System-Level Model for Analysis of Dipole Antenna Response to Electromagnetic Pulse

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Abstract**—In this paper, we developed an analytical model that makes it possible to estimate the response (i.e., the voltage or current at the output) of a dipole antenna to arbitrary-shaped electromagnetic pulse if the minimum information about the antenna is available (it is enough to know the following parameters of the antenna: working frequency range, gain, and wave impedance of the radiofrequency port). The developed model is validated by comparing the computed responses of VHF- and UHF-band dipole antennas to wideband electromagnetic pulses with the measurement results published in the literature. The validation demonstrates that the model estimates the values of the most important antenna-response parameters (total energy, amplitude, and voltage rate), which define the requirements to the radio-equipment terminal protection devices, with reasonable accuracy. The possibilities of increasing the response estimation accuracy by numerical modeling of the antenna are investigated (MoM and FDTD methods are involved).**

Keywords—dipole antennas; EMP radiation effects; systems engineering and theory; analytical models

I. INTRODUCTION

One of the ways of radio-electronic equipment damage by high-power electromagnetic pulses (EMPs) is their reception by antennas of radio devices [1], [2], [3]. For development of requirements to equipment's radio-frequency port protection devices, it is necessary to estimate the response of each antenna to EMP, i.e., to estimate the time-domain realization or spectrum of voltage (or current) pulse at the load connected to the antenna output.

Models intended for express-analysis of antenna response to EMP must satisfy the following requirements. 1) The model must have a high computational efficiency and it must be applicable to the widest possible class of antennas since there are many antennas different in purposes and construction in a complex system (aircraft, car, ship, building, etc.). 2) The model must be usable in a wide frequency range since various types of EMPs that have components of spectrum with various frequencies (from 300 Hz for lightning-induced EMPs to 50 GHz for EMPs radiated by high-power radio transmitters [3], [4], [5]) may influence to system. 3) It is important to have a possibility to synthesize the antenna model based on characteristics given in its specification only, since detailed information about antenna construction is often not available (e.g., if it is commercial secret of manufacturer). 4) Since the antenna characteristics given in specification describe its behavior in working frequency range only (but the characteristics are not standardized and not examined by manufacturers out of this range [6, p.297], [7, p.2-106]), one can not expect a high-precision estimation of antenna response to the most types of EMP. Therefore it is reasonable to require that the model must have a worst-case behavior (in particular, it must not permit the underestimation of energy and amplitude, as well as the overestimation of the duration of pulse response front).

Known methods for calculation of antenna response to EMP do not satisfy to the requirements given above. Experimental methods based on measurement of impulse [8] or frequency [9] response of antenna need in large expenses of time and resources. Methods of computational electromagnetics [10, p.587, p.806] require detailed information about antenna construction and large computational burden. The detailed information about antenna construction is necessary for application of equivalent circuit method, too [1], [11] (with the exception of the simplest antennas, such as single dipoles, monopoles, loops [2], [3]). The effective area method [2], [3] and the method of antenna gain (they are equivalent) have a wideband formulation [12], [7], [13] taking into account the mismatch between antenna and feeder but these methods do not permit to estimate the Phase-Frequency Characteristic (PFC) of the antenna.

The objective of this paper is to develop such model for express-analysis of dipole antenna response to EMP that satisfies to the requirements formulated above.

II. TRANSFER FUNCTION OF RECEIVING ANTENNA

The antenna in receiving mode may be represented by Thevenin equivalent circuit (Fig. 1) [14, p.6-3]. Then the antenna response to incident EMP is determined by the complex spectra of voltage $U_L(f)$ and current $I_L(f)$ at the radiofrequency output of the antenna:

$$I_L(f) = \frac{V_{oc}(f)}{Z_{in}(f) + Z_L(f)}, \quad U_L(f) = Z_L(f) \cdot I_L(f), \qquad (1)$$

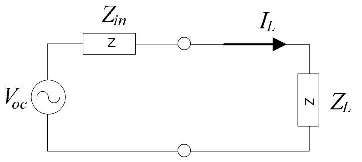

Figure 1. Equivalent circuit of antenna in receiving mode.

