EMC Diagnostics of Complex Radio Systems by the Use of Analytical and Numerical Worst-Case Models for Spurious Couplings Between Antennas

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***Abstract*—A technique of two-phase EMC diagnostics of complex ground-based radio systems with the use of worst-case models of electromagnetic spurious couplings between antennas is introduced. At the first phase, the ultra wideband analytical model of antenna coupling developed in the framework of IEMCAP program is used, and the ensemble of potentially dangerous spurious couplings is found. For these couplings, the improved numerical worst-case models for the reduced frequency bands, as well as for given types, orientations, and relative positions of the antennas are developed at the second phase of EMC diagnostics. Each of these improved models is obtained by finding the envelope of results of multiple (based on variations of model parameter values) FDTD modeling of the corresponding coupling. The example of application of the introduced technique for diagnostics of intrasystem EMC of an operating radio-TV complex is provided: the computer model of its radio mast is developed, and the two-phase EMC diagnostics of this complex (which contains radio equipment of more than 20 systems of radio-TV broadcasting, fixed and mobile radio communication, radio navigation, and other services) is performed. The obtained results have confirmed the efficiency of the presented technique for the analysis of intrasystem EMC due to significant improvement in estimation of potentially dangerous spurious couplings between antennas at the second phase of EMC diagnostics (by 5…20 dB in comparison with analytical model of IEMCAP) with acceptable computational burden.**

Keywords—EMC diagnostics, systems engineering and theory, worst-case models, electromagnetic coupling.

I. INTRODUCTION

Operation of compound radio objects which are include a considerable quantity of radio transmitters and radio receivers of various radio services, is appreciably defined by EMC of radio equipment placed on this object. The most complicated problems of computer EMC diagnostics of such objects are

a) absence of full and reliable information about characteristics of the object's equipment (for example, about radiation spectra of transmitters, susceptibility characteristics of receivers, parameters of antennas and feeders, etc.),

б) large quantity (reaching several thousand) of potentially dangerous parasitic electromagnetic spurious couplings on considered object, and

в) limited resources (time, spending) for its execution.

Effective method of overcoming of the specified problems, offered within the IEMCAP R&D program [1]-[3], is the use of analytical worst-case models for the description of spurious couplings between antennas allocated on object. This method allows performing of the primary pessimistic EMC analysis taking into account all possible spurious couplings between antennas of object at acceptable computing timetable. As a result of such analysis it is possible to define all potentially dangerous "Antenna-antenna" spurious couplings, which are usually sporadic and are a subject of the subsequent detailed analysis (with use of more exact models or experimentally). Efficiency of a similar technique of EMC diagnostics of complex board systems is confirmed in practice [4]-[6].

The objective of this paper is to investigate possibility and also to develop and test a technique of specification of an analytical estimation of spurious electromagnetic couplings between antennas allocated on the radio mast of compound radio-TV complex, by use of numerical methods in conditions of partial prior uncertainty or limited reliability of initial data.

Thereto a number of problems have been solved: the computer model of a real multifunctional radio complex created at tall radio-TV antenna mast have been developed (Section II), and the 1st phase of intrasystem EMC diagnostics of this radio complex on the basis of analytical worst-case models of "Antenna to antenna" couplings have been executed (Section III). As a result of this phase the potential danger of several spurious couplings between antennas have been detected, and thereupon the improved numerical worst-case models of these couplings for the reduced frequency band have been developed (section IV) and the specified 2nd phase of intrasystem EMC diagnostics of given complex have been performed (section V).

II. DESCRIPTION OF MULTISERVICE RADIO COMPLEX UNDER SIMULATION

The simulated multiservice radio-TV complex is created on basis of high-altitude radio mast. On two upper tiers of this mast a set of different antennas of broadcastings radio-service (FM and TV), of different radio communication (fixed and mobile), radio navigation and other services (overall more than

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20 radio systems) are disposed. A fixed operating frequencies and the frequency bands are assigned to these radio systems over the frequency range from 60 MHz to 18 GHz. An output power of radio transmitters of these systems take on values from 1 W (VHF radio transmitters of service communication systems) to 1 kW (2 transmitters of FM sound broadcasting of frequency range 87.5 … 108 MHz and 2 transmitters of TV broadcasting of frequency range 470 … 862 MHz). On this mast antennas of different types (reflecting, dipole, panel, etc.) are allocated; for FM broadcasting VHF transmitters, as well as for TV broadcasting UHF transmitters, common antennas are used. An external view of two top tiers of an antenna mast with antennas of different services is resulted in Figures 1, 2.

