA for the purpose of thermal analysis in paper [10] which improves the environmental immunity of the module.

It is possible to find articles presenting the need for performing device operation simulation before testing [11] in the relevant literature. A schematic diagram and an advance analysis of GA in terms of designing a protection module in railway industry is presented in [12], but some improvements are possible. The question is what will happen when the disturbance does not reach sparkover voltage, i.e. the GDT will not be involved in power dissipation. The implementation of GA for the purpose of performing such analysis is presented below.

III. DESCRIPTION OF THE METHOD

To implement the GA a Matlab environment was used with LT Spice to perform simulation of the circuit under analysis. Surge immunity test [13] was chosen as the test case. It is often used to certify and examine devices in industrial environments. The test amplitude could certainly be increased if necessary due to client’s or local market requirements.

Two steps of analysis will be investigated, when input voltage is:

1) below the sparkover voltage, maximum power dissipation in respect of transils and resistors.
2) higher than the sparkover voltage, GDT is involved in testing.

A simplified algorithm flow is shown in Figure 1.

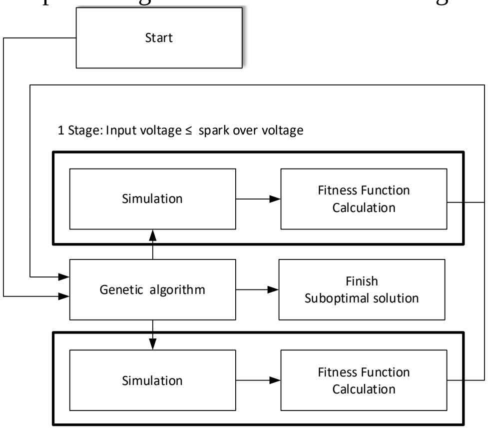

Figure 1. A simplified algorithm flow.

The goal of the fitness function is to select a suboptimal specification of the protection module with preselected components and avoid critical overload parameters (voltages, currents and power defined by a manufacturer for a specific component). It is done by rating the solution provided by the GA. Detailed information, i.e. the configuration of the GA’ and stopping criteria, parameters description, algorithm flow etc. are presented in [12].

But due to research some improvements were done:

- Update of parameters of GDT model in LT Spice;
- Change from a single resistor R9 and R10 to a group of resistors connected in series, the number of resistors is chosen by algorithm.

Schematic diagram of the circuit under analysis is shown in Figure 2.

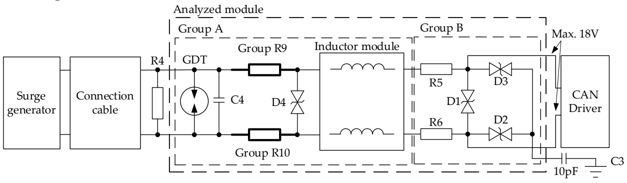

Figure 2. Updated schematic diagram of the protection module.

The unit consists of: a surge generator, a connection cable, terminator resistor (R4) and the analyzed module. The module has been divided into two groups:

- Group A components that could be replaced (connection module with cable), critical parameters may achieve 110% of the nominal value
- Group B components that are integrated with the wayside device, and damage to one of the components from the group will result in the fault of the device, critical parameters may achieve 50% of the nominal value

Critical parameters of each of the components were examined based on the datasheets. In case of Group B CAN drivers some limitations were translated to the component limitations e.g. a maximum voltage at the CAN driver’s input of 18V was set as D1’s maximum voltage.

The input vector (gene) structure is presented in Table 1.

Table 1. Input vector structure.

Component	Input vector bits
Group R9 Group R10	1:4
R5 & R6	5:7
D4	8:12
D1	13:17
D2&D3	18:22
C4	23:25
Number of resistors in Group R9 and R10	26:27

The input vector was expanded by adding a number of resistors in Group R9 and R10 due to the inability to meet test requirements by a single resistor.

The following settings for GA were used:

- Selection option: “selectionstochunif”, i.e. parents are chosen randomly with uniform distribution
- Reproduction: “EliteCount” 5% of the best parents from the population size
- Crossover was set to: “crossoverscattered”, which uses a random binary vector to combine two individuals, to form a child for the next generations multi point mutations
- Mutation options is set to: “mutationgaussian”, which uses Gaussian distribution to make a small

change to the parent vector.

