Worst-case model of spurious resonances appearing in radio-frequency cables and degrading electromagnetic compatibility characteristics of wireless equipment at out-of-band frequencies

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***Abstract*—A worst-case model of spurious resonances which can occur in electromagnetic system consisting of an antenna, cable and transmitter output filter (or receiver input filter) is proposed. These resonances may cause significant increase in power of spurious emissions for transmitting equipment and the decrease in out-of-band radiated susceptibility levels for receiving equipment. Three amplitude-frequency characteristics (AFCs) are the initial data for the model synthesis: AFC of the cable attenuation, AFC of the transmitter output port impedance (or AFC of the receiver input port impedance), and AFC of the antenna input impedance. It is assumed in the model that the cable length and phases of the impedances are unknown, therefore, at each frequency, the maximum possible increase in power of spurious emissions or the decrease in radiated susceptibility levels is estimated. Validation of the developed model is performed by numerical computation of an equivalent circuit containing a circuit-level model of the transmitter output filter, two-port network described by scattering matrix of the cable and one-port network characterized by the antenna input impedance. Measured AFC of the input impedance for antenna S65-8262-2, calculated AFC of the attenuation in radio-frequency cable RG58, and parameters of the transmitter output filter (pass band, attenuations in pass band and stop band, shape factor) are used as initial data for the validation. As a result of the numerical modeling, the influence of the cable is estimated: the AFC maximum for ratio of spurious emission power accepted by the antenna to the power of this emission accepted by the 50 ohm load is 7.7 dB; the AFC maximum for ratio of spurious emission powers accepted by the antenna using 2 m cable and without the cable is 29 dB. The validation demonstrates the worst-case behavior of the developed model.**

Keywords—transmitters; receivers; cables; RF interference

I. Introduction

Spectra $P_{TX50}(f)$ of transmitters, susceptibility characteristics $M_{RX50}(f)$ of receivers and realized gains G_R of antennas are usually measured for fixed impedances of a generator and/or a load equal to the cable wave impedance (commonly equal to 50 Ohm) [1, Method 1]. But in an out-of-band frequency range, antenna impedance and impedance of the receiver input port (or transmitter output port) can significantly differ from impedance of the cable. This can lead to considerable resonances and appearance of spurious bandwidths for the electromagnetic system consisting of the antenna, the cable and the transmitter output circuits (or the receiver input circuits) [2], [3].

Influence of the resonances arising between the transmitter and the antenna can be significant [4]: "Unusual or unanticipated impedance conditions can sometimes raise the harmonic levels of a Tx power amplifier by 10 or even 20 dB." Note that this effect is first of all actual when frequencies of the resonances are coinciding with frequencies of the spurious emissions (in case of transmitters) or the spurious responses (in case of receivers).

In [3], measurement results of ratio $P_{TX\,Ant}(f)/P_{TX50}(f)$ (where $P_{TX\,Ant}(f)=P_{TX\,Rad}(f)/\eta$, $P_{TX\,Rad}$ are powers accepted and radiated by the antenna, respectively; η is the antenna efficiency) against length L of the cable connecting the transmitter and the antenna are cited from [5] (unfortunately, we do not have access to the primary paper [5]). $\max_L\left(P_{TX\,Ant}(f)/P_{TX50}(f)\right)$ for the second harmonic is 9 dB.

In [6], measured value of $P_{TX\,Ant}(f)/P_{TX50}(f)$ in case of the antenna matched to the transmitter is 5.6 dB for the second harmonic. In [7], $\max_f\left(P_{TX\,Ant}(f)/P_{TX50}(f)\right)$ is about 10 dB.

In [8], coupling factors between the transmitter and the receiver (through the antennas) are computed with a glance of multiple reflections at the cable terminations due to the mismatches as well as ignoring reflections. At one of the frequencies, calculated coupling factor accounting for multiple reflections turned out to be 25 dB more than the coupling factor ignoring reflections.

