EMC Diagnostics of Complex Ship Radioelectronic Systems by the Use of Analytical and Numerical Worst-Case Models for Spurious EM Couplings

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***Abstract*—The technique for EMC computer diagnostics of ship radio equipment is presented. This technique is based on preliminary detection and identification of all potentially dangerous on-board electromagnetic spurious couplings between antennas with the use of the broadband analytical worst-case model developed within the framework of IEMCAP program, and further corrected EMC diagnostics with the use of the adjusted worst-case models for the elements of potentially dangerous interference propagation paths identified before (adjusted numerical models of frequency characteristics of spurious couplings, numerical or analytical models of emission spectra and susceptibility characteristics of the equipment), and discrete nonlinear EMC analysis with the use of high-order front-end nonlinearity models and frequency selectivity models of radio receivers (these models are obtained on the basis of the results of double-frequency testing of the receivers). High computational efficiency are the main advantages of the technique; that is demonstrated by the example of EMC diagnostics of ship on-board system containing a set of HF, VHF, UHF and SHF radio equipment operating in severe external electromagnetic environment.**

Keywords—EMC diagnostics, on-board system, worst-case models, electromagnetic coupling, intermodulation

I. Introduction

Electromagnetic compatibility (EMC) largely determines operability and overall performance of radio and electrical different-purpose equipment that constitutes complex on-board radioelectronic systems (OBRES). Computer analysis of intra-system and inter-system EMC is a critical part of designing and ensuring normal operation of OBRES, which allows early detection and elimination of potentially dangerous spurious electromagnetic (EM) couplings among the elements of these systems, as well as early detection and elimination of undesired impact of external sources of EM fields (EMF) on these elements. Development of the techniques and software for EMC analysis and diagnostics of OBRES enables to automate not only identification of potentially dangerous EM couplings among system elements but also selection of appropriate protection solutions to verify efficiency of the elements, which significantly decreases or completely excludes losses caused by limited operation of OBRES in severe electromagnetic environment (EME) resulted from the impact of intra-system and inter-system interferences of various origins.

Implementation of EMC computer diagnostics of OBRES usually requires multi-variant analysis of danger of EM couplings among OBRES different-purpose equipment and different types of cable lines (power, signal radiofrequency, etc.), i.e., analysis of different location variants and operation modes of radioelectronic and electrical OBRES equipment with different variants for implementation of protective solutions, different external EME, etc. For example, the analysis of different variants of antennas location on a ship hull is designed to ensure selection of a variant with the smallest spurious EM couplings among the antennas placed close to a high-conductivity surface. In practice, it is required to analyze tens or even hundreds of variants of OBRES implementation and operation, so decrease in timetable of EMC analysis for each variant is becoming particularly relevant.

When detecting and identifying spurious EM couplings among OBRES elements, as well as linear and nonlinear interferences to operation of OBRES radio receivers (RR), it is reasonable to focus on worst-case EMC estimations that tolerate errors of the first kind ("false alarm") though excluding errors of the second kind ("erroneous undetection"). The cost of errors of the second kind is much higher because they have to be eliminated at subsequent stages of OBRES life cycle, or put up with a limitation of OBRES performance due to the presence of interference in actual operating conditions.

The most complicated problems of EMC computer diagnostics of OBRES are as follows:

a) absence of complete and reliable information on characteristics of OBRES equipment (e.g., information on radiation spectra of radio transmitters (RT) and susceptibility characteristics of RR in a wide frequency range; design features of antennas and feeder circuits; shielding characteristics of cables and equipment cases and so forth both at the design stage and when changing OBRES operational conditions;

b) numerous spurious EM couplings to be analyzed (10^2–10^4 and more), external EM impacts (10^2–10^4 and more), as well as variants of OBRES implementation and application (10^1–10^2 and more) including related high complexity, cost and computational burden.

