Automated Selection of Solutions for Protection of On-board System from External Electromagnetic Disturbances

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***Abstract*—Selection of solutions for protection of on-board system from electromagnetic disturbances is considered as an optimization problem. The solution to the problem is found in the form of a set of linear protection elements, for example, shields, gaskets, and filters. The objective function of the optimization problem is the cost of a set of utilized protection elements. The following algorithms were used to solve the optimization problem: "Exhaustive search" algorithm, genetic algorithm, and the algorithm based on "Coordinate descent" method. We considered two variants of defining the descent direction applied in the algorithm based on "Coordinate descent" method: 1) by the random selection; 2) by the use of the values of "Protection Efficiency-To-Cost" coefficient. This coefficient is determined by the protection element cost and partial protection index of the element. To choose the most suitable algorithm for solving the problem, the comparative analysis of the results obtained using all the considered algorithms was performed. The results of the comparison demonstrate that the use of the algorithm based on "Coordinate descent" method with "Protection Efficiency-To-Cost" coefficient make it possible to find an appropriate solution and reduce the computational burden as compared to the other considered algorithms.**

Keywords—automation, genetic algorithm, optimization, protection, software algorithms

I. INTRODUCTION

The impact of the external electromagnetic disturbances (EED) must be taken into account under the design and during the solving the EMC problem of on-board radio and electronic systems [1]. The energy of EED penetrates inside the system via various influence paths, which leads to malfunctions in operation of equipment and damaging of the whole system.

Decrease of EED impact on the on-board radio and electronic systems is ensured by using protection elements (PE), for example, filters, wire meshes, cable shields, etc. The measure to decrease EED impact caused by insertion of a protective element into the system is called partial protection index of the element. The system is protected when all values of parameters of the system response to EED are less than the threshold values specified by the manufacturer or established empirically. However, achievement of required protection level by using more expensive PE or increase in PE number leads to increased cost of the designed system, which is not permissible in most cases. At the same time, overprotection must be excluded. Apart from the cost of PE, the technical features of PE are considered. For example, when designing an aircraft, the weight of the product is the critical parameter and PE with the minimum weight should be chosen as an acceptable one.

Therefore, the choice of an optimum set of PE (SPE) which ensures the required protection level of the system and has the minimum cost, is a topical problem.

Automated selection of SPE has the following advantages: high speed of the search, the large number of considered combinations, which ensures required protection level of the system and has an acceptable (the minimum or almost the minimum) cost. Most of these combinations are not obvious from the designer's point of view.

The objective of this work is the justification of a choice of the algorithm for automated selection of solutions to protect an on-board system against external electromagnetic disturbances. The justification is performed by the comparative analysis of the "Exhaustive search" algorithm, genetic algorithm, and the algorithm based on "Coordinate descent" method (in two approaches).

The article is organized as follows. The selection of solutions for protection of on-board system from external electromagnetic disturbances is formulated as an optimization problem in Section II. Section III presents a brief description of the algorithms, which were used in solving the given optimization problem. The numerical experiment and the results of the comparative analysis applied to implementation of each algorithm are described in Section IV. Section V states the main conclusions.

II. FORMULATION OF THE OPTIMIZATION PROBLEM

Let us consider system *Sys*, that includes n positions for Protection Element (PPE) e_i, $i = 1,\ldots,n$. PPEs are the objects belonging to the system for which PEs are implemented or those replaceable with the identical ones having improved features. For example, a non-shielded cable can be replaced by a shielded one and an open aperture can be closed by a wire mesh. There are m_i variants of PE for every position e_i. The number of chosen PE is designated by x_i for e_i ($0 \le x_i \le m_i$). For example, if $m_1 = 5$, it means six possible variants of protection solutions at position e_1. Designation

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$x_1 = 0$ corresponds to the case, when PEs are not applied at position e_1. Designation $x_1 = 3$ corresponds to applying of PE No.3 at position e_1. Designation $x_2 = 2$ corresponds to applying of PE No.2 at position e_2 and so forth.

Port is introduced for describing the equipment susceptibility, which is defined as the threshold values of corresponding quantities. For protection of a port, PE must change the parameters of response to EED in a required manner. PE is capable of performing its function if operating frequency band thereof corresponds (at least partially) to the frequency band in which the response parameters must be changed. Also, using PE must not lead to unallowable reduction of useful signal level in operating frequency band of the port.