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where f is the frequency (below, the dependence of quantities on frequency is omitted for short of formulas), Z_{in} is the antenna input impedance ($Z_{in} = R_{in} + jX_{in}$, $j = \sqrt{-1}$), Z_L is the load impedance ($Z_L = R_L + jX_L$), V_{oc} is the complex e.m.f. of the equivalent source

$$V_{oc} = \vec{h}_e \cdot \vec{E}_i = \xi \cdot h_e \cdot E_i, \qquad (2)$$

where $\vec{h}_e$ is vector complex effective length of the antenna [14, p.6-5]; $\vec{E}_i$ is the vector complex amplitude of the incident plane monochromatic wave considered as a component of EMP spectrum; ξ is the complex polarization mismatch factor by field [15, p.167], note that the magnitude of ξ arises the maximum when the polarization of the incident wave coincides with the eigenpolarization of the antenna (in this case $\xi = |\xi| = 1$). Below, only the most dangerous case $\xi = 1$ is considered, and the quantities h_e and E_i in (2) have the following meaning in this case: E_i is the complex amplitude of the incident wave, the polarization of which coincides with the eigenpolarization of the antenna, h_e is the complex effective length of the antenna for its eigenpolarization [15, p.166]

$$h_e = j\frac{c}{f}\sqrt{\frac{G \cdot R_{in}}{\pi \cdot Z_w}} \cdot F(\phi,\theta) = 2j\sqrt{\frac{A_e \cdot R_{in}}{Z_w}} \cdot F(\phi,\theta), \qquad (3)$$

where c is the speed of light ($c = 3 \cdot 10^8$ m/s), G is the antenna gain in the direction of maximum radiation, A_e is the effective area of the antenna in the direction of maximum radiation, Z_w is the wave impedance of free space ($Z_w = 120\pi$ Ohm), $F(\phi,\theta)$ is the complex (amplitude and phase) normalized radiation pattern (by field) of the antenna. Below, only the most dangerous case is considered, in which the antenna is illuminated from the direction (ϕ_0, θ_0) of its maximum radiation, therefore $F(\phi,\theta) = F(\phi_0,\theta_0) = \exp\{j\Phi(\phi_0,\theta_0)\}$, where $\Phi(\phi,\theta)$ is the phase pattern of the antenna.

Below, we consider the antenna output voltage as the response in order to be more specific.

By the use of (1), (2), and (3), one can obtain the complex transfer function $H(f)$ of the antenna in receiving mode:

$$H \equiv \frac{U_L}{E_i} = \frac{Z_L}{Z_{in} + Z_L} \cdot j\frac{c}{f}\sqrt{\frac{G \cdot R_{in}}{\pi \cdot Z_w}} \cdot e^{j\Phi(\phi_0,\theta_0)}. \qquad (4)$$

III. TECHNIQUE FOR COMPUTATION OF ANTENNA RESPONSE TO EMP

The following are initial data for calculation of antenna response: 1) time-domain realization of EMP $e_i(t)$, i.e., the dependence of incident-wave electric field intensity on time; 2) Impulse Response (IR) $h(t)$ or complex transfer function $H(f) \equiv FFT\{h(t)\}$ of antenna. Here and below, $FFT\{\cdot\}$ is the operator of direct Fast Fourier Transformation (FFT).

The calculation is performed by the following algorithm. First, the time-domain realization of response is computed [8]:

$$u_L(t) = IFFT\{H(f) \cdot E_i(f)\}, \quad E_i(f) = FFT\{e_i(t)\}, \qquad (5)$$

where $IFFT\{\cdot\}$ is the operator of Inverse FFT. Then, the characteristics of pulse $u_L(t)$ at the antenna output are calculated: energy, amplitude, etc. (see Section VI).