Necessity of EMC diagnostics of the given radio object was stipulated by a changing of frequency channels FM and TV broadcasting, and also by upcoming installation of additional radio equipment. In similar cases EMC diagnostics involves the analysis of various scenarios of joint operation of the numerous radio systems disposed on the object.

III. Analytical Worst-Case Model for Calculation of Electromagnetic Coupling Between Antennas

For calculation of the mutual coupling coefficient H for two antennas allocated on the object of finite dimensions, the following analytical worst-case model is proposed [2], [3]:

$$H \equiv P_R / P_T = S_f \cdot K(D), \quad (1)$$

$$K(D) = \begin{cases} 1, & D \le D_A; \\ \left(\dfrac{D}{D_A}\right)^{\frac{\lg[K(D_{FAR})]}{\lg(D_{FAR}/D_A)}}, & D_A < D < D_{FAR}; \\ G_T(\theta_R, \varphi_R) \cdot G_R(\theta_T, \varphi_T) \cdot T_{FS}, & D \ge D_{FAR}, \end{cases} \quad (2)$$

$$D_{FAR} = max[3\lambda,\ 2D_A^2 / \lambda], \qquad T_{FS} = (\lambda / 4\pi D)^2, \quad (3)$$

where P_R is the power at the output of receiving antenna, P_T is the power at input of transmitting antenna, S_f is the factor describing the attenuation by diffraction and shading (formulas for calculation of it are given in [2]); D is the distance between antennas; $D_A = \max\{D_T, D_R\}$, D_T is the maximal size of transmitting antenna; D_R is the maximal size of receiving antenna; $K(D_{FAR})$ is the factor $K(D)$ value calculated for $D = D_{FAR}$; $G_T(\theta_R, \varphi_R)$ is the transmitting antenna gain in direction to receiving antenna; $G_R(\theta_T, \varphi_T)$ is the receiving antenna gain in direction to transmitting antenna; D_{FAR} is the far-field zone boundary, λ is the wavelength, T_{FS} is attenuation at free space propagation (basic losses).

The advantages of model (1)–(3) are its worst-case nature, high computationally efficiency and wide frequency range. Furthermore, the model does not require the presence of detailed information about antenna construction.

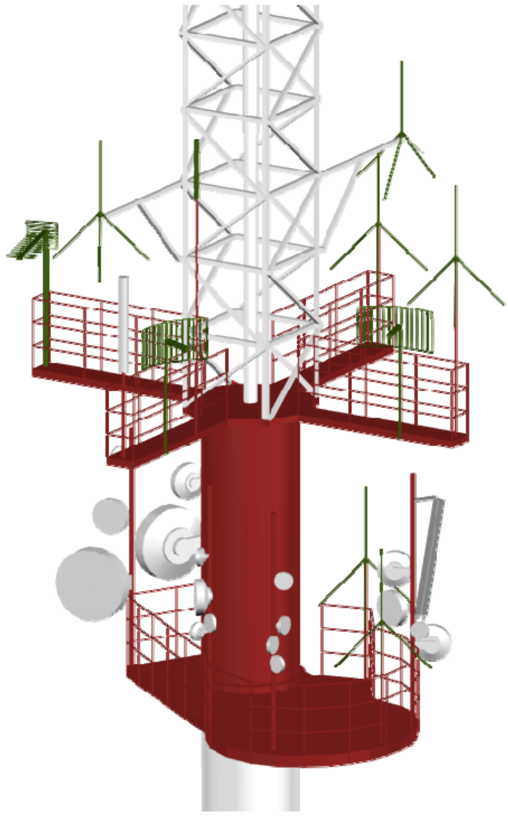

Fig. 1. Medial tier with antennas of the fixed and mobile radiocommunication services.