An effective technique to overcome these problems is the use of analytical worst-case models describing spurious EM couplings among OBRES elements developed within the framework of IEMCAP program [1-3], as well as application of system EMC energy criteria and procedures of discrete analysis of transfer characteristics of these elements at a limited set of samples in the frequency domain. This

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technique allows implementation of primary worst-case analysis of interferences taking into account all possible spurious couplings among OBRES elements and danger of external EMFs impact at an acceptable computational burden. Such analysis makes it possible to detect potentially dangerous spurious EM couplings (whose number is significantly less than overall number of EM couplings) to be analyzed in detail with the use of refined models or empirically. Effectiveness of such technique of EMC diagnostics has been repeatedly proved in practice [4-6]. In addition, significant complication of OBRES, expansion of functionality and enhancement of effective frequency band, as well as complication of external EME leads to the need for development and improvement of existing techniques of intra-system and inter-system EMC analysis and development of new techniques related to analysis of nonlinear interferences to the reception.

Effectiveness of the technique [1-6] of OBRES EMC analysis can be significantly increased by using the following methods and approaches:

a) technology of discrete nonlinear analysis (DNA) of EMC intended for simulation of RR behaviour in severe EME taking into account nonlinear effects (intermodulation, blocking, crosstalks, etc.) [7];

b) technology of double-frequency testing (DFT) intended for testing radio receivers to obtain required information on their susceptibility, selectivity and input nonlinearity, as well as for testing input radio components of radio receivers (radiofrequency amplifiers, mixers, etc.) to obtain information on their nonlinearity and selectivity [8];

c) technology of synthesis of adequate mathematical models of RR and radio components based on the testing results using the DFT method [9-11];

d) method of construction and refinement of worst-case models describing transfer characteristics of different, potentially dangerous spurious EM couplings based on the use of analytical and (or) numerical methods in the absence of complete and error-free input data [11-13].

Application of these technologies in combination with CAD models of analyzed OBRES and modification of procedures of frequency discretization of usable models of spectra and frequency responses of interference propagation paths allowed significant increase in computational efficiency of EMC computer analysis, which has been practically proved by the approbation results [14-16], as well as development of efficient software for expertise and technical diagnostics of OBRES EMC [17, 18].

The purpose of this paper is to present developed and practically approbated technique of EMC computer diagnostics of ship OBRES radio equipment in severe external EME on the basis of IEMCAP ideology using specialized methods and approaches (proposed by the authors) that assure higher computational efficiency.

II. Technique of Discrete EMC Analysis of Ship Radio Equipment with the Use of Worst-Case Models of Spurious EM Couplings

A. *Basic algorithm of EMC analysis of ship OBRES*

The technology of multi-variant discrete linear and nonlinear EMC analysis of ship OBRES in severe EME with the help of worst-case models includes the following main stages:

1) Development of OBRES 3D geometric model with variants to place sources and receptors of EM interferences (RT and RR antennas) and determination of all OBRES characteristics that influence EM couplings among them (geometry and hull material, characteristics of antenna placement including the type, dimensions and matching conditions).

2) Development of worst-case models of spurious EM couplings for different variants of OBRES implementation including

a) worst-case models of spurious EM couplings among antennas, cables, equipment cases and so forth in accordance with [1-3];

b) models of antenna patterns (AP) to analyze external EME impact;

c) models of main and spurious emission spectra for each RT in a wide frequency range (the right boundary ten times exceeds the maximum working frequency);

d) models of frequency selectivity characteristics of each RR via the main, adjacent and spurious reception channels in the frequency range ten times exceeding the peak adjustment frequency of RR;

e) models of frequency selectivity of input/output filters of RT and RR (preselectors, combiners, etc.).

3) Development of external EME model (in the form of an ensemble of external EMFs with predefined energy characteristics, frequency spectra, direction of incidence parameters and polarization) on the basis of data on placement and operation of external RT (ground-based, RT of OBRES of other ships, aircrafts, etc.), as well as on the basis of radiomonitoring data.

4) Implementation of discrete linear analysis (DLA) of EMC with the use of worst-case models [1-3] of EM couplings and taking into account external EME for each variant to mount OBRES antennas. The results of this analysis serve the basis for determination of potentially dangerous spurious EM couplings that can cause high-power input disturbances and radio interferences in each RR within OBRES.