The frequency range of analysis $[f_{\min}, f_{\max}]$ is chosen by the following empirical rule:

$$\begin{aligned} f_{\min} &= \min\{f_{\min,P},\ f_{\min,A} / K_{\min}\}, \quad K_{\min} \in [2,5]; \\ f_{\max} &= \max\{f_{\max,P},\ K_{\max} \cdot f_{\max,A}\}, \quad K_{\max} \in [2,5], \end{aligned} \qquad (6)$$

where $[f_{\min,P}, f_{\max,P}]$ is the effective frequency range of EMP, $[f_{\min,A}, f_{\max,A}]$ is the working frequency range of antenna, $K_{\min}, K_{\max}$ are coefficients defined empirically.

IV. SYSTEM-LEVEL MODEL FOR AMPLITUDE-FREQUENCY CHARACTERISTIC (AFC) OF ANTENNA

A. Model for Working Frequency Range of Antenna

In the worst case, the antenna output power at load (at feeder) is maximal at every frequency. This means that the antenna matching device has negligible losses, input impedance $Z_{L,M} = Z^*_{in,R}$ (where $Z_{in,R} = R_{in,R} + jX_{in,R}$ is the input impedance of radiating system of the antenna), and output impedance equal to wave impedance R_F of the feeder.

By applying (1), (2), and (3) not to the antenna as a whole but to its radiating system only, one can find the maximal power that can be delivered from antenna radiating system to the matched load $Z_{L,M}$ [10, pp.102, 108], [15, p.173]:

$$P_{\max} = \frac{|V_{oc}|^2}{8R_{in,R}} = \frac{|E_i|^2}{2Z_w} A_e, \quad A_e = \lambda^2 \frac{G}{4\pi}, \quad \lambda = \frac{c}{f}. \qquad (7)$$

The matching device transfers this power to feeder without losses. Then, according to (4), the model of antenna AFC for working frequency range $[f_{\min,A}, f_{\max,A}]$ takes the form

$$|H_{WF}| \equiv \frac{|U_L|}{|E_i|} = \frac{\sqrt{2R_F P_{\max}}}{|E_i|} = \frac{c}{2f}\sqrt{\frac{G_{WF} \cdot R_F}{\pi \cdot Z_w}}, \qquad (8)$$

where G_{WF} is the antenna gain in working frequency range. If the frequency dependence $G_{WF}(f)$ is not given in the antenna specification then the maximal value of antenna gain $G_{WF\max}$ specified in the documentation should be used in (8) in order to obtain the worst-case model.

B. Low-Frequency Model

Outside the working frequency range of antenna, we need to account for the mismatch between antenna and feeder.

Let us define the low-frequency (LF) band by inequality $f \le f_{\max,LF} \equiv f_{\min,A}/K_{LF}$, where K_{LF} is the empirical coefficient (in this paper, we assume $K_{LF} = 2$). Similarly to [11, p.81], let us assume for LF band that the matching device is absent (i.e., its transfer function is equal to 1), so the feeder is connected to the antenna radiating system directly (this corresponds to the worst case, see below). Let us represent the antenna as an equivalent short dipole. Then, according to (4), the antenna AFC in LF band takes the form

$$|H_{LF}| = \frac{R_F}{|Z_{in,sd} + R_F|}\,\frac{c}{f}\sqrt{\frac{G_{LF}\,R_{in,sd}}{\pi \cdot Z_w}}, \quad G_{LF} = 1.5, \qquad (9)$$

where $Z_{in,sd}$ is the input impedance of a short cylindrical dipole with the arm length L_s and the radius a [15, p.77]:

$$\begin{aligned} &Z_{in,sd} = R_{in,sd} + j \cdot X_{in,sd}, \quad R_{in,sd} = 2\pi Z_w \eta_\lambda^2/3, \\ &X_{in,sd} = -(Z_w/\pi) \cdot \{\ln(\eta_a) - 1\} \cdot \cot(2\pi\eta_\lambda), \\ &\eta_\lambda \equiv L_s/\lambda, \quad \eta_a \equiv L_s/a, \quad \eta_a \ge 10. \end{aligned} \qquad (10)$$

The radius of the primary radiator (which is coupled to feeder) of dipole antenna should be used as the radius a of the equivalent dipole in (10). If there are several such radiators, the radius of the longest of them should be chosen. If its radius is not known then it is reasonable to accept the worst case in which $\eta_a = 10$.