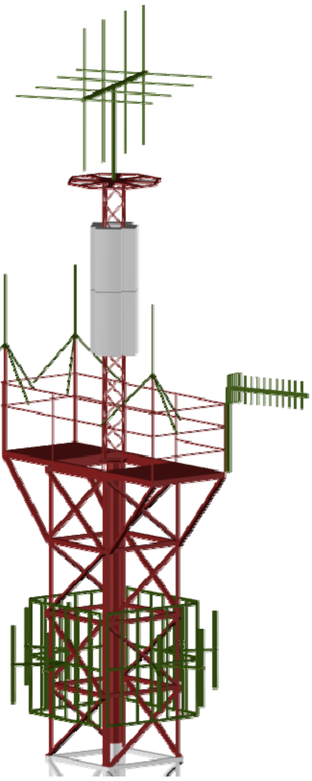

Fig. 2. The upper tier with antennas of broadcasting, fixed and mobile radio communication services.

The drawback of model (1)–(3) is the low accuracy of analysis. It caused by the following reasons.

1) For small distances between antennas ($D < D_A$), the coefficient $K(D)$ in model (1)–(3) becomes equals to 1 [3], that is possible for complete matching of transmitting and receiving antennas (taking into account of mutual coupling between them) only; in other cases this worst-case estimation is essentially overrated. In intermediate zone $D_A \le D \le D_{FAR}$ the interpolation used in (2) can lead to sufficient overestimation of mutual antenna coupling.

2) Diffraction model used in [1]–[6] for calculation of coefficient S_f , is based on model of wave propagation over convex surfaces of rotation bodies and on Geometrical Theory of Diffraction (GTD) in a deep shadow zone (taking into account diffraction by edges), that leads to calculation errors for objects having the geometry presented in Fig. 1, 2 (see also [11]). In particular, GTD model leads to inadequate physical results at the boundary of light and shadow. Application of Uniform Theory of Diffraction (UTD) for calculation of S_f may remove this problem.

3) The partial shading off antennas by hull is not taking into account in model (1)–(3) to improve its computational efficiency. As result, jumping of factor S_f (no less than in 2 times) even by little variation of antenna coordinates (which are associated with phase centers of antennas in framework of the model) can occur. The absence of exact information about antenna coordinates may be a reason of transition of antennas from line-of-side to shading zone at variation of their spatial location.Smooth variation of coupling coefficient may be provided by taking into account of antennas sizes and consideration of their partial shading.

Generally, the possibility of improvement of analytical model (1)–(3) for near-field and intermediate zones is problematic by following reasons. The analytical solution of the field equations [13] for near-field zone of reactive field $D < \lambda/(2\pi)$ (in which electromagnetic oscillations are characterized by active and reactive power, notion of antenna pattern is not usable, and polarization of wave is not defined [12]) can not be obtained owing to its complexity. Accounting of peaks in intermediate zone is possible on basis of additional information about radiating system geometry and construction of matching devices of each antenna. Therefore, the consideration of antenna decoupling in these two zones is suitability to carry out based on numerical or empirical methods [14].

An additional problem, which is not connected with the model (1)–(3), but caused by low accuracy of initial data, is in following. By analysis of narrow-beam directive antennas allocated in far-field zone or in close proximity of its boundary, even the small variation of coordinates and orientation of antenna (caused by errors in initial data) may lead to sufficient change of antenna coupling coefficient (1) including its underestimation. This problem can be solved by variation of antennas coordinates and orientation, and by selection of the largest value of antennas coupling coefficient calculated for all considered variations, to provide the model's worst-case nature.

IV. Numerical Worst-Case Model for Calculation of "Antenna-to-Antenna" Coupling

Numerical simulation of spurious couplings between antennas allocated at objects of considered type allows to eliminate the drawbacks and to solve the problems noted in Section III, but leads to increasing of laboriousness and computational complexity of analysis, especially in cases of absence of full and exact information about antennas (its radiating systems, matching devices etc).

Traditional approaches associated with the synthesis of numerical worst-case model based on Monte-Carlo method are usually used when the number of parameters under variation is not large for every element of the system. For example, at modeling of spurious couplings of various types (wire-to-wire, wire-to-antenna, etc.) [15], [16] the multiple numerical calculations of amplitude-frequency characteristic (AFC) of coupling are executed using pseudorandom values of parameters, and AFC worst-case model is obtained by selection of maximal value detected in set of calculated AFC realizations for every point of considered frequency range. It is empirically exposed that the choice of maximal value for all realization permit to eliminate the high irregularity of AFC curve only in the case of large number of variations, therefore the numerical calculations are repeated of 20…60 times [15].