PEs must correspond to additional technical requirements regarding, for example, weight, overall dimensions, etc. PEs which satisfy these requirements are defined as acceptable ones. Only acceptable PEs are considered as possible variants for a given position *i*. PEs realized as one product (filter, mesh, film etc.) are considered as elementary ones. It is possible to apply two or more identical elementary PEs at the same position. The result of multiple identical implementation of PE at one position corresponds to a new variant of PE at this position. Therefore, the maximum value of m_i is limited by the technological requirements.

Notation $\vec{x}$ corresponds to the vector that characterizes applying of x_i variant of PE in all possible positions:

$$\vec{x} = (x_1, x_2, ..., x_n) \tag{1}$$

Zero vector $\vec{o} = (0, 0, \ldots, 0)$ defines the initial configuration of the system including all influence paths without PEs.

Thus, every set of protection elements (SPE) is uniquely defined by a corresponding vector $\vec{x}$, and neither vector can correspond to two different SPEs.

Let us consider power $P_q(\Delta f_k, \vec{x})$ received by port R_q in frequency range Δf_k in the case of continuous wave disturbance:

$$P_q(\Delta f_k, \vec{x}) = \sum_{z=1}^{N_Z} \left[S(f_k) \cdot \Delta f_k \cdot \prod_{j=1}^{N_{ZO}} T_{qzj}(f_k, \vec{x}) \right], \tag{2}$$

where:

$S(f_k)$ is the power spectral density, which is formed by the emitter at frequency f_k (f_k is the central frequency for *k*-th frequency range Δf_k);

$T_{qzj}(f_k, \vec{x})$ is the value of the transfer function at the *k*-th frequency sample of the *j*-th object in influence path *z,* when applying SPE defined by vector $\vec{x}$;

N_Z is the number of influence paths associated with port R_q;

N_{ZO} is the number of transferring objects in the influence paths *z*.

The expression for integrated interference margin $IIM_q(\vec{x})$ takes the following form [2]:

$$IIM_q(\vec{x}) = \sum_{k=1}^{N_f} \frac{P_q(\Delta f_k, \vec{x})}{\eta_q(f_k)}, \tag{3}$$

where:

$\eta_q(f_k)$ is the susceptibility level (by power) at the *k*-th frequency sample of port R_q;

N_f is the number of frequency samples, which is specified for port R_q.

Let us define protection index $g_q(\vec{x})$ for port R_q through the following expression:

$$g_q(\vec{x}) = IIM_q(\vec{o}) - IIM_q(\vec{x}), \tag{4}$$

where:

$IIM_q(\vec{x})$ is the integrated interference margin, which is calculated for port R_q with the use of PEs defined by vector $\vec{x}$.

$IIM_q(\vec{o})$ is the integrated interference margin, which is calculated for port R_q without insertion of any PE into the system.

System *Sys* is protected, when protection index $g_q(\vec{x})$ began exceeding a specified value of b_q for every reception port R_q of the system, $q = 1, \ldots Nr$ (*Nr* is the number of reception ports belonging to system *Sys*):

$$\begin{aligned} g_1(\vec{x}) &\geq b_1, \\ \vdots \quad &\quad \vdots \\ g_{Nr}(\vec{x}) &\geq b_{Nr} \end{aligned} \tag{5}$$

The cost of SPE $f_C(\vec{x})$ is calculated by the following expression:

$$f_C(\vec{x}) = \sum_{i=1}^{n} c_i(x_i), \tag{6}$$

where $c_i(x_i)$ is the cost of the x_i-th variant of PE at position e_i.

Particular interest to SPEs with the minimum cost is the reason to formulate the final problem in the following way:

$$\text{Minimize } f_C(\vec{x}) = \sum_{i=1}^{n} c_i(x_i), \tag{7}$$

$$g_q(\vec{x}) \geq b_q \ \ (q = 1, \ldots, Nr), \tag{8}$$

where x_i can be represented only by integers from range $[0; m_i]$, $i = 1, \ldots, n$.