Let us assume that the frequency f_{sd} of the first resonance of equivalent short dipole is equal to $f_{\min,A}$. This corresponds to the worst case (since the decrease of f_{sd} leads to increase of AFC (9) at every frequency in LF band) and has a physical foundation (for log-periodic antenna, the resonance frequency of the longest primary radiator is near to $f_{\min,A}$). Then

$$L_s = \frac{c}{4f_{\min,A}}, \qquad \eta_\lambda = \frac{f}{4f_{\min,A}}. \qquad (11)$$

Formulas (9), (10), (11) are the model of AFC of the dipole antenna at LF. By expanding this AFC in a series in the neighborhood of zero frequency, we obtain the equation

$$|H_{LF}| \underset{f \to 0}{\cong} \frac{c\pi^2 R_F \sqrt{6G_{LF}}}{24 Z_w f_{\min,A}^2 \ln(\eta_a - 1)} \cdot f \equiv |H_{LF0}| \qquad (12)$$

that corresponds to known results: since $|H_{LF0}| \sim f$ [9, Fig.2], antenna behaves as differentiating circuit in LF band. As it follows from definition of H in (4), the power P_{LF0} at the load $Z_L = R_F$ of antenna is $P_{LF0} = |H_{LF0}|^2 \cdot |E_i|^2/(2R_F) \sim f^2$, then realized (taking into account the mismatch) effective area of antenna is given by $A_{e,r,LF0} = P_{LF0}/\{|E_i|^2/(2Z_w)\} \sim f^2$ (20 dB/decade) that corresponds to [12, eq.(7), Fig.4]. Realized (taking into account the mismatch) gain of antenna is given by the formula $G_{r,LF0} = A_{e,r,LF0} \cdot 4\pi/\{(c/f)^2\} \sim f^4$ (40 dB/decade) that corresponds to measurement results and model given in [13]. The error $|(|H_{LF0}|/|H_{LF}|) - 1| < 22\%$ for $K_{LF} = 2$.

Worst-case behavior of model (9), (10), (11) is confirmed experimentally and by numerical modeling: with decreasing of the frequency, the speed of AFC decrease for dipole and loop antennas is more than theoretical values presented above [16], [17] or is equal to them [13].

C. High-Frequency Model

The High Frequency (HF) band we define by inequality $f \ge f_{\min,HF} \equiv K_{HF} f_{\max,A}$, where K_{HF} is the empirical coefficient (in this paper we assume $K_{HF} = 2$). Results of measurements and numerical modeling [12], [13], [6, p.297-303], [17] show that the radiation pattern of antenna is poorly predictable in HF band: at pseudorandom frequency (which may not be multiple to resonance frequency of antenna radiators [6, p.298]) in pseudorandom direction may arise the peak of antenna gain, the value of which may exceed the value of G_{WF}. Therefore, in HF band it is appropriate to use the worst-case model of antenna given in [13]: the mismatch with feeder is not taken into account, antenna directional pattern is isotropic, and antenna gain is

$$G_{HF} = \gamma_{HF} \cdot G_{WF}, \qquad (13)$$

where γ_{HF} is the constant depending on antenna construction. For example, $\gamma_{HF} = 3.16$ (i.e., 5 dB) for aircraft blade antennas operating at frequencies of 1…6 GHz [13]; $\gamma_{HF} = 10$ for antenna “DM N4-4” (VOR, 108…122 MHz) [12]. In the absence of other information, for definition of value G_{HF} one can use the model given in [18, p.5.25, p.5.35].

Therefore, in HF band the model of antenna AFC $|H_{HF}|$ differs from (8) by replacement of G_{WF} to G_{HF} only.