In [9], a worst-case ratio $\min_L(P_{TX\,Ant}(f))/\max_L(P_{TX\,Ant}(f))$ is obtained for given VSWRs of the transmitter and the antenna with accounting of cable losses, but other important relations are not considered.

The objective of the paper is to develop a worst-case model intended to estimate influence of the resonances in the

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cable 1) on power increase of the spurious radiations, created by the transmitting equipment containing the transmitter connected to the antenna by the cable; 2) on decrease of the radiated susceptibility characteristic of the receiving equipment containing the receiver connected to the antenna by the cable. The model must account the cable attenuation.

Only part of more general problem of electromagnetic compatibility analysis is considered in the paper. For example, radiation of radiofrequency cable is not considered. But the developed model can be useful for estimation of cable radiation because it makes it makes it possible to estimate amplitude of the signal in the cable at resonance frequencies.

II. Ratio of Spurious Emission Power Accepted by Antenna to Power of This Emission Accepted by 50 ohm Load

To calculate the cable influence on the power of spurious emission accepted by the antenna, one can analyze an equivalent circuit shown in Fig. 1, a. Used symbols: L is the cable length; k is the wave number in the cable; β is the cable attenuation factor; Z_{wave} is the cable characteristic impedance; Z_S, Z_L are the source and the load impedances, respectively; R_{S50}, R_{L50} are reflection factors for the connection of cable to source and to the load, respectively; P_{in} is the source power; $U_{cableIn}$ is the initial complex voltage amplitude of the TEM wave in the cable created by the source; $P_{L\inf}$ is the power accepted by the load; U_0, U_1, U_m are comlpex voltage amplitudes of the TEM waves incident on the load after number of reflections from the source and the load equal to 0, 1, and m, respectively.

The transmitter and the transmitting antenna are treated as the source and the load, respectively.

Z_{wave} is assumed to be equal to 50 Ohms in all considered frequency band. Only the case of low cable attenuation ($k >> \ln(\beta)/L$) is considered.

If a lumped element model replacing the cable and the load is used, then its impedance can be calculated on basis of the transmission line theory [9], [10]. But this approach requires to perform many mathematical manipulations and is not useful for us.

To solve the problem, an analysis of an infinite number of consecutive reflections of a TEM wave propagating in the cable between the source and the load is done.

Expressions for R_{S50}, R_{L50} [11]:

$$R_{S50} = \frac{Z_S - Z_{wave}}{Z_S + Z_{wave}};\ R_{L50} = \frac{Z_L - Z_{wave}}{Z_L + Z_{wave}}. \qquad (1)$$

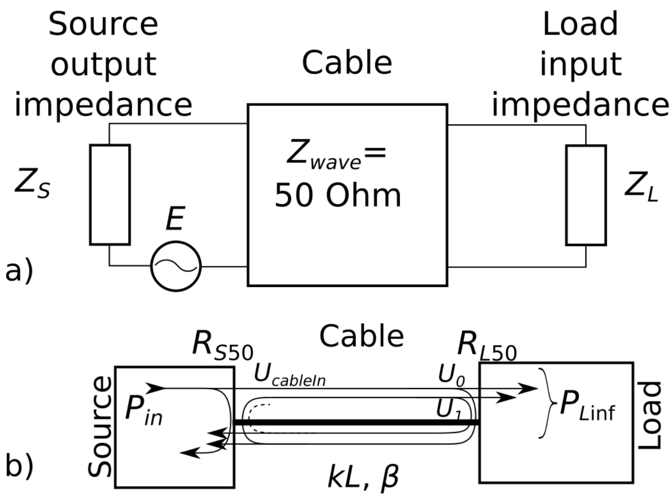

Fig. 1. a) Equivalend circuit of the cable connection between the source and the load; b) Demonstration of multiple reflections of a cable TEM wave from its connection points.

$|R_{S50}|$, $|R_{L50}|$ also can be expressed in terms of respective VSWRs (voltage standing wave ratios).