To provide the representativeness of sample of AFC realizations it is necessary to vary all unknown parameters of the coupling independently from each other. Therefore this approach requires the unacceptable large computational burden for EMC diagnostic of complex radio system, since it is necessary to carry out the numerical modeling of tens spurious couplings, and each antenna has some unknown parameters. In this way, for analysis of two antennas, if n parameters are not defined for each antenna, and each of parameter can take of m values by variation, then the number of independence variations will be $N = m^{2n}$.

For decreasing of number of independent variations it is necessary to decrease the number of possible values of each undefined parameter. Further it is supposed that each parameter can take 3 possible values: the reference value (X_{ref}), the minimal value ($X_{min} = X_{ref}(1-\delta_X)$), and the maximal value ($X_{min} = X_{ref}(1+\delta_X)$), where δ_X is the relative error of parameter's definition.

To provide the worst-case nature of AFC model of spurious coupling at decreasing of variations number, the special algorithm of AFC envelope definition is developed. It is based on small sampling of AFC realizations; synthesis of worst-case numerical model is implemented like this:

1) For various values of antennas parameters the set (sample of N volume) $\{H_1(f), H_2(f), \ldots, H_N(f)\}$ of AFC realizations for spurious coupling is calculated by methods of computational electrodynamics.

2) On the Base of calculated sample of AFC realizations the "maximal" AFC $H_M(f)$ of coupling coefficient is obtained:

$$H_M(f) = max\{H_1(f), H_2(f), \ldots, H_N(f)\}. \quad (4)$$

Estimation (4) is not worst-case, because it does not eliminate the AFC irregularity. To obtain the worst-case estimation it is necessary to define the envelope going through maximums of $H_M(f)$ function as it shown below.

3) Differences ΔH_{Mj} are calculated at frequency grid with step Δf:

$$\Delta H_{M\,j} = H_M(f_j + \Delta f) - H_M(f_j)\,, \qquad (5)$$

where $j = 0 \ldots (f_{max} - f_{min})/\Delta f$ is the number of frequency interval in considered frequency range $[f_{min}, f_{max}]$. Then frequencies $f_q = f_{j\ max}$ are detected, for which differences (5) change the sign from positive to negative; $q = 0 \ldots Q$; Q is the number of maximums.

4) The auxiliary piecewise smooth function, which connects the values of function $H_M(f_q)$ of adjacent maximums by rectilinear segment, is build:

$$H_L(f) = \text{linterp}(f_q, H_M(f_q), f)\,, \qquad (6)$$

where the «linterp» is used for the designation of this action.

5. The maximal value for two functions $H_M(f)$ and $H_L(f)$ is selected in whole frequency region under consideration:

$$H_W(f) = max\{H_M(f), H_L(f)\}; \qquad (7)$$

resultant function $H_W(f)$ is the worst-case estimation of AFC of coupling coefficient.

As a result, this algorithm of envelope definition, based on small sample volume of AFC realizations, make it possible to decrease the number of calculated AFC realization and time of model's synthesis on 1-2 orders.

The further reduction of computational burden connected with decreasing of the number of varied parameters, is carried out with taking into account peculiarities of every specific case (symmetry of the object structure, relative spatial density of equipment, etc).

V. Algorithm and Results of EMC Diagnostics of Complex Radio System

EMC diagnostics of equipment allocated on the radio mast is carried out by software "EMC-Analyzer" [10] in two phases.

The first phase of EMC diagnostics is performed with the use of analytical model (1)-(3). As a result, five potentially dangerous spurious couplings were detected. In these couplings the antenna of FM broadcasting mounted on upper tier of radio mast (Fig. 2) is defined as the emitter. It consists of four identical sections allocates at angles of 90° to each other; length of vertical monopoles is 1.5 m, working frequency range is 88…108 MHz. Antennas of various types (monopole antenna with counterpoises, dipole, disk-cone antenna) of mobile and fixed communication services allocated on the upper and middle tiers of radio mast (Fig. 1, 2) are defined as receptors of couplings mentioned above.. Working frequency bands of antennas - receptors belongs to the range 50…400 MHz. All five antennas - receptors are located in near-field and intermediate zones of antenna - emitter.