5) After determination of potentially dangerous spurious EM couplings in OBRES that can cause interferences to the reception, these couplings are analyzed using the numerical methods (FDTD, MoM, FEM, MAB). For antenna-to-antenna EM couplings in particular, this analysis is performed in the following order:

a) models of amplitude-frequency characteristic (AFC) of S-matrix elements which characterize spurious couplings among the antennas in predefined frequency ranges and at different values of antennas parameters are refined;

b) worst-case envelope of AFC of antenna-to-antenna couplings is constructed;

c) models of AP taking into account antennas' design features, orientation to the elements of ship hull structure and underlying surface taking into account conductivity thereof are refined using computational electrodynamics methods for more detailed analysis of external EME impact;

d) discrete models of RT radiation spectra are refined;

e) models of RR susceptibility characteristics are refined;

f) discrete linear EMC analysis for each variant of antennas location in OBRES using refined models of potentially dangerous EM couplings and refined RR susceptibility characteristics, which refines the danger of detected spurious EM couplings and the levels of generated interferences at different adjustment frequencies of OBRES RR with quantitative estimation of Integrated Interference Margin (IIM) for each RR being the interference receptor.

For antennas with the couplings therebetween defined as potentially dangerous, variations of the parameters for determination of these couplings are carried out [14]; simulation is performed in the frequency range which potentially dangerous EM couplings are determined for.

6) Selection of one or several of the most promising (with no interferences via the main reception channels and the least possible levels of out-of-band input disturbances) variants of OBRES implementation for further detailed analysis. Regarding the selected variants of antennas location on ship hull:

a) a set of measures to eliminate linear interferences among RR and RT within OBRES is worked out and discrete linear EMC analysis of OBRES is performed taking into account implementation of these measures (if necessary);

b) potential danger for each RR to be damaged by nonlinear radio interferences (exceeding by total interference level at the inputs of each OBRES RR of their susceptibility levels to intermodulation as the least value of susceptibility to certain kinds of nonlinear radio interferences) is estimated.

It should be noted that the number of situations with unacceptably high levels of out-of-band input disturbances that are dangerous in terms of nonlinear radio interferences is decreased significantly due to implementation of linear interferences protection solutions.

7) Implementation of discrete nonlinear EMC analysis for the situations remaining potentially dangerous in terms of nonlinear interferences by methodology [7] including

a) determination of nonlinearity and selectivity characteristics of RR through the antenna input taking into account features of structure, components and conversion of frequencies in RR (the best result can be achieved based on the results of testing RR by the DFT method [9, 10] allowing detection, identification and measurement of the parameters of all real linear and nonlinear paths of RR damage by interferences through the antenna input, as well as rather accurate measurement of RR input nonlinearity);

b) synthesis of structural and functional model of each RR including determination of the parameters of worst-case polynomial models of RR input nonlinearity suitable for analysis on behavior in that EME; instantaneous values of voltage of total signal at the input of each RR must not exceed the upper boundary of the range where the polynomial model of its input nonlinearity is determined;

c) implementation of discrete nonlinear analysis of RR behavior in EME formed as a sum of signals of OBRES RT and those of external EME and determination of the situations in which DNA results validate the danger for RR to be damaged by nonlinear radio interferences for all potentially dangerous situations of the considered variant of OBRES implementation.

Such analysis is carried out for each variant of antennas location in OBRES recognized as the most promising one by the results of refining models of potentially dangerous spurious EM couplings and those of susceptibility characteristics of RR, with identification of situations in which the danger of RR damage by nonlinear radio interferences is revealed by the results of analysis.

8) Determination of technical and organizational measures (not related to change of relative arrangement of antennas) to eliminate nonlinear radio interferences in OBRES.

9) In the course of EMC diagnostics of OBRES, it is essential to take into account and analyze other kinds of spurious EM couplings (antenna-to-cable, cable-to-cable, antenna-to-equipment case, external EM field-to-cable, etc.) along with RT antenna-to-RR antenna ones; to this end, procedures 1-7 are carried out as part of EMC analysis based on these couplings.