The results obtained in [3] demonstrate that problem (7) with condition (5) or equivalent condition (8) is reduced to the nonlinear integer-programming problem (NIP) since functions $g_q(\vec{x})$ defined by expression (4) are nonlinear, as determined by (2) and (3). The considered problem belongs to the class of optimization problems of non-linear programming [4].

III. ALGORITHMS FOR SELECTION OF A SET OF PROTECTION ELEMENTS

The following algorithms are implemented to solve the above optimization problem:

1. Exhaustive search algorithm. This is a type of algorithm which guarantees that each acceptable solution will be obtained because the value of objective function $f(\vec{x})$ is considered for every possible vector $\vec{x}$ [5].

2. Genetic algorithm [3]. The main idea of this algorithm is in applying of the mechanisms, similar to those of biological evolution, for solving the optimization problems. The initial data of the algorithm are a set P of Np vectors $\{\vec{x}_p\} = \{\vec{x}_1, \vec{x}_2, ..., \vec{x}_{Np}\}$. The basic procedures of genetic algorithms are "Selection" and "Recombine" which are realized by procedures "Crossover" and "Mutation". The essence of procedure "Crossover" is in forming of a new vector $\vec{x}'_p$ based on a combination of two existing vectors. Procedure "Mutation" randomly changes the values of coordinates of vector $\vec{x}$. Procedure "Selection" consists in choosing $\vec{x}_p$ from the set for which the objective function takes the most optimal values when SPE $\vec{x}_p$ is applied [3]. The algorithm is to be performed in the following order:

1) Calculate the value of the cost-function for each vector in space P;

2) Apply procedure "Selection" to the vectors in space P; the result of this operation is denoted as P';

3) Apply procedures "Crossover" and "Mutation" to P';

4) If the condition (the obtained cost-function value is minimal) is false, then assume $P = P'$ and go to item 1.

3. The algorithm based on "Coordinate descent" method. In "Coordinate descent" algorithm, solving the optimization problem is carried out by iterations. The optimization is performed by the variation of a variable (chosen coordinate of vector $\vec{x}$) or a set of variables (a subset of coordinates of vector $\vec{x}$) at each iteration [6]. This procedure corresponds to motion along the axis (for the case of one variable) or on the hyper-plane (for a subset of coordinates) in the n-dimensional space with the axes corresponding to the variables.

Modified algorithm realization presented in this article assumes solving the optimization problem formulated in Section II by motion in the n-dimensional space of cost of PE denoted as C. In this space, the value of a coordinate assigned number i of the vector in the n-dimensional space is equal to the cost of PE applied to the i-th position. SPE in space C corresponds to the point with coordinates $D = (c_1(x_1), c_1(x_1), c_2(x_2), \ldots, c_n(x_n))$, where $c_i(x_i)$ denotes the cost of x_i variant of PE applied to position i. The origin of space C corresponds to SPE Z, which is the initial configuration of the system (the system does not include any PE). Let us define two types of points in space C. A-type point corresponds to SPE which ensures protection of the system, and B-type point corresponds to SPE which does not. Space of cost C for $n = 2$ is illustrated in Fig. 1.

The space of cost can include isolated points. These are A-type points surrounded by B-type points. Illustration of the space of cost in the presence of isolated points is given in Fig. 2.

Proposed algorithm consists of two stages: the ascent stage and the descent one. The ascent stage is implemented to find a solution corresponding to the isolated points (with a certain probability) and the decent stage eliminates the solutions leading to overprotection which can be obtained at the first stage.