The power of the electromagnetic wave excited in the cable near to the source: $P_{cableIn} = P_{in}\left(1 - |R_{S50}|^2\right)$, and $|U_{cableIn}|^2 / Z_{wave} = P_{cableIn}$. Les us define a complex voltage amplitude of this wave as $U_{cableIn}$ ($|U_{cableIn}|^2 / Z_{wave} = P_{cableIn}$). Then, for complex voltage amplitude in the cable nearly to the load:

$$\begin{aligned}
&U_0 = U_{cableIn} e^{ikL} \beta^{-1};\\
&U_1 = U_0 e^{i2kL} \beta^{-2} = U_{cableIn} e^{i3kL} \beta^{-3} R_{L50} R_{S50};\\
&U_m = U_{cableIn} e^{i(1+2m)kL} \beta^{-1-2m} (R_{L50} R_{S50})^m,\ m = 0,1..;\\
&U_\Sigma = \sum_{m=0}^{\infty} U_m = U_{cableIn} e^{ikL} \beta^{-1} \sum_{m=0}^{\infty} \left(e^{i2kL} \beta^{-2} R_{L50} R_{S50}\right)^m =\\
&= \frac{U_{cableIn} e^{ikL} \beta^{-1}}{1 - e^{i2kL} \beta^{-2} R_{L50} R_{S50}};
\end{aligned} \qquad (2)$$

since $\left.\sum_{m=0}^{\infty} q^m\right|_{|q|\le 1} = (1-q)^{-1}$ where $q = e^{i2kL} \beta^{-2} R_{L50} R_{S50}$.

Power of the total TEM wave in the cable incident on the load is $|U_\Sigma|^2 / Z_{wave}$. Then, for the power $P_{L\inf}$ in accordance to the energy conservation law:

$$
\begin{aligned}
&P_{L\inf} = \left|U_{\Sigma}\right|^2 / Z_{wave}(1-\left|R_{L50}\right|^2) = \\
&= \left|U_{cableIn}\right|^2 / Z_{wave}(1-\left|R_{L50}\right|^2)\frac{\beta^{-2}}{\left|1-e^{i2kL}\beta^{-2}R_{S50}R_{L50}\right|^2} = \\
&= P_{in}(1-\left|R_{S50}\right|^2)(1-\left|R_{L50}\right|^2)\frac{\beta^{-2}}{\left|1-e^{i2kL}\beta^{-2}R_{S50}R_{L50}\right|^2} = \\
&= P_{in}(1-\left|R_{S50}\right|^2)(1-\left|R_{L50}\right|^2)\frac{\beta^{-2}}{\left|1-e^{i\arg(R_{Total})}\left|R_{Total}\right|\right|^2}, \\
&\arg(R_{Total}) = 2kL + \arg(R_{S50}) + \arg(R_{L50}), \\
&\left|R_{Total}\right| = \left|\beta^{-2}R_{S50}R_{L50}\right|,
\end{aligned}
\tag{3}
$$

where $\arg(R_{Total})$ and $\left|R_{Total}\right|$ are phase and amplitude of the loop-transmission coefficient (system represented in Fig. 1, b can be considered as a passive feedback system).

Let us consider the transmitter connected to the transmitting antenna as the source and the load, respectively. In this case $P_{cableIn} = P_{TX50}$, $R_{L50} = R_{Ant50}$, where R_{Ant50} is the antenna reflection coefficient. Then:

$$
\frac{P_{L\inf}}{P_{TX50}} = K = \frac{\left(1-\left|R_{Ant50}\right|^2\right)\beta^{-2}}{\left|1-e^{i\arg(R_{Total})}\left|R_{Total}\right|\right|^2}; \tag{4}
$$

Analogous results are presented in [6] but without accounting of the cable attenuation.