B. *Construction of OBRES 3D geometric model*

Ship OBRES is designed using modern computer-aided design (CAD) systems such as Pro/Engineer, CATIA, SolidWorks, etc. Computer 3D geometric models of OBRES constructed thereby with radio equipment, power supply and control systems, and connecting lines (radio frequency, data transmission, power supply, etc.) arranged therein are used for intra-system and inter-system EMC analysis. Examples of the use of such 3D models for EMC computer diagnostics are given in [14, 16]. Fig. 1 demonstrates 3D model of analyzed ship OBRES and Fig. 2 shows a fragment of this model with antennas of various services – maritime mobile service, maritime mobile-satellite service, port operations service, ship movement service, maritime radionavigation service, etc.

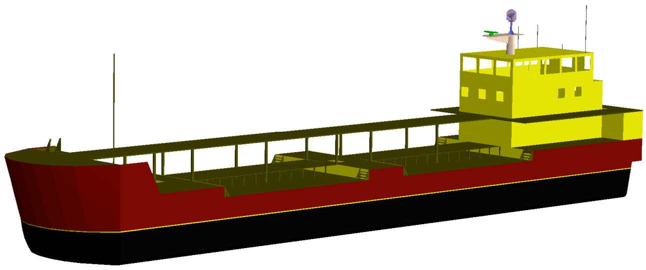

Fig. 1. 3D model of the diagnosed ship (a sea-river tanker for coastal shipping)

The final stage of designing this OBRES determined the need for in-depth diagnostics of intra-system EMC thereof and estimation of danger of RR damage by interferences in HF range.

On the basis of assumed operational conditions of this OBRES, analysis of its EMC was performed for the following conditions:

a) OBRES operation far from other radio interference sources (EME at the input of each RR is formed predominantly by radio emission of OBRES RT);

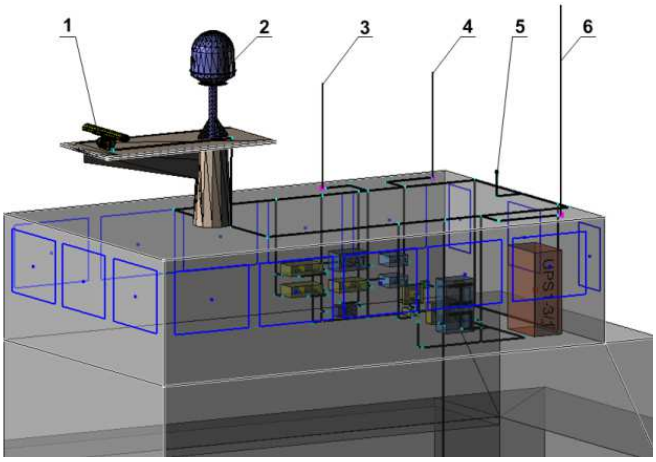

Fig. 2. A fragment of 3D model of the ship with antennas of radio systems of different radio services

b) OBRES operation in a coastal zone with high area density and activity of radio systems of different services in HF, VHF and UHF ranges (EME at the input of each RR is generated by both radio emission of OBRES RT and a set of external RT).

C. Detailed analysis of potentially dangerous antenna-to-antenna couplings

Detailed analysis of antenna-to-antenna coupling is performed in accordance with technique developed in [14], [16], which is based on the consideration of the set of S-parameters AFC obtained by the numerical simulation of the coupling between antennas when parameters of antennas and their location are varied. The result of this procedure is the worst-case envelope of AFC of S-parameters for each antenna:

$$H_{WC\ ik}(f) = Env_{WC}\{H_{1ik}(f), H_{2ik}(f), ..., H_{Nik}(f)\}, \quad (1)$$

where f is the frequency, $H_{1ik}(f)$ is AFC of S-parameter S_{ik} obtained for the coupling between antennas with the numbers i and k for the first fixed set of antenna parameters, $H_{2ik}(f)$ is AFC of S_{ik} obtained for the second set of antenna parameters, etc. Env_{WC} denotes the procedure of the worst-case envelope plotting described in [14].

Variant of antenna allocation on the ship hull is presented in Fig. 2. The problem under analysis is spurious couplings between antennas of radio systems of maritime mobile service: between HF antenna No. 6 and two VHF antennas No. 3 and No. 4.

In accordance with technique presented in [14], initially it is necessary to define the reference value of antennas parameters and placement locations based on information presented in corresponding technical specifications.