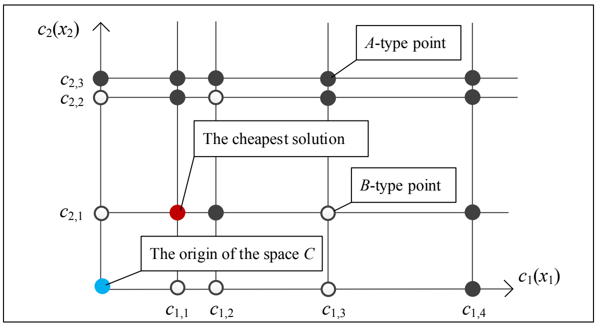

Fig. 1. Illustration of space of cost C for $n = 2$

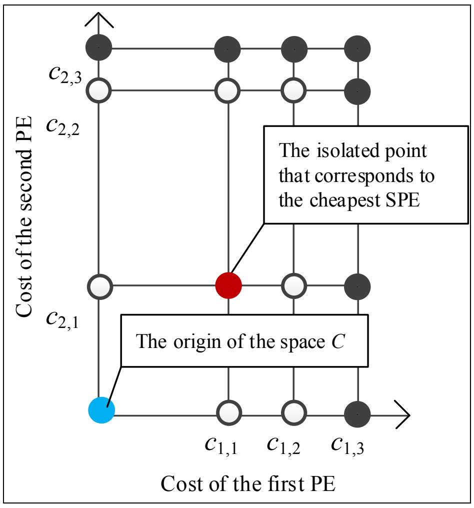

Fig. 2. Illustration of the presence of isolated points

The upper boundary of the search region in the space of cost is limited by the maximum cost of acceptable PEs for each axis. It is assumed that a set of acceptable PEs had been prepared for each position (corresponding algorithm is not considered therein) prior to performing the algorithm. The algorithm under consideration is as follows.

1. The initial point for the ascent stage is non-protected case Z that corresponds to the origin of C.
2. Check conditions (8) for this point.
    2.1. When (8) is true, point Z is the solution and the algorithm is stopped.
3. The ascent stage
    3.1. Define the current point as D
    3.2. Select axis L_i, (i=1...n) to move along
        3.2.1. The axes, for which the upper boundary is achieved, are excluded from possible direction of motion.
        3.2.2. If the upper boundary is achieved for all of the axes, then the algorithm is stopped. In this case, a solution ensuring the required protection level of the system has not been obtained.
    3.3. Shift to neighboring point D' in direction of axis L_i, i.e., towards cost increasing.
    3.4. Calculate protection level $g_q(\vec{x})$ for each port and analyze condition (8) at point D'.
        3.4.1. If the result is true (i.e., point D' is A-type), then go to item 4.
        3.4.2. Otherwise, go to item 3.1.
4. The descent stage
    4.1. Define the current point as D.

4.2. Select axis L_i, (i=1,...,n) to define the direction of motion. The motion will be against the axis, i.e. towards cost decreasing.
  4.2.1. The axes, for which the lower boundary is achieved ($c_i(x_i)$ = 0), are excluded from possible direction of motion.
  4.2.2. If the axes along which the motion is possible are absent, then the algorithm is stopped. The obtained result is SPE that corresponds to point *D*.

4.3. Shift to neighboring point *D'* in direction of cost decreasing, i.e., towards axis L_i.

4.4. Calculate protection level $g_q(\bar{x})$ for each port and analyze condition (8) at point *D'*.
  4.4.1. If the result is false, (i.e. point *D'* is *B*-type), then
    4.4.1.1. Exclude axis L_i from possible direction of motion.
    4.4.1.2. Return to point *D*.
  4.4.2. Otherwise, go to step 4.1.

Two approaches are used to choose the axis L_i which defines direction of motion in item 3.2 of the developed algorithm.

The first approach is based on the random choice of an axis to move along. The second (modified) approach of the algorithm implementation is based on introduction of the coefficient called “Protection efficiency-to-Cost” (PETC) C_Q. For the analysis based on the energy impact, one can define total protection deficiency $Is(\bar{x})$ of the system as follows:

$$Is(\bar{x}) = \sum_{q=1}^{Nr} \max(b_q - g_q(\bar{x});0) \tag{9}$$

where:

$g_q(\bar{x})$ is the protection level for port R_q;

b_q is the minimal required protection level for port R_q;

Nr is the number of reception ports belonging to the system.

PETC coefficient C_Q is introduced for x_i variant of PE for position *i* by the formula:

$$C_Q(\bar{x},x_i') = \frac{\Delta Is(\bar{x},x_i')}{c(x_i)} \tag{10}$$

where:

$\Delta Is(\bar{x},x_i') = Is(\bar{x}|_{x_i=0}) - Is(\bar{x}|_{x_i=x_i'})$ is the difference between the total protection deficiency obtained without PE at position *i* and with x'_i variant of PE at this position;

$c_i(x_i)$ is the cost of x_i variant of PE for the position *i*.