III. Ratio of Radiated Fields (or Radiated Susceptibilities) Obtained by Accounting for Single and Multiple Reflections in Cable

If the transmitter and the transmitting antenna are treated as the source and the load in Fig. 1 and in (2)-(3), then the power flux densities at given observation point placed in far-field zone of the transmitting antenna accounting for single ($I_{cable50}$) and multiple ($I_{\inf}$) reflections from the cable terminations are as follows [12]:

$$
\begin{aligned}
&I_{\inf} = P_{L\inf}GF^2(\theta_0,\varphi_0)\left|\xi\right|^2 / 4\pi r, \\
&I_{cable50} = P_{TX50}G_{\text{cable50}}G_R F^2(\theta_0,\varphi_0)\left|\xi\right|^2 / 4\pi r,
\end{aligned}
\tag{5}
$$

where G is the antenna gain; $G_R = G(1-\left|R_{Ant50}\right|^2)$ is the realized antenna gain; $G_{\text{cable50}} = \beta^{-2}$; $\left|\xi\right|^2$ is the polarization loss factor, $F(\theta_0,\varphi_0)$ is the antenna pattern; θ_0, φ_0, r are coordinates of the observation point in the spherical coordinate system associated with the antenna.

Then, accounting (4)

$$
\begin{aligned}
&K_{field} = \frac{I_{\inf}}{I_{cable50}} = K\frac{G}{G_{\text{cable50}}G(1-\left|R_{Ant50}\right|^2)} = \\
&= \frac{1}{\left|1-e^{i\arg(R_{Total})}\left|R_{Total}\right|\right|^2}.
\end{aligned}
\tag{6}
$$

To analyze the cable length influence on the susceptibility of the wireless equipment, the receiving antenna and the receiver can be treated in Fig. 1 and in (2)-(3) as the source and the load, respectively. Then, recalculation of radiated susceptibility levels $M_{field\inf}$, $M_{field50}$ of the receiving equipment (receiver and the antenna connected to it) accounting multiple ($M_{field\inf}$) and single ($M_{field50}$) reflections from the cable terminations [12] should give the same susceptibility characteristic M_{RX50} equal to $\left|U_{\Sigma}\right|^2 / Z_{wave}$ (ref Section II, (2) and (3)):

$$
\begin{aligned}
&P_{in} = M_{field\inf}\frac{\lambda^2 G}{4\pi}F^2(\theta_0,\varphi_0)\left|\xi\right|^2; \\
&P_{in}\left(1-\left|R_{S50}\right|^2\right)\frac{\beta^{-2}}{\left|1-e^{i\arg(R_{Total})}\left|R_{Total}\right|\right|^2} = \\
&= M_{RX50}; \\
&M_{field50}\frac{\lambda^2 G_R}{4\pi}F^2(\theta_0,\varphi_0)\left|\xi\right|^2 G_{\text{cable50}} = M_{RX50};
\end{aligned}
$$

$$
\begin{aligned}
&\frac{M_{field50}}{M_{field\inf}} = \frac{G}{G_R G_{\text{cable50}}}(1-\left|R_{S50}\right|^2)\frac{\beta^{-2}}{\left|1-e^{i\arg(R_{Total})}\left|R_{Total}\right|\right|^2} = \\
&= \frac{1}{\left|1-e^{i\arg(R_{Total})}\left|R_{Total}\right|\right|^2} = K_{field}.
\end{aligned}
\tag{7}
$$

Therefore, K_{field} characterizes the cable influence in case of the antenna and the transmitter as well as the antenna and the receiver.

Dependence of K_{field} on the cable length for various phases of the reflection factors is shown in Fig. 2.

IV. Worst-Case Estimation of Cable Influence

According to (3), (4) and (7), for given β, $\left|R_{Ant50}\right|$ and $\left|R_{Total}\right|$, values of $P_{L\inf}$, K and K_{field} will be maximum if value of $\arg(R_{Total})$ will be the most closely to 0. The uncertainty of $\arg(R_{Total})$ depend on the uncertainties of kL and phases of the reflection factors (these quantities may be changed due to replacement of the equipment, especially change of the cable length). If nothing is known about $\arg(R_{Total})$, then it is necessary to consider a worst case for the transmitting as well as for the receiving equipment: $\arg(R_{Total}) = 0$. Then