Since, in this paper, the responses of low-gain antennas to EMPs coming from the direction of intentional radiation are analyzed only, it is assumed that $G_{HF,dB} = 0 + 3\sigma = 6$ (dBi), $\sigma = 2$ (dB) [18, p.5.25], which is in agreement with experimental results (Section VI).

D. Combined Model

In order to combine the AFC models obtained for different frequency bands in Subsections IV.A, IV.B, IV.C, let us use a weight function $w(x)$ providing the absence of discontinuities of AFC and its derivative in transition regions between the frequency bands. So, the combined model of antenna AFC

$$|H_C| = \begin{cases} |H_{LF}|, & f < f_{\max,LF}; \\ T\{f_{\max,LF}, f_{\min,A}, |H_{LF}|, |H_{WF}|\}, & \\ & f_{\max,LF} \le f < f_{\min,A}; \\ |H_{WF}|, & f_{\min,A} \le f, \end{cases} \tag{14}$$

$$\begin{gathered} T(f_1, f_2, y_1, y_2) \equiv y_1 \cdot \{1 - w_0(f_1, f_2)\} + y_2 \cdot w_0(f_1, f_2), \\ w_0(f_1, f_2) = w\{(f - f_1)/(f_2 - f_1)\}, \quad w(x) = 3x^2 - 2x^3, \end{gathered} \tag{15}$$

where $|H_{LF}|$ is defined by (9), $|H_{WF}|$ is defined by (8), moreover, G_{LF} and G_{WF} in (9) and (8) should be replaced by

$$G_C = \begin{cases} G_{LF}, & f < f_{\max,LF}; \\ T(f_{\max,LF}, f_{\min,A}, G_{LF}, G_{WF}), & \\ & f_{\max,LF} \le f < f_{\min,A}; \\ G_{WF}, & f_{\min,A} \le f < f_{\max,A}; \\ T(f_{\max,A}, f_{\min,HF}, G_{WF}, G_{HF}), & \\ & f_{\max,A} \le f < f_{\min,HF}; \\ G_{HF}, & f_{\min,HF} \le f. \end{cases} \tag{16}$$

V. SYSTEM-LEVEL MODEL FOR PFC OF ANTENNA

It is proposed in [7], [19] to calculate the EMP response parameters of antenna based on amplitude spectrum without calculation of time-domain realization of response. In this way, one can assess the energy of the response and obtain the worst-case estimation of some parameters of its time-domain realization such as amplitude and maximal rate of change.

Representation of the response in time-domain makes it possible to increase the informativity of analysis. It is necessary to know not only amplitude but phase spectrum of response for calculation of time-domain realization of antenna response, therefore the model of antenna PFC is required.

One can obtain the model of antenna PFC by analogy with the model of AFC: to calculate the PFC analytically based on (9), (10), (11) for LF band, to assume the PFC equal to zero in working frequency range and equal to −90° in HF band, then to combine these models by analogy with (14). But if this PFC model is used in common with (14), the impulse response $h(t)$ of antenna model does not satisfy the following condition of physical realizability: $h(t) = 0$ for $t < t_0$, where t_0 is the moment of illumination of antenna by EMP in the form of Dirac delta function (i.e., by delta EMP).

Therefore, it is reasonable to synthesize the antenna PFC model by selecting such physically realizable system that its AFC approximates the antenna AFC with sufficient accuracy. The popular realization of this approach is the application of Prony's method and its modifications [9], [20]. If Prony's method is applied, it is necessary to select the parameters of approximation (the number of system poles, etc.) manually, therefore the use of Prony's method is reasonable when the AFC is measured.