The more $C_Q(x_i)$, the more appropriate implementation of PE in form of x_i at position *i*.

At the ascent stage, for choosing the axis to move along, the values of coefficients $C_Q(x_i)$ are calculated for all possible one-step shifts in cost increasing direction from the current point. Then, the one-step shift is performed in direction of the axis corresponding to the maximum value of PETC coefficient.

No matter which approach was used at the ascent stage, at the descent stage the axis to move along is selected randomly.

Let us consider the example to demonstrate the selection of SPE corresponding to isolated points in *C*-space under the two approaches. Formulation of the problem is as follows. Protection index $g_1(\bar{x})$ of port R_1 of system Sys_2 is less than 14 dB relative to the required margin. This insufficient protection level is caused by the CW radiation at a frequency of 1 kHz, which leads to interference at port R_1. The influence paths associated with the port have two positions for implementation of PE, i.e., the dimension of the corresponding space of cost is 2. The overall dimensions of PE installed at each position are limited by the threshold value of 10×10×10 cm. Only acceptable types of PEs are given in Table I. Note that combinations ($2\cdot V_1$, 0), (V_1+V_2, 0), (0, $2\cdot V_1$) and so forth are excluded from acceptable SPEs as a result of exceeding the threshold dimensions. It is worth to mentioned that the parameters of PEs in Table I are simplified to clarify the example. PE is assumed to operate only in the frequency band given in Table I, and in case of series connection of PEs the dimensions are summed.

TABLE I. PE VARIANTS FOR SYSTEM Sys_2

PE Variants	**Cost, EUR**	**PE operating frequency band, kHz**	**Dimensions, cm**	**Attenuation, dB**
V_1	5	[0.5; 2]	7×7×7	8
V_2	10	[0.5; 10]	5×5×5	5
V_3	22	[0.5; 10]	9×9×9	17

Therefore, the points belonging to the first axis of *C*-space have coordinates (V_1,0), (V_2,0), ($2V_2$,0), (V_3,0) etc., and the points on the second axis are (0, V_1), (0, V_2), (0, $2V_2$), (0, V_3).

The algorithm based on coordinate decent method with the random selection of the shift direction can obtain SPE (V_1, V_1) with the minimum cost at the ascent stage with a probability of 0.5. The overall probability of SPE (V_1, V_1) is also 0.5, because point (V_1, V_1) is isolated and it can be not obtained at the decent stage. The algorithm based on the value of coefficient $C_Q(x_i)$ selects SPE (V_1, V_1) with a probability of 1.

In case of more complex systems, the second approach (by using “Protection efficiency-to-cost” coefficient $C_Q(x_i)$) of the algorithm based on coordinate decent method is not suitable enough because some isolated points can be missed. However, the accuracy of this approach can be regulated by a number of points, which are considered before the direction of motion is selected. In the example considered this number is 1 for each axis, and the motion along each of them is performed independently of the others. Increasing the number of analyzed points leads to increased probability to find SPEs corresponding to isolated points. However, the computational burden increases either and tends to that of the exhaustive search algorithm when all solutions are to be considered.

IV. COMPARATIVE ANALYSIS OF THE ALGORITHMS

A set of systems consisting of different number of objects, PPEs and PE variants were considered to establish the features of the “Exhaustive search” algorithm, genetic algorithm and the algorithm based on “Coordinate decent” method (in the two approaches) when applied to the problem of selecting the cheapest SPE to ensure protection of the system against EED.

A typical model of a vehicle with on-board radio and electronic systems is presented herein. External view and schematic diagram of the system are shown in Figures 3 and 4, respectively. Radio and electronic equipment in the vehicle is mounted into two compartments. The first compartment is the driver’s cab and the second one is the car body containing most of the equipment. The compartments are shielded from each other by a solid metal wall (steel 1010), and the penetration of EM energy between the compartments is negligibly small.