Fig. 3 shows the results of the numerical calculation of antenna coupling performed by FDTD method. The red solid line corresponds to the worst-case envelope of the results of simulation obtained by the variation of parameters of the problem. All antennas are considered as monopoles. The following parameters are varied: conductivity of underlying surface, antenna length, position of antenna No. 6 mounting. Black solid line corresponds to the initial (reference) set of parameters and the antenna placements presented in Fig. 2, black dotted line and black dashed line – to the maximum and minimum values of varied parameters respectively.

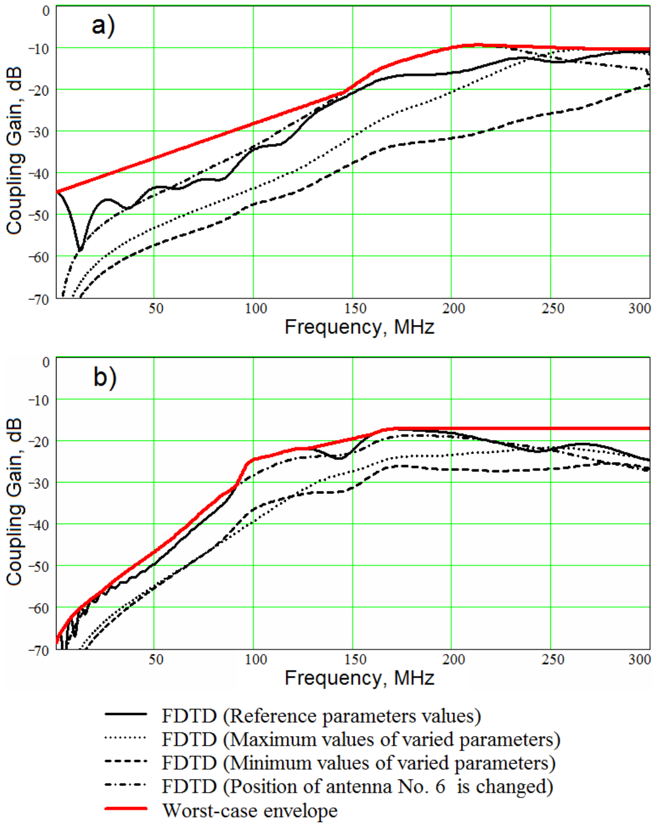

Fig. 3. AFC of spurious couplings between antennas No. 6 and No. 4 (a) and between antennas No. 6 and No. 3 (b)

Analytical model based on IEMCAP provides values of coupling near to 0 as the result of big length of antenna No. 6 (l_6 = 6 m). EMC analysis of OBRES performed with the use of refined numerical worst-case models (see Fig. 3) allows to establish the absence of mutual interferences between radio-equipment connected to antennas No. 3, No. 4 and No. 6. But the future analysis of danger of nonlinear interferences to radio receiving at HF range is necessary due to high level of expected external EMF irradiating the system.

D. Analysis of nonlinear interferences and identification of the sources

Danger of nonlinear radio interferences to occur in HF range stems from specificity of static characteristics of EME in this range. As a result of the analysis and interpretation [19, 20] of statistical data [21], the following expression for the distribution probability function of dynamic range D of signals at the input of RR operating in HF range can be obtained:

$$P(D) = \exp\left(-ND^{-1/4}\right), \quad D = \Pi_{max}/\Pi_0, \quad (2)$$

where Π_{max} is the level of the prevailing signal at the input of RR, Π_0 is the susceptibility threshold of RR, N is the number of signals at the input of RR beyond the threshold level Π_0. Acceptable quality of EMC assurance is reached at a low probability of non-exceeding the dynamic range of RR by intermodulation D_{IM} through the dynamic range of the input signals:

$$P(D_{IM}) = \exp\left(-ND_{IM}^{-1/4}\right) \le 0.1 . \qquad (3)$$

We can clearly see that at $N = 10$, $P(D_{IM}) = 0.1$ the 80 dB dynamic range of RR by intermodulation is required, which is stretched to the limit of physical feasibility (it does not exceed 75-80 dB in the most advanced narrowband radio receivers operating in HF range) and requires protection of RR input by front-end band-pass frequency selectivity.