At the second phase, the above-mentioned five spurious couplings were specified using the particular numerical worst-case models. The synthesis of these numerical worst-case models is performed according to the following algorithm:

1) List of varied antenna parameters is determined. Parameters of antenna - emitter are known with high accuracy, therefore only uncertain parameters of antennas – receptors specified below in items *a),b),c)* are varied only:

a) Geometrical parameters of radiating system, for example length, number and diameter of roads of dipoles and reflectors for dipole antennas, diameter of disk and vertex angle of cone for disk-cone antenna, clearance for the load connection;

b) Load resistance;

c) Coordinate of load point of antenna which affect considerably on antenna mutual coupling coefficient. In present case of radio mast it is the coordinate along the vertical axes.

2) For each antenna-receptor the following reference values of varied parameters are defined:

a) Diameter of rods of dipoles and reflectors are defined based on technological requirements (structural strength, structural weight, aerodynamic properties). Reference value of rod's length of dipole antennas (taking into account the shortening coefficient depending on rod's diameter) is calculated for antenna resonance at medium frequency of working frequency range. The length of clearance for load connection is chosen equal to minimal distance between points which provide correct meshing for realization of numerical simulation.

b) The theoretical values of input impedance of radiating system for antenna of corresponding type given in [12], [13] are used as reference values of load resistance (which is connected under modeling directly to the antenna radiating system since information about antenna matching devices, as a rule, is not available). For example, the radiation resistance (which is equal to load resistance) of half-wave dipole is accepted equal to 73 Ohm, for disk-cone antenna – 90 Ohm, and for log periodic antenna – 130 Ohm.

c) Reference values of coordinates of load point for every antenna are defined using visual estimations of antenna type, radio service, frequency range.

3) Reference values of parameters of each antenna-receptor are specified by numerical modeling of antennas in radiation mode taking into account the influence of radio mast. Validation criteria of parameter's choice are **(a)** obtaining of minimal antenna WSVR, **(b)** equality of calculated value of antenna gain to rated value (presented in specification or manuals for antennas of corresponding type) in working frequency range. Additional validation criterion is the coincidence of antenna pattern obtained as result of modeling with known theoretical antenna pattern for antennas of corresponding type

4) The numerical modeling of AFC realizations for spurious couplings between antenna-emitter and all of antenna-receptors is made by FDTD method for different values of parameters varied independently. All six antennas and the part of radio mast are considered as a one electrodynamic system, therefore the variation of the one parameter may be specified simultaneously for all of antenna-receptors, that permit to decrease of number of AFC calculations. For example, if for each of two antennas three parameters are varied and each of parameter can accept of 3 various values by variation (the reference value and two (maximal and minimal) differs from it to 25%) than the number N of AFC realization of spurious couplings for each antenna-receptor is $N = 27$.

As a result the set of AFC realizations for each "antenna-to antenna" coupling is obtained: $\{H_1(f), H_2(f),\ldots H_N(f)\}_k$, where f is the frequency, $H_1(f)$ is AFC defined numerically for reference values of antenna-receptor parameters; $H_i(f)$ is AFC obtained at variation of parameters; $i = 2\ldots N$, $k = 1\ldots 5$ is the number of antenna-receptor.

5) For each of five spurious couplings {antenna-emitter to antenna-receptor} the set $\{H_1(f), H_2(f),\ldots H_N(f)\}$ of AFC realizations is obtained, and the worst-case numerical model is obtained with the use of technique presented in Section IV.

In Figs. 3 – 7 some results of synthesis of numerical worst-case models for spurious couplings between FM broadcasting antenna-emitter ad antenna-receptors of the considered complex ground-based radio object, obtained during the second stage of its EMC diagnostics, are presented. Solid red curve corresponds to analytical model (1)-(3), blue solid line correspond to numerical worst-case model. Examples of AFC realizations calculated by FDTD method are depicted by broken blue lines: AFC obtained on the basis of reference values of parameters (dotted line); AFC corresponding to the choice of maximal (dashed line) and minimal (dash-dotted line) values of all parameters.

Peculiarity of operation of antennas-receptors No.4 and No.5 is that these spaced antennas are two parts of compound antenna system of VHF base station of mobile service. For such antenna system more complicated technique of creation of particular worst-case numerical model of spurious coupling with FM broadcasting antenna – emitter must be used.