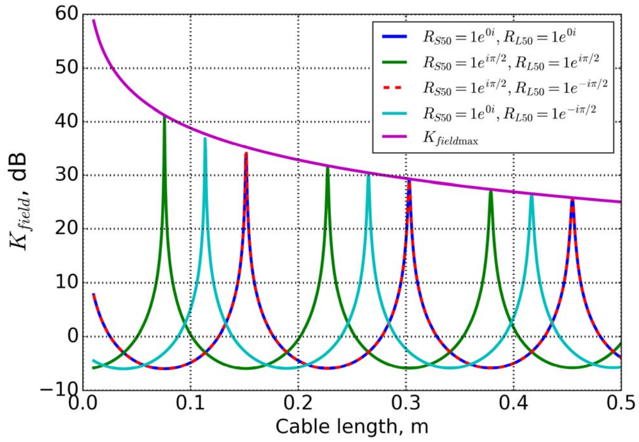

Fig. 2. Ratio of the radiated fields accounting for single and multiple reflections versus the cable length in cases of various phases of the reflection factors. The per-unit attenuation of the cable is 0.5 dB/m, permittivity of the cable dielectric is 2, f=700 MHz.

$$K_{\max} = K\big|_{PI=0} = \frac{\left(1-\left|R_{Ant50}\right|^2\right)\beta^{-2}}{\left(1-\left|R_{Total}\right|\right)^2} = \frac{\left(1-\left|R_{Ant50}\right|^2\right)\beta^{-2}}{\left(1-\left|R_{Ant50}\right|\left|R_{TX50}\right|\beta^{-2}\right)^2}, \quad (8)$$

$$K_{\max} \approx K_{\max\,appr} = \frac{\left(1-\left|R_{Ant50}\right|^2\right)}{\left(1-\left|R_{Ant50}\right|\left|R_{TX50}\right|\beta^{-2}\right)^2}; \quad (9)$$

$$K_{field\,\max} = K_{field}\big|_{PI=0} = \frac{1}{\left(1-\left|R_{Total}\right|\right)^2}. \quad (10)$$

$K_{\max\,appr}$ dependence on $\left|R_{TX50}\right|\beta^{-2}$ and $\left|R_{Ant50}\right|$ is shown in Fig. 3. $K_{\max\,appr}$ is introduced only for purpose to represent graphically behavior of $K_{\max}$.

Note that it is assumed in (8)-(10) that $\beta = const$. Usually the cable per-unit length attenuation $\beta_{dB/L} = 20\log(\beta)/L$ is constant, and β is changed with the change of L. But $\beta = const$ can be assumed to be true for small changes of L (β^{-2} expressed in decibels decreases by 20% in case of L increase by 10%).

V. Ratio of Maximum to Minimum Radiated Fields (Levels of Radiated Susceptibility)

Another important parameter in case of the transmitter and the antenna connected to it is a ratio of the maximum to the minimum field spectra $I_{\inf\max}/I_{\inf\min}$. This ratio is equal to the ratio of the maximum power accepted by the transmitting antenna to the minimum power $P_{L\inf\max}/P_{L\inf\min}$. Also, according to (7), $I_{\inf\max}/I_{\inf\min}$ is equal to the ratio of the minimum radiated susceptibility level to the maximum $M_{field\inf\min}/M_{field\inf\max}$ in case of the antenna and the receiver connected to it. According to the Section IV, $I_{\inf}$ is maximum when $\arg(R_{Total})=0$ (see (3)). $I_{\inf}$ is minimum when $\arg(R_{Total})=\pi$:

$$I_{\inf\max}/I_{\inf\min} = P_{L\inf\max}/P_{L\inf\min} = K_{\max/\min} = M_{field\inf\min}/M_{field\inf\max} = \frac{\left|1+\left|R_{Total}\right|\right|^2}{\left|1-\left|R_{Total}\right|\right|^2}; \quad (11)$$

Analogous expression for $P_{L\inf\max}/P_{L\inf\min}$ (i.e., in case of the transmitter and antenna connected to is) is derived in [9]. Equation (11) is presented in Fig. 4.