To obtain the simplified theoretical model of antenna transfer function it is sufficient to define the antenna PFC on the basis of its AFC by the use of relations for minimum phase circuits [21, p.293]. Therefore, in this paper, the model of antenna PFC $\arg\{H_C(f)\}$ is calculated as the inverse Hilbert transform from AFC model (14) by means of FFT [21, p.142]:

$$\arg\{H_C(f)\} = IFFT\{j \cdot FFT\{\ln|H_C(f)|\}\}. \tag{17}$$

Since the developed model (14), (17) of transfer function is a minimum phase model [21, p.288], this model is called System-Level Minimum Phase (SLMP) model.

VI. VALIDATION OF DEVELOPED ANTENNA MODEL

The validation is carried out by comparison of results (AFC and time-domain realization of voltage at the antenna load $R_F = 50$ Ohm) obtained by SLMP model with experimental results for antennas AS-1852 [8] and AS-2169 [22], [23], as well as with results of numerical modeling performed by FDTD and MoM methods for antennas AS-1852, AS-2169, and aircraft blade antenna AT-1076 [1], [11].

For modeling of AS-1852 antenna (which is a dipole with corner reflector), the values of the input impedance and antenna gain for working frequency range, as well as the overall dimensions of the radiating system, are defined in accordance with antenna specification [24]. Parameter values, which are not specified in documentation, are determined based on antenna photos in such a way to provide the correspondence of modeling results (e.g., calculated value of standing wave ratio) to specification data. As a result, the following values of modeling parameters are chosen. The parameters of primary radiator (dipole): radius is of 1.6 cm, length is of 54 cm, length of gap between arms is of 3 mm. Parameters of reflector: radius of the axis is of 2.5 cm, included angle between parts is of 135°, number of rods in each part is 30, radius of rods is of 0.5 cm, thickness of the framework is of 2.0 cm. The distance from dipole to reflector axis is chosen equal to 41 cm, material of antenna is perfect electric conductor, and the surrounding medium is vacuum. Since the structure of matching device is not known, this device is presented by ideal transformer “110 Ohm to 50 Ohm” for modeling by FDTD and MoM methods.

The AFC of antenna AS-1852 is given in Figure 2. Etalon AFC (red line) is obtained on the basis of measured Impulse Response (IR) by normalization, FFT, and LF-filtering [8].

Figure 3 presents time-domain realizations of AS-1852 antenna response to EMPs of various shapes. Etalon responses are obtained experimentally for cases a) and b), and by convolution of measured IR with EMP (18) for case c) [8].

$$e_{i,\,4EXP}(t)=137\{e^{-b_1\cdot t}-e^{-b_2\cdot t}-0.22(e^{-b_3\cdot t}-e^{-b_4\cdot t})\},\qquad (18)$$
$$b_1=1.5\cdot 10^6,\ b_2=2.6\cdot 10^8,\ b_3=2\cdot 10^5,\ b_4=5\cdot 10^5.$$

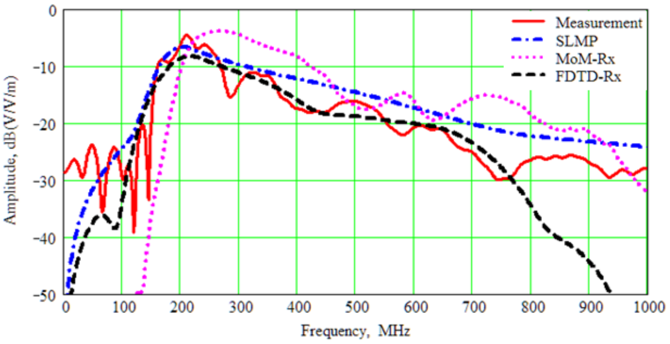

Figure 2. The AFC of antenna AS-1852 obtained by various methods.