Discrete nonlinear EMC analysis of OBRES taking into account presence of both OBRES RT signals and external EME signals is implemented in the following sequence:

1) Worst-case models of the spectra of transmitters' radiation and those of susceptibility of the receivers are defined.

2) Refined worst-case models describing spurious EM couplings between OBRES antennas are defined.

3) Analysis of expected EME at the input of each OBRES RR in a wide frequency range is performed using data on radio monitoring and area density of RT operating in different frequency ranges is performed.

4) Analysis of expected EME at the input of each RR is performed and further testing of each RR by the DFT method is carried out with the identification of potentially dangerous situations for RR to be damaged by nonlinear interferences and the construction of worst-case polynomial models of RR input nonlinearity in the corresponding dynamic range of input disturbances. Fig. 4 illustrates the view of 3D double-frequency characteristic (DFC) of RR of on-board HF radio station when being adjusted to a frequency of 12.579 MHz (maritime safety transmission channel) obtained by the DFT method. Fig. 5 illustrates double-frequency diagram (DFD) of this RR, i.e., the section of DFC by the level of –95 dBm and by the levels of test signals of –22 dBm.

5) Polynomial model of the front-end nonlinearity (Table 1) is synthesized on the basis of the measured receiver's spurious-free dynamic range (IDR) for 3rd order intermodulation (70.2 dB) with the use of intermediate theoretical model [9].

TABLE I. COEFFICIENTS OF THE SYNTHESIZED POLYNOMIAL MODEL OF THE RECEIVER FRONT-END NONLINEARITY

Degree	Calculated IDR, dB	Polynomial coefficient
1	0.00	+3.980276791421916e+001
2	126.55	–2.086610385495390e–014
3	**70.2**[1)]	–2.036852703970892e+003
4	126.80	–1.653526285558095e–012
5	88.98	+5.836746744537299e+004
6	127.23	–1.091942062286514e–011
7	96.48	–8.444216668396010e+005
8	127.86	+2.163263102264054e–010
9	101.23	+6.592665063666725e+006
10	128.72	0
11	104.70	–2.820259508984238e+007
12	129.88	0
13	107.49	+6.212593206169277e+007
14	131.51	–6.570503016837812e–009
15	109.95	–5.501638718313641e+007

[1)] Measured IDR value for 3rd order intermodulation

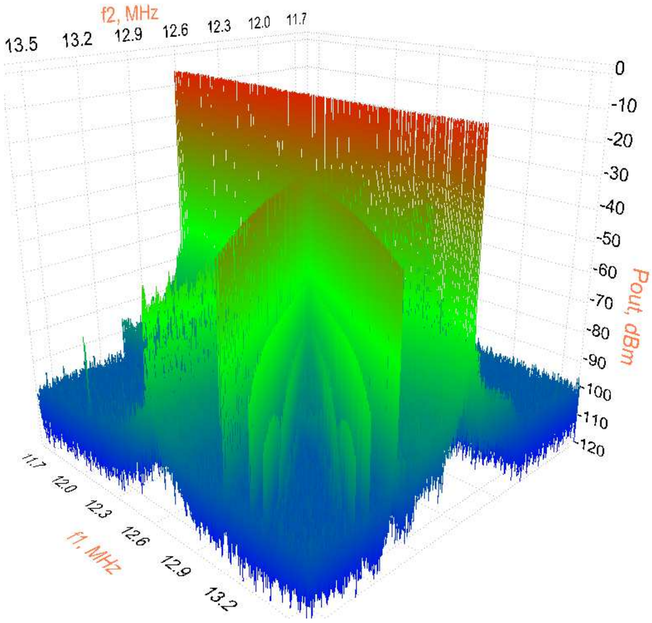

Fig. 4. DFC of radio receiver of HF radio station for an adjustment frequency of 12.579 MHz and the levels of test signals of –26 dBm