The following PPEs are introduced (they are marked by colored circles in Figure 4). PPEs No. 1 and No. 2 correspond to implementation of shields (in the form of a wire mesh) closing the apertures in the first and the second compartment, respectively. PPEs No. 3–18 are intended to decrease the impact of wire-to-wire coupling by replacing the cables being the information links in the on-board system. Two types of cables are considered: the unshielded twisted pair and the shielded one. PPEs No. 19–26 are intended to mount the filters on the power supply ports. The “PE types” parameter was defined for each PPE. This parameter determines the correspondence between PPE and types of PE that can be applied to it. For example, if PPE is an aperture, it is possible to add a wire mesh but not a filter. The following influence paths are considered:

1) external EM field – internal field (a field inside the compartment) P – wire W cabled in compartment P – equipment port R which wire W is connected to;

2) external EM field – internal field inside compartment P – wire W_A cabled in compartment P – wire W_B cabled together with wire W_A in the same segment –equipment port R which the wire W_B is connected to;

3) external EM field – external wire W_{ext} cabled in the outdoor segment – equipment port R which wire W_{ext} is connected to;

4) external EM field — external wire W_{ext} – wire W_B, cabled together with wire W_{ext} in the same segment – equipment port R which wire W_B is connected to;

For example, the wire to connect ports “Power supply” and “220V-connector” is laid in the outdoor segment of a bundle and the other wires are laid inside the compartments only in the considered vehicle model.

The calculation of EED impact on the system without PE was performed and insufficient protection level was established for power-supply ports and signal ports of “Commander PC”, “Tactical data router”, “Commander VoIP”; signal ports of “VSAT”, “WAN connector”; power-supply ports of “Power supply”, “Driver VoIP”, “Gunner VoIP”.

EMC-Analyzer software [7] was used to define the interference for each port belonging to the system without PE. Thereafter, SPEs were selected using the algorithms described in Section III. The below results of analyzing this example characterize precisely the main features (advantages and drawbacks) of all the considered algorithms.

“Exhaustive search” algorithm. The number of SPEs analyzed by the algorithm is 33,554,432. At the same time, the number of acceptable SPEs ensuring protection of the system is 8,704. There is a single variant with the minimum cost. The cheapest SPE costs 640.00 EUR. This SPE was found by 61,502nd iteration of the algorithm. The cost of the most expensive SPE is 1,049.95 EUR. The number of acceptable SPEs whose cost differs from the cheapest SPE for no more than 1% (no more than 646.40 EUR) is 59.

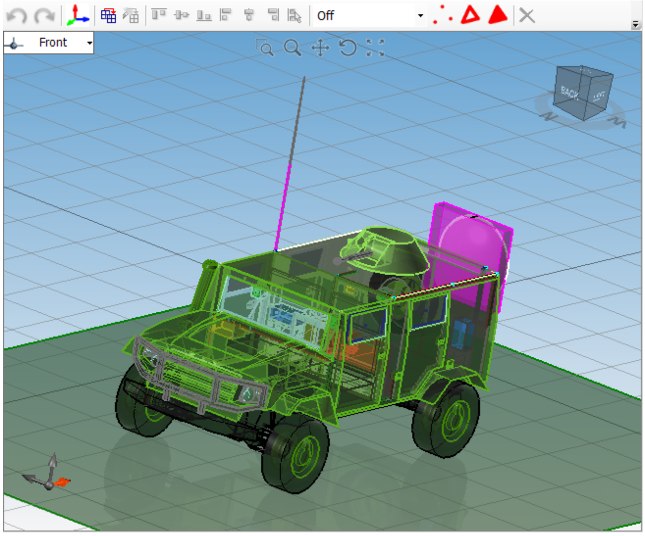

Fig. 3. External view of the on-board system under test

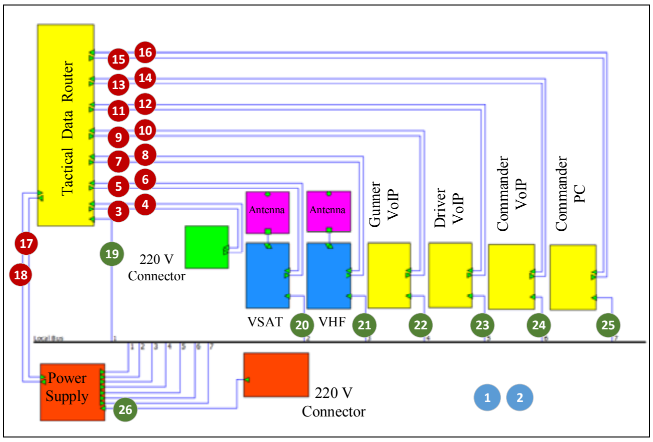

Fig. 4. Structure of the analyzed on-board system (PPE are marked by circles)