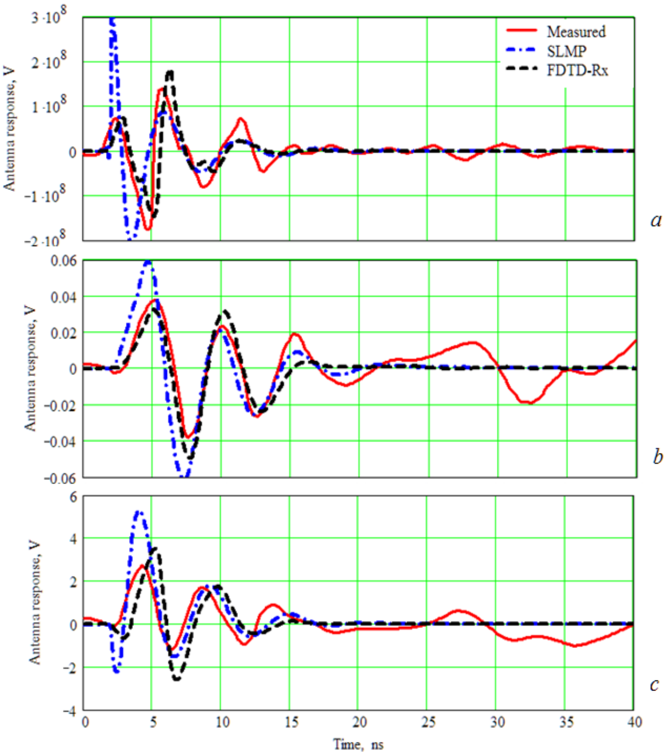

Figure 3. Time-domain realizations of antenna AS-1852 response to EMP of various shapes: a) impulse response (response to delta EMP 0.4/0.9 ns); b) response to EMP 2/5 ns, generated by EMP simulator; c) response to EMP 9/430 ns given by formula (18).

TABLE I. VALUES OF RESPONSE PARAMETERS (PARAMETERS ARE LISTED IN ROWS, METHODS ARE LISTED IN COLUMNS)

	Etalon	**FDTD-Rx**	**MoM-Rx**	**SLMP**
TE, J	1.35E+06	1.00E+06	2.86E+06	1.79E+06
PA, V	1.75E+08	1.84E+08	3.57E+08	3.53E+08
PD, s	1.19E-09	1.63E-09	7.29E-10	4.21E-10
RD, s	1.13E-09	4.77E-10	4.46E-10	1.47E-10
RR, V/s	1.25E+17	3.08E+17	6.41E+17	1.92E+18
TD, s	2.64E-08	9.72E-09	1.17E-08	7.22E-09
Fe, Hz	2.07E+08	1.69E+08	3.95E+08	2.20E+08

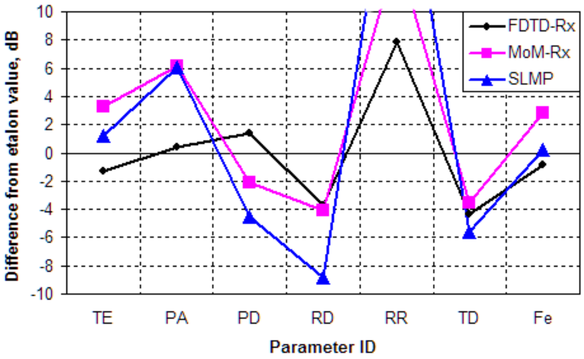

Figure 4. Divergences of delta-EMP response parameters from values calculated for etalon IR.

Based on time-domain realizations of AS-1852 antenna response to delta EMP obtained by various methods (see Figure 3, a), the parameters of response are computed (Table I): Total Energy (TE), Peak Amplitude (PA), Peak Duration (PD), Rise Duration (RD), Rate of Rise (RR), Total Duration (TD), oscillation Frequency (Fe). Values of PA, PD, RD, RR are defined for the largest peak of the response, and the value of TD is defined for the 10% level of the rectified response.

Based on Table I, the differences of delta-EMP response parameter values obtained by modeling of various methods from the parameter values obtained on the basis of the etalon response are calculated (Figure 4). Similar analysis is carried out for responses to EMPs of other shapes (see Figure 3, b, c).