IV. RESULTS AND DISCUSSION

Based on the above described algorithm, the implementation was made in Matlab environment in the PC. The goal of fitness function is to find a suboptimal specification of a protection module with preselected components and avoid critical overload parameters (voltages, currents and power defined by a manufacturer for a specific component). Therefore, the fitness function evaluates the solution provided by GA [12] and takes the voltages, currents and power dissipation on an element (M_k^i) into account, compares the obtained values to maximum conditions (maximum stress in terms of voltage/current/power $\widehat{M}_k^i$). The denominator has a valuation parameter (β_k^i) in order to limit any damage to the most critical elements. Parameter α is penalty factor, it is introduced if a single parameter exceeds its maximum value ($\widehat{M}_k^i$). Working beyond the range of this value $\widehat{M}_k^i$ caused damage to the component and the test failed. This formula was modified by adding the segment responsible for selecting the number of resistors to groups R9 & R10.

Fitness function was defined as:

$$fitness = \left(\sum_{k=1}^{N_e} \sum_{i=1}^{N_p} \frac{M_k^i}{\beta_k^i \cdot \widehat{M}_k^i} \cdot \alpha + (l-1) \cdot \gamma \right),$$

M_k^i- it is a calculated value of i-th parameter for component k e.g. power peak for R9;

$\widehat{M}_k^i$- it is a maximum value of i-th parameter for component k, e.g. voltage, power or current defined in the manufacturer's documentation without margin;

β_k^i – it is a valuation parameter in respect of components in Group A - Figure 2) - it can be replaced with the maximum ratio factor (110% of maximum value [4]). In the case of the other one (Group B), it was defined as 50% ([4]) of the value declared by the manufacturer. This factor represents the valuation parameter of a component damage [4];

N_p – it is a number of analyzed parameters per a single component, e.g. for R9 N_p = 3, namely average power, peak power and voltage. i = 1, …, N_p, where i is the following index of the simulated parameter;

N_e – it is a number of analyzed components $N_e = 9$ in the diagram presented (Figure 2), Indicator k = 1, 2, … 9;

α – it is a penalty factor which can have values 1 or 26, i.e.: if $M_k^i \leq \widehat{M}_k^i$ then $\alpha = 1$, otherwise $\alpha = 26$. The penalty factor (α) was set to 26, so if the value of a parameter is above the limitation multiplied by a ratio factor, the goal function will have the value of 26 instead of the ratio of the calculated value to the limit to avoid a situation when one component is overloaded but there are no limitations for the others;

l – it is a number of resistors in groups R9 & R10, it must be adapted due to the manufacturer's overload parameters;

γ – it is a punishment factor for increasing the number of resistors in groups R9 & R10, it was implemented to minimize the number of components.

The calculation was finished after 24 hours and 30 minutes, 1441 iterations were simulated and verified. Time needed per one simulation amounted to c.a. 55 seconds, but it was not constant. Trends in genes changing for 6kV test case are presented in Figure 3. It could be observed that during finding the optimal solution, the algorithm selected the group of genes and tuned it.

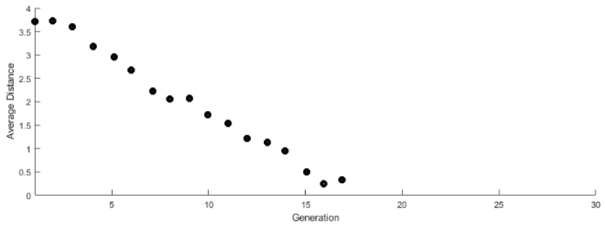

Figure 3. Average distance between genes.

The output specifications of different values of surge amplitude 2kV (Table 2), 4kV (Table 3) and 6kV (Table 4) are presented below. Power parameters were selected as critical for analysis.

Table 2. Output specification for surge amplitude 2kV.

Comp.	Spec.	Max Vol [V]	Max curr. [A]	Power Avg. [W]	Power Peak [W]
C4	1nF	674.2	6.1	1.3	1031.2
GDT	SG75	674.2	439.8	326.2	14722.2
GR9	8.2R	299.8	36.6	201.2	10960.6
GR10	8.2R	299.7	36.5	201.2	10953.5
D4	SMDJ51CA	74.7	36.2	66.5	2703.3
R5	1R	6.1	6.1	4.2	37.8
R6	1R	6.1	6.1	4.2	37.8
D1	SMDJ6.0CA	7.1	6.1	7.2	43.8
D2	SMDJ6.0CA	6.6	0.0	0.0	0.0
D3	SMDJ6.0CA	6.8	0.0	0.0	0.3
Number of resistors in Group R9 and R10:					2

An interesting thing could be observed during this simulation, as higher part of energy is absorbed by resistors from Group R9 & R10 plus D4: 468.9W (sum of power average), than GDT 326.2W. It means the GDT is less active during the exposure than it could be expected. Maximum peak power 10.9kW is on the margin set to 2 resistors in the group (max value 11kW). Input of CAN driver is well protected (max voltage on D1 amounts to less than 15V) and there is no risk of damage.