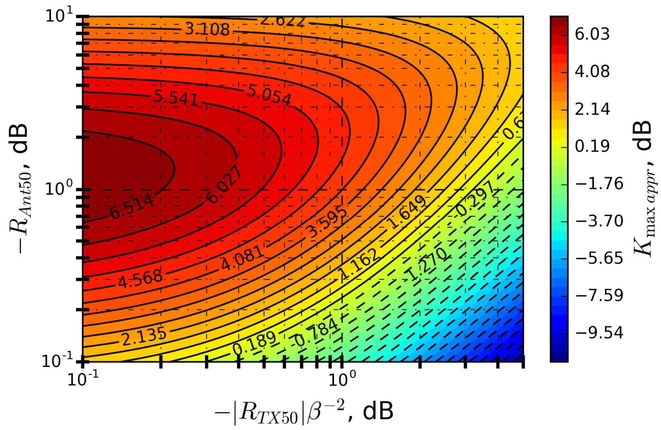

Fig. 3. The approximate expression (9) for maximum ratio of spurious emission power accepted by the antenna to spurious emission power accepted by 50 ohm load versus the reflection factor of the antenna and product of square of the cable attenuation and the reflection factor of the transmitter.

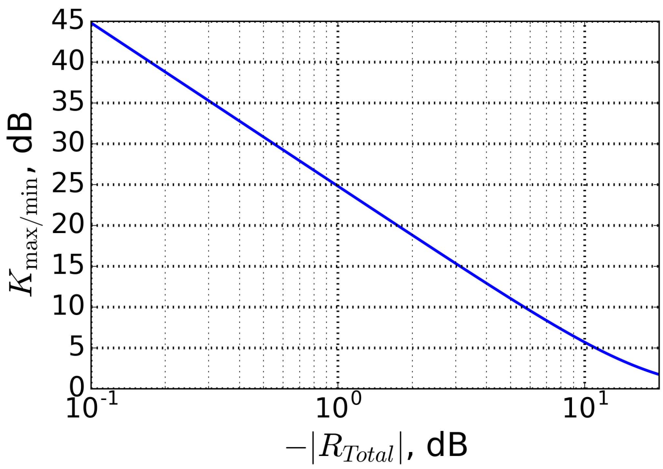

Fig. 4. Ratio of maximum to minimum radiated fields (levels of radiated susceptibility) versus absolute value of the loop-transmission coefficient.

The parameter $K_{\max/\min}$ is actual when measurement results are presented for one equipment configuration, and it is necessary to estimate how they can change due to replacement of the equipment, especially due to change of the cable length. As it follows from Fig. 2, small values of $K_{\max/\min}$ are more probable than big ones.

Output circuits of the transmitters and input circuits of the receivers are usually filters, but this is not a rule. For example, an attenuator is connected to the input of the receiver AR5000 for some ranges [13].

Let's give some data to estimate reflection factors of antennas and receivers/transmitters. Worst-case behavior of the model developed in [14] is related to determining minimum falloff rate of $1-\left|R_{Ant50}\right|^2$ (difference between the gain and the realized gain of the antenna) at low out-of-band frequencies, which is equal to 40 dB per decade (this is not correspond to the worst case estimation of the antenna reflection coefficient for problem considered in this paper). In [15], the falloff rate of the monopole realized gain is 55 dB per decade at low out-of-band frequencies. Reflection factors of the receiver in high frequency band measured in [6] are: 0.85 (-1.41 dB) for second harmonic and 0.90 (-0.92 dB) for third and fourth harmonics.

VI. Validation of Developed Model

Validation of the developed model is performed in two ways.