In Fig.6 an AFC of spurious coupling between FM broadcasting antenna – emitter and antenna-receptor No.4 (VHF monopole with counterpoises as a part of compound antenna system) is given.

But in case when two antenna-receptors are connected to the one radio receiver, the ratio of the sum of power at each antenna-receptor output to power radiated by emitter must be calculated for analysis of antenna decoupling. Summation may be performed in two ways: **1)** the envelope of variations of coupling coefficient for each antenna-receptor is obtained and then the summation of envelopes is carried out, or **2)** the results obtained for various realizations are summarized in pairs, and then the envelope of all of sum in pairs is build. The first approach has a more pessimistic nature (Fig. 7).

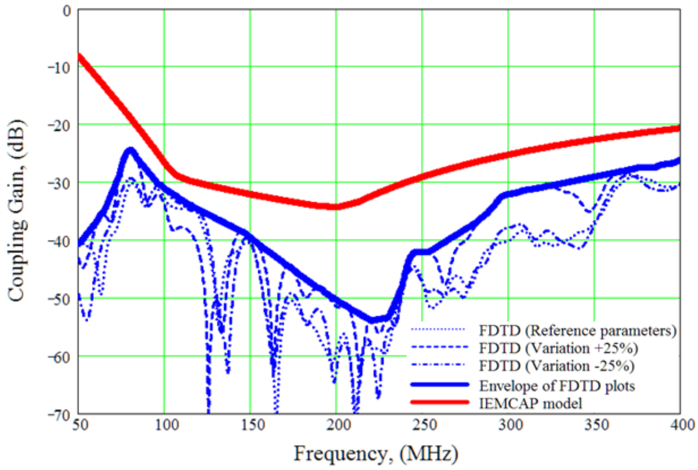

Fig. 3. AFC of spurious coupling between FM broadcasting antenna-emitter and antenna-receptor No.1 of VHF repeater of mobile service (monopole with counterpoises, vibrator length is of 1.2±0.3m, counterpoises length is 0.50±0.15 m, load resisrance is of 73±20 Ohm; vertical polarization).

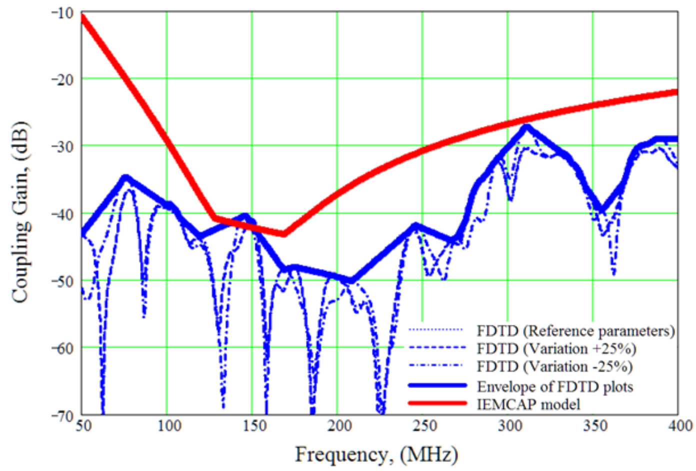

Fig. 4. AFC of spurious coupling between FM broadcasting antenna-emitter and antenna-receptor No.2 of VHF mobile service (disk-cone antenna).

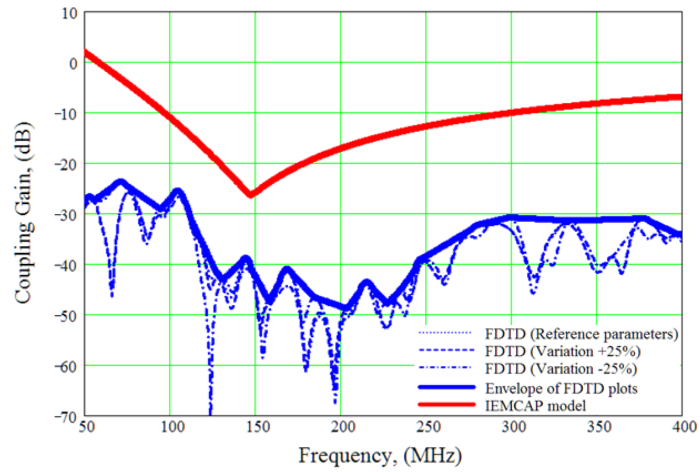

Fig. 5. AFC of spurious coupling between FM broadcasting antenna-emitter and antenna-receptor No.3 of VHF mobile service (dipole antenna).