Table 3. Output specification for surge amplitude 4kV.

Comp.	Spec.	Max Vol [V]	Max curr. [A]	Power Avg. [W]	Power Peak [W]
C4	1nF	691.2	7.6	1.9	1235.9
GDT	SG75	691.2	887.7	827.5	21801.9
GR9	7.5R	301.1	40.2	97.6	12091.7
GR10	7.5R	300.9	40.1	97.6	12073.1
D4	SMDJ58CA	89.1	39.9	39.1	3555.8
R5	1R	5.2	5.2	2.4	27.2
R6	1R	5.2	5.2	2.4	27.2
D1	SMDJ6.0CA	7.1	5.2	5.3	37.0
D2	SMDJ6.0CA	6.7	0.0	0.0	0.2
D3	SMDJ6.0CA	6.8	0.1	0.0	0.4
Number of resistors in Group R9 and R10					2

At this stage, similar specification of components was selected by the algorithm. It could be observed that the algorithm stabilizes maximum peak power for resistors from group R9 and R10. In this case, maximum peak power is overloaded, but probably that has a smaller impact than the increase in the number of resistors. The GDT power absorption (average) is higher that in 2kV test: GDT 827.5W vs. 234.2W (sum of D4, resistor group R9 and R10). Other parts of protection module (R5, R6 and D1) are less vulnerable than in the case of 2kV amplitude. Also in this case, components from Group B are well protected.

Table 4. Output specification for surge amplitude 6kV.

Comp.	Spec.	Max Vol [V]	Max curr. [A]	Power Avg. [W]	Power Peak [W]
C4	1n	709.1	10.2	2.2	1477.0
GDT	SG75	709.1	1334.7	1250.5	26081.8
GR9	9.1R	311.5	34.2	130.1	10659.5
GR10	9.1R	311.9	34.3	130.1	10687.4
D4	SMDJ58CA	85.8	34.1	46.0	2926.1
R5	1R	6.2	6.2	3.7	38.6
R6	1R	6.2	6.2	3.7	38.6
D1	SMDJ6.0CA	7.1	6.2	6.5	44.3
D2	SMDJ5.0CA	6.8	0.1	0.0	0.4
D3	SMDJ5.0CA	6.9	0.1	0.0	0.6
Number of resistors in Group R9 and R10:					1

In this case, the GDT absorbs significantly more energy than the other components (Table 4), i.e. 1250W vs. 306W (GR9, GR10 and D4). In this specific scenario, we have a situation that the higher amplitude of the input surge is less demanding, because the GDT is involved in power dissipation much earlier.

Table 5.Surge 6kV specification analysis for input amplitude 650V.

Comp.	Spec.	Max Vol [V]	Max curr. [A]	Power Avg. [W]	Power Peak [W]
C4	1n	505.5	0.6	0.5	43.1
GDT	SG75	505.5	0.0	0.0	0.0
GR9	9.1R	213.5	23.5	262.9	5006.9
GR10	9.1R	213.4	23.5	262.9	5004.6
D4	SMDJ58CA	78.7	21.6	78.1	1699.0
R5	1R	7.2	7.2	5.9	52.2
R6	1R	7.2	7.2	5.9	52.2
D1	SMDJ6.0CA	7.2	7.2	8.5	51.7
D2	SMDJ5.0CA	4.3	0.0	0.0	0.0
D3	SMDJ5.0CA	5.7	0.0	0.0	0.1

Based on the data presented in Table 5 it could be observed, that with lower surge input amplitude, higher power could be dissipated on the other components in Group B (GR9, GR10 and D4), than with almost 10 times higher amplitude, i.e.: 604W (Table 5 – 650V) vs. 306W (Table 4 – 6kV). It certainly depends on the sparkover voltage of the GDT, so it is a critical parameter. It must be pointed out that not only the amplitude has to be considered in this case, but also the rising time. Detailed information can be found in the dedicated GDT's data sheet.

V. CONCLUSIONS AND OUTLOOK

The article presents a new philosophy of designing protection modules in the railway industry. However, nothing prevents the implementation of the discussed approach in other areas of the economy, because it is very flexible and could be easy adopted to different critical parameters (e.g. temperature, price etc.).

It will certainly not guarantee the indestructibility of the device, but it will significantly increase the probability of correct operation and increase its availability which is also very important.

It should be pointed out that while designing surge arrester systems the test conditions must be specified according the characteristic of individual components. Not only one worst case scenario may lead to an optimal solution.

Furthermore, a specification can be adapted to the conditions on site, because in real environment the disturbances might not reflect the standard ones. The algorithm is only an optimization tool, but it is the engineer that always has the final word.

VI. ACKNOWLEDGMENTS

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