In the first way, validation is performed by numerical calculation of currents and voltages in the equivalent circuit (see Fig. 1) using scattering matrix of the radiofrequency cable and circuit diagram of the transmitter output filter. Initial data for the validation: measured AFC of the input impedance for antenna S65-8262-2 [16], calculated AFC of the attenuation in radio-frequency cable RG58, and parameters of the transmitter output filter (the pass band corresponds to the working frequency band of the S65-8262-2 antenna and is equal to 116-156 MHz, the pass band attenuation is 3 dB, the stop band attenuation is 35 dB and approximately corresponds to the same parameter of the AR300 receiver [17], shape factor is 2) are used as initial data for the validation. Circuit diagram (Fig. 5) of the filter is automatically generated by its parameters. It is assumed during the modeling that output inductance L6 has Q=100.

Used parameters of the coaxial cable (RG58): conductance of the braid and inner conductor is 56 MS (copper); permittivity is 2.3; dielectric loss tangent is $2\cdot10^{-4}$. Values of L used for the modeling are 2 m and 5 m. Obtained cable attenuation for L=2 m is 0.1..0.3 dB in range f=20..200 MHz.

$P_{L\inf}$ in given case is equal to power $P_{TX\,Ant}$ of spurious emissions accepted by the antenna (see (3)). As it follows from Figs. 6 and 7, the worst-case models (8) and (11) are properly estimate peaks values arising due to the resonances in the cable. $\max\limits_f\left(P_{TX\,Ant}(f)/P_{TX50}(f)\right)$ is 7.7 dB for L=2 m (Fig. 6). $\max\limits_f\left(P_{TX\,Ant}(f)\big|_{L=2\,м}/P_{L\inf}(f)\big|_{L=0\,м}\right)$ is 29 dB (Fig. 7).

Results from [18] are used for the validation in the second way. In this paper, influence of the cable connecting a frequency converter and an AC motor on common-mode currents through the motor is considered. The model (11) can be applied to this case if the converter and the motor will be treated as the transmitter and transmitting antenna, respectively. Measured value of $\max\limits_f\left(P_{TX\,Ant}(f)\big|_{L=L1}\Big/P_{TX\,Ant}(f)\big|_{L=L2}\right)$ is 15 dB, where $L1$=100 m and $L2$=0.2 m are two different cable lengths.

Absolute value of reflection factor of the motor in case of common-mode current is calculated and presented in [18]. Using this result, assuming that the cable attenuation is 0.98 dB/100 m at frequency 1 MHz (corresponds to RG58/U [19]) and assuming that reflection factor of the converter R_{S50} is equal to 1 (the worst case), the developed model (11) gives results shown in Fig. 8. The model satisfactorily estimates the maximum values of the theoretical curve, but gives significant overestimation for the measured curve. Most probably, this is due to inconsistent assumption about closeness of the converter reflection factor to 1.

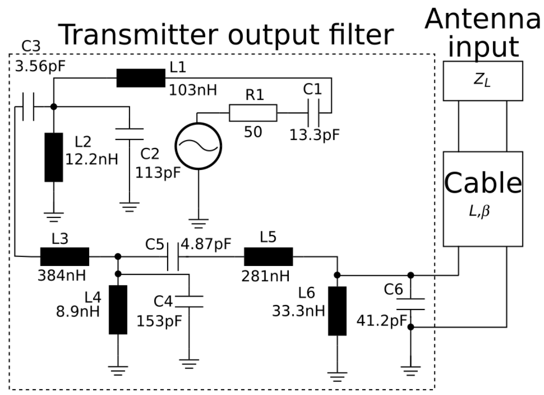

Fig. 5. Equivalent circuit used to validate the developed model (including the transmitter output filter).

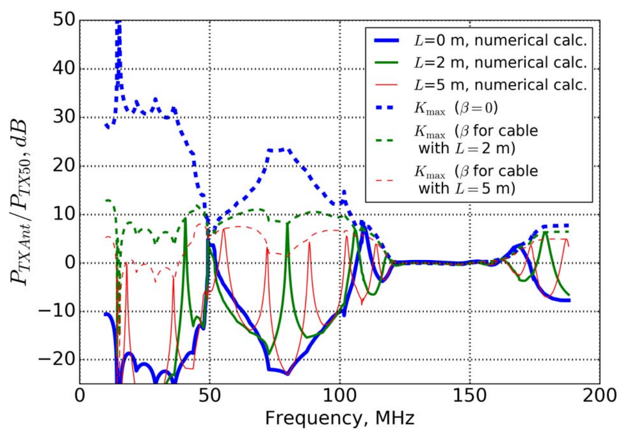

Fig. 6. Amplitude-frequency characteristic of ratio of spurious emission power accepted by the antenna to spurious emission power accepted by 50 ohm for the circuit shown in Fig. 5.