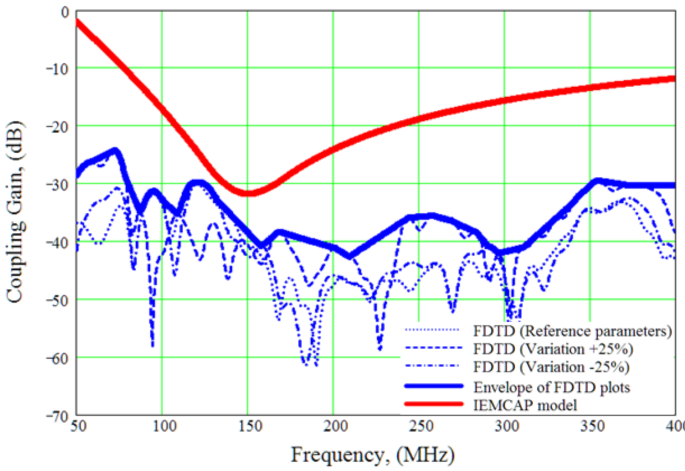

Fig. 6. AFC of spurious coupling between FM broadcasting antenna-emitter and antenna-receptor No.4 of VHF repeater of mobile service (monopole with counterpoises).

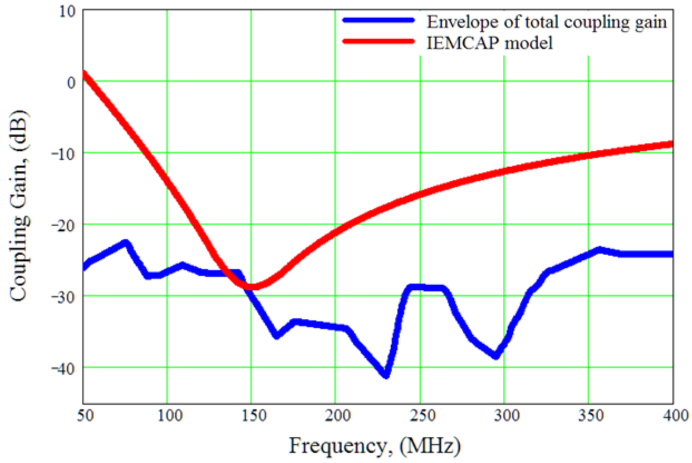

Fig. 7. AFC of spurious coupling between FM broadcasting antenna-emitter and system of antenna-receptors No.4 and No.5 (monopoles with counterpoises) of VHF base station of mobile service

Adjusted EMC diagnostics of the 2nd phase with the use of particular numerical worst-case models of potentially dangerous spurious couplings permitted to find out that antenna decoupling between antenna of FM broadcasting (emitter) and antennas-receptors examined above provide the absence of interference for radio equipment allocated on radio mast under the planned variation of frequencies of FM broadcasting. Experimental EMC validation (trial running of all radio equipment allocated on radio mast in planned mode of operation) corroborated the validity of this conclusion.

VI. Conclusion

The presented technique of synthesis of numerical worst-case models of spurious electromagnetic couplings between antennas at the second phase of EMC diagnostics allows to specify essentially estimations of an interdependence of close located antennas (on 5 … 20 dB in comparison with analytical model (1) - (3)) at preservation of pessimistic character of these estimations in conditions of absence of full and authentic initial data. As a result the further specification and reduction of the list of potentially dangerous spurious couplings, demanding detailed numerical modeling at specified initial data or experimental verification, and, thereby, reduction of laboriousness and cost of EMC diagnostics of complex ground-based radio objects is provided.

Practical application of the developed technique for EMC diagnostics of multiservice radio-TV complex created on basis of high-altitude radio mast has confirmed its efficiency from the viewpoint of linear EMC analysis. The third stage of EMC diagnostics based on the use of EMC Discrete Nonlinear Analysis technique [17] make it possible to predict and detect all nonlinear interferences (intermodulation, cross-modulation, etc.) and specify its sources.

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