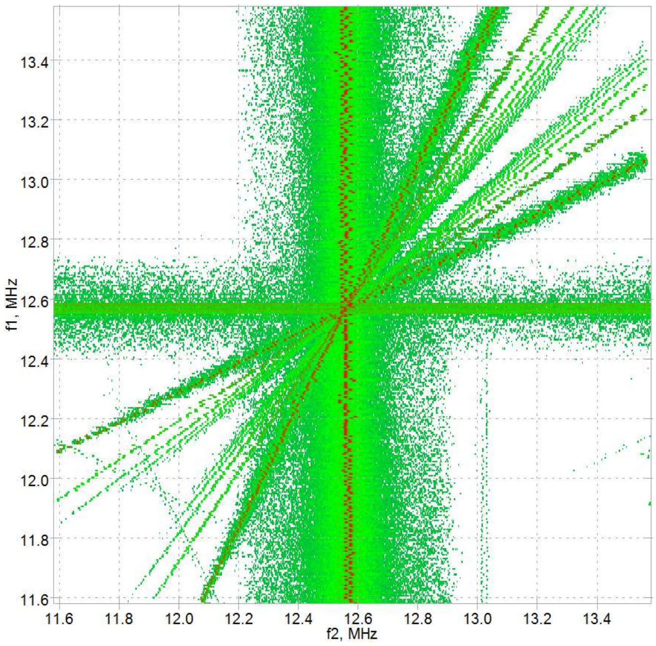

Fig. 5. DFD of radio receiver of HF radio station the level of –95 dBm for an adjustment frequency of 12.579 MHz and the levels of test signals of –22 dBm

6) Discrete nonlinear EMC analysis is performed for potentially dangerous situations, i.e., discrete nonlinear analysis of RR behavior in EME formed as a sum of signals of OBRES RT and those of external EME. Situations in which the results of the analysis proved danger of RR damage by nonlinear radio interferences are determined. As an example of EMC DNA, Fig. 6 illustrates spectra of the total signal at the input and output of structural model of RR belonging to HF radio station when it is adjusted to a frequency of 12.579 MHz. The spectra were obtained using the technologies and algorithms [7-10] and 15th order polynomial model of input nonlinearity of RR obtained by the results of its testing by the DFT method.

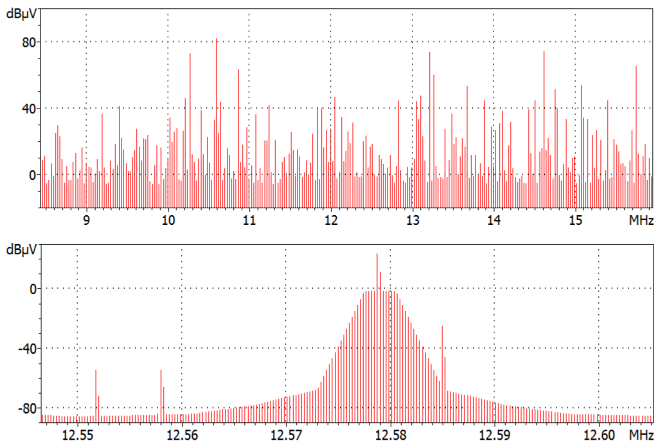

Fig. 6. Spectra of total signal at the input (upper) and output (lower; fed to RR input) of the model of RR belonging to HF radio station; 3rd order intermodulation is observed in the output spectrum close to the adjustment frequency of RR

DLA and DNA of OBRES EMC detected unacceptable variants of joint operation of separate radio stations and determined operational conditions for each radio station without interferences via the main, adjacent and spurious reception channels. There were also detected and identified the situations in which damage to on-board RR by intermodulation interference of 3rd to 5th order was revealed, which made it possible to determine the measures to exclude these situations during OBRES operation in severe external EME.

III. Conclusion

The technology of EMC analysis of OBRES has the following advantages that determine its practical importance: high accuracy of representing spectra of radiations, AFC of spurious couplings, as well as susceptibility and nonlinearity characteristics of radio receivers; high computational efficiency of procedures of discrete linear and nonlinear EMC analysis; worst-case behavior of EMC estimations and tolerance thereof to errors in input data; iterative refinement of the models of potentially dangerous undesired impacts. The above advantages are proved through the results of solving practical problems of EMC analysis and diagnostics of a number of on-board and ground-based radio stations, which enables to recommend using this technology when developing and upgrading, as well as when solving the problems of OBRES EMC of different type and complexity.

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