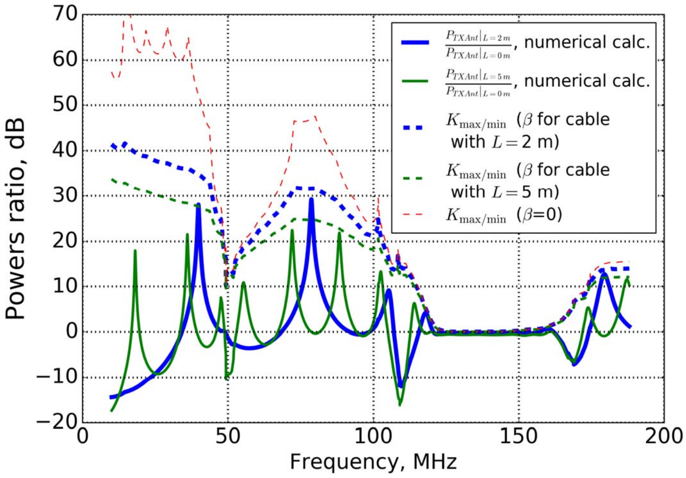

Fig. 7. Amplitude-frequency characteristic for ratio of powers accepted by the antenna in case of the cable replacement (i.e., for the cables of different lengths) for the circuit shown in Fig. 5.

VII. CONCLUSION

Analysis of processes in the cables (connecting antennas with transmitters and receivers) is performed taking into account the cable attenuation. The worst-case model is developed on basis of this analysis. The model describes possible influence of the cable on degrading of such EMC properties of the wireless equipment as spectrum of the spurious emissions and the radiated susceptibility characteristic. The numerical modeling demonstrates validity of the model and shows the increase of spurious emission after replacement of the cable equal to 29 dB at one of the frequencies.

Importance of accounting for the cable attenuation to estimate the influence of the cable resonances follows from (3) and Fig. 4. If the cable attenuation is equal to 3 dB, then absolute value of the loop-transmission coefficient is -6 dB, and the maximum increase of the spurious emission power (decrease of the radiated susceptibility) due to replacement of the equipment is only 10 dB even in the worst case of ideal reflections from the antenna and the transmitter (receiver).

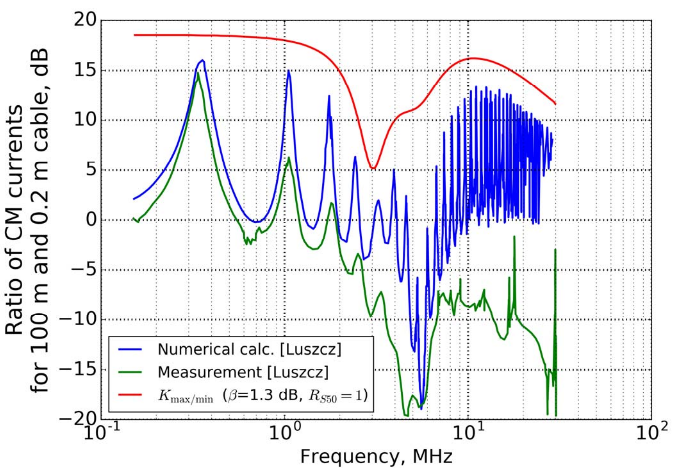

Fig. 8. Influence of the feeding cable on common-mode currents of the motor [18].

The developed worst-case model can be applied for diagnostics (express analysis) of EMC between on-board radio-electronic equipment of big systems [20].

Further plans include experimental demonstration of importance to account for the cable resonances in case of the receiving equipment.

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