Genetic algorithm. For testing this algorithm, the following values of parameters are applied: the size of population Np is 20; the probabilities for performing procedures “Crossover” and “Mutation” are 0.6 and 0.2, respectively; the number of generations is 100. If the initial set of vectors $\{\vec{x}_p\} = \{\vec{x}_1, \vec{x}_2, ..., \vec{x}_{Np}\}$ had been generated randomly, acceptable SPEs ensuring the required protection level were not found by the algorithm, though the number of analyzed SPEs was 6,274. Thereafter, the initial vector was constructed as SPE ensuring the required protection of the system, and the algorithm found the solution with the minimum cost of 640.00 EUR at 384th iteration. The overall number of analyzed variants of SPE is 6,285 in this case.

The algorithm based on “Coordinate descent” method with random selection of shift direction. In this case, the results of algorithm implementations are sufficiently different from one another. In more than 75% of cases the algorithm found the acceptable SPE ensuring the required protection level and having the cost of 914.56 EUR. In addition, an acceptable variant of SPE with the minimum cost of 640.00 EUR was obtained approximately in the quarter of cases. The number of iterations of the algorithm is no more than 60 for all the implementations. Note that the cost of an acceptable SPE after the ascent stage is performed was above 1,040.00 EUR in all of the cases. Therefore, the implementation of the descent stage allows the decrease in the cost of SPE by at least 10%.

The algorithm based on "Coordinate descent" method with the selection of shift direction according to PETC coefficient value. The overall number of analyzed SPEs was 388. The cost of SPE obtained after the ascent stage was 652.95 EUR. This stage was performed in 365 iterations. After the decent stage, SPE ensuring the required protection and having the cost of 640.00 EUR is obtained. It is worth mentioning, that the last three iterations of the algorithm were unnecessary because they found SPEs which do not ensure protection of the system.

As it follows from the numerical experiment result, the algorithm based on "Coordinate descent" method with random selection of shift direction shows the minimum number of iterations (less than 60). However, in more than 75% of the cases, this algorithm enables to obtain the solution with excessive cost, and the implementation of this algorithm is useful only for those cases when the time for calculation must be minimized and no strict requirements are imposed on the cost of obtained SPE. The exhaustive search algorithm enables to obtain all acceptable solutions, but if the number of PE (and, respectively, SPE) under analysis is large, this algorithm is only suitable with sufficient computational power or without hard time limitations. The genetic algorithm can be applied successfully when the solution must be refined. The algorithm based on "Coordinate descent" method with the selection of shift direction by using PETC coefficient enables to obtain SPE ensuring the required protection level and having the minimum cost by consideration of 388 variants (this number is relatively small in comparison with the number of analyzed variants in other approaches). Therefore, this algorithm proved to be the most reliable for the selection of SPE in practice.

V. CONCLUSION

Selection of solutions to protect on-board system from external electromagnetic disturbances is considered herein as an optimization problem of non-linear programming. To solve the problem, the efficiency of implementation is considered for the following algorithms: the "Exhaustive search" algorithm, genetic algorithm, and the algorithm based on "Coordinate descent" method. The numerical experiment has established that the algorithm based on coordinate descent method with the selection of shift direction using the value of PETC coefficient is suitable for practical problems related to the selection of the cheapest set of protection elements ensuring protection of complex on-board systems against external EM disturbances.

The advantages of automated selection are high speed, the possibility to obtain a wide range of acceptable SPE with a low cost (not always minimum, but close to it) ensuring the required level of system protection. The developed approach allows taking into account some technical features of protection elements and sets of protection elements, which is important when addressing practical problems with the large number of protection variants.

The future development of the automated selection of solutions to protect on-board system from external electromagnetic disturbances will imply the analysis of applicability of differerent algorithms which have not been considered herein (for example, the branch and bound algorithm, as well as other possible generalizations of the exhaustive search) and use the combined approaches which allow realization of the advantages of each algorithm and elimination of their drawbacks.

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