For log-periodic antenna AS-2169, the SLMP model is developed on the basis of available information about the antenna [22], [25]: working frequency range is 30…76 MHz, antenna gain is 3…7 dBi, wave impedance of feeder is 50 Ohm. Modeling of the antenna by MoM is performed in [26]. The antenna AFC is given in Figure 5; etalon AFC is obtained on basis of measured IR of the antenna by normalization, FFT, and LF-filtering [23]. Time-domain realizations of antenna response to EMP of two types are presented in Figure 6.

The results of validation showed that the SLMP model often does not permit to reproduce the shape of time-domain realization of antenna response to EMP, but it provides the ability to estimate the behavior (nonperiodic or oscillating) and parameters of the response. Just these parameters (see Table I) are the initial data for development of equipment terminal protection devices [27]. The accuracy of estimation of these parameters by means of SLMP model is comparable to the accuracy achieved by the use of numerical methods (FDTD, MoM) in case of absence of information about the construction of antenna matching device. The use of SLMP model permitted to obtain the worst-case estimation of PA parameter in all considered cases, of TE and RR parameters – in most of the cases; the degree of IR amplitude overestimation depends on value of G_{HF} (13).

VII. CONCLUSION

The use of computational electromagnetics (e.g., FDTD, MoM) makes it possible to increase the accuracy of estimating the parameters of antenna response to EMP, only if the detailed information about the antenna construction (including the construction of its matching device) is available. It is reasonable to use the SLMP model for development of techniques and tools for protection of radio equipment against EMP influence in case of absence of mentioned information, since, in this case, the SLMP model is comparable to FDTD / MoM by accuracy (see Section VI) but it has much higher computational efficiency, requires the minimal set of initial data, and provides near to worst-case estimations of the response parameters.

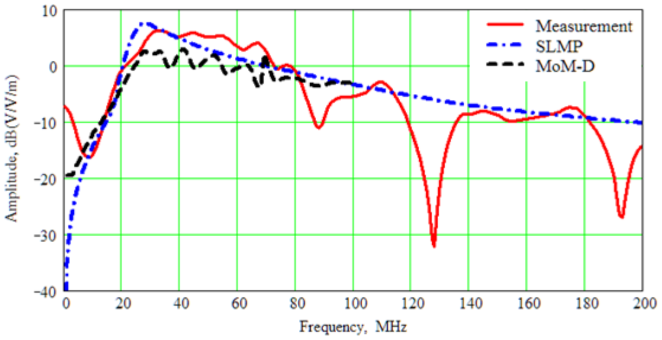

Figure 5. Comparison of AFC obtained by SLMP model for antenna AS-2169 (blue line) with etalon AFC [23] (red line) and with results of calculation by MoM [26] (black line).

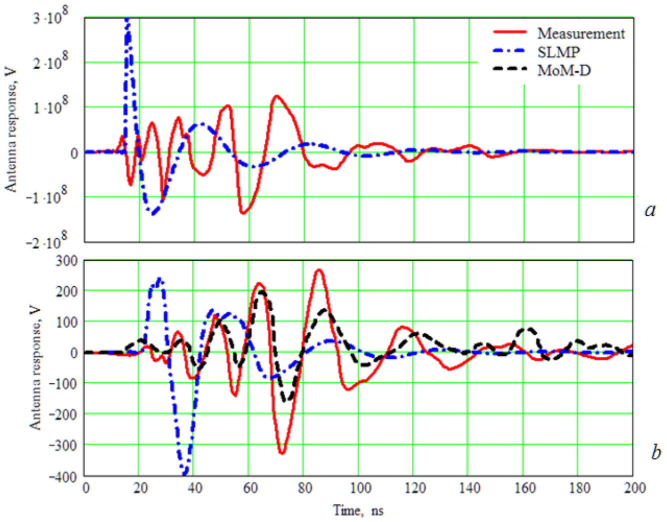

Figure 6. Comparison of antenna AS-2169 responses obtained by SLMP model (blue line) with measured responses [22], [23] (red line) and with results of calculation by MoM [26] (black line): a) response to delta EMP (impulse response); b) response to simulator EMP 2/6 ns.

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