

An Analytical Model to Evaluate the Radiated Power Spectrum of a Multipactor Discharge in a Parallel-Plate Region

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Abstract—This paper is aimed at studying the electromagnetic radiation pattern of a multipactor discharge occurring in a parallel-plate waveguide. The proposed method is based on the Fourier expansion of the multipactor current in terms of time-harmonic currents radiating in the parallel-plate region. Classical radiation theory combined with the frequency domain Green's function of the problem allows the calculation of both the electric and the magnetic radiated fields. A novel analytical formula for the total radiated power of each multipactor harmonic has been derived. This formula is suitable for predicting multipactor with the third-harmonic technique. The proposed formulation has been successfully tested with a particle-in-cell code.

Index Terms—Microwave discharges, multipactor effect, parallel-plate waveguide, radiated power, third-harmonic detection technique.

I. INTRODUCTION

THE MULTIPACTOR effect is a phenomenon of RF breakdown occurring in microwave components for space telecommunications subsystems [1] and accelerator structures [2] working under high-power conditions, which represents a possible failure mechanism. Multipactor dissipates power, loads cavities, degrades components, increases system noise level, and generates undesirable harmonics [3], [4]. As it is well known, multipactor occurs when a harmonic electric field exists in a parallel-plate region, which accelerates the electrons from one surface to the other. After impact, more electrons are released: If certain resonant conditions are satisfied, and the secondary-electron-yield coefficient is higher than unity, an electron avalanche is generated. Classical multipactor theory derives analytical expressions for such resonant conditions of the electron phases and voltages in which steady-state multipactor may exist [5]–[7]. In addition, multipactor has been

recently studied in more complex structures, such as the rectangular waveguide [8].

The main effort of previous works has been focused on the prediction of the multipactor threshold voltage, the study of the higher order resonant modes, the analysis of steady-state trajectories, and the study of multipaction detection methods. Also, different technical aspects, as the modeling of dielectric windows used in high-power RF systems, have been investigated [9]. However, the problem of the radiated power by a multipactor discharge has not been studied in detail. Such problem is very important from a practical point of view, because the noise created by a discharge is a method typically used to experimentally detect the phenomenon (third-harmonic detection technique) [4], [10], [11]. From a qualitative point of view, the total radiated power of an electron can be estimated by means of the Larmor formula, which states that such power is proportional to the square of the electron acceleration [4]. Larmor formula evaluates the total radiated power by an electron moving in free space, not considering the effect of the realistic parallel-plate scenario. Our main goal has been to calculate the total radiated power by a discharge in the context of the parallel-plates classical multipactor theory.

In this paper, we present a simple and novel model to evaluate the electric and magnetic radiated fields as well as the radiated power by a multipactor discharge excited in a parallel-plate region driven by an RF electric field. In this first approach to the problem, the discharge is modeled as a uniform electric current radiating inside an infinite parallel-plate waveguide region. The electromagnetic field radiated by the multipactor current has been evaluated using the frequency domain Green's function of the problem, which allows the direct calculation of the complex Poynting's vector of the radiated fields for each harmonic. Next, the total radiated power is expressed in terms of the most relevant parameters of the problem. Finally, comparisons with numerical results using a particle-in-cell (PIC) code validates this novel formulation.

II. THEORY

A. Time-Harmonic Representation of the Multipactor Current

For simplicity, we shall use a 1-D model where multipactor occurs inside a parallel-plate region of width d driven by the RF voltage $V(t) = V_{\text{RF}} \cos(\omega t)$, where V_{RF} is the voltage amplitude, $f = \omega/(2\pi)$ is the RF frequency, and t is the time;

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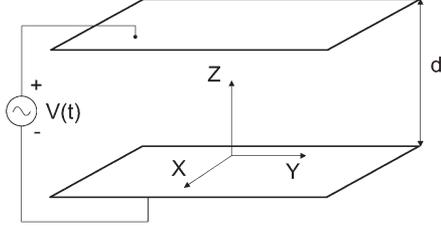


Fig. 1. Parallel-plate waveguide region driven by an RF voltage $V(t)$.

the period of this signal is $T = 1/f$, and the direction of motion is z (see Fig. 1). The discharge is described using an effective electron model which operates in perfect multipactor resonant conditions: An electron launched from one plate is accelerated by a uniform electric field $\vec{E} = (V/d)\hat{z}$ impacting to other plate in a transit time which is N half RF periods (N is odd). We have considered that the initial velocity is constant in all launches, as stated in Sombrin's [12] model. Assuming that the electron is emitted at time $t_\alpha = \alpha/\omega$, the equation of motion (directly derived from the Lorentz force) can be analytically integrated by just obtaining both electron velocity $v_e(t)$ and electron position $z_e(t)$ as a function of time; obviously, $v_e = (dz_e/dt)$. Thus, by considering that the electron is launched from the plate situated in $z = 0$, with initial velocity $v_e(t_\alpha) = v_{e0}$, and operating under multipactor order $N = 1, 3, 5, \dots$, the electron velocity can be expressed as follows:

$$v_e(t) = \begin{cases} v_{e0} + G(\sin(\alpha) - \sin(\omega t)) & t \in \left[t_\alpha, t_\alpha + \frac{NT}{2} \right] \\ -v_{e0} - G(\sin(\alpha) + \sin(\omega t)) & t \in \left[t_\alpha + \frac{NT}{2}, t_\alpha + NT \right] \end{cases} \quad (1)$$

where $G = (eV_{\text{RF}})/(m_e\omega d)$, being m_e and $-e$ the electron mass and charge, respectively. Note that the electron velocity is a periodic function of period NT . In this context, the multipactor RF breakdown voltage can be simply calculated as described in [6], resulting

$$V_{\text{RF}} = \frac{m_e}{e} \frac{\omega d(\omega d - N\pi v_{e0})}{N\pi \sin(\alpha) - 2\cos(\alpha)}. \quad (2)$$

The multipactor current created by the effective electron J_z can be expressed as a single current density which is function of the position z and time t

$$J_z(z, t) = -ev_e\delta(z - z_e(t))$$

where δ is the Dirac Delta function, v_e is the electron velocity given in (1), and $z_e(t)$ is the electron position. For far-field observation points, we might consider that such multipactor electric current is homogeneously distributed throughout the gap. Thus, we define an equivalent multipactor thin wire current $I(t)$ as the spatial average of the current

$$I(t) \equiv \langle J_z(z, t) \rangle = \frac{1}{d} \int_0^d -e v_e \delta(z - z_e(t)) dz = \frac{-e}{d} v_e(t). \quad (3)$$

In order to study its power radiation pattern, we consider that this current radiates in the parallel-plate region. Note that, although $v_e(t)$ in (3) is not a harmonic function, $I(t)$ is a periodic function of period NT , so we can expand it in terms of an infinite Fourier series

$$I(t) = \frac{-e}{d} \sum_{m=1}^{+\infty} c_m \cos\left(m\frac{\omega}{N}t + \psi_m\right). \quad (4)$$

The Fourier coefficients c_m and ψ_m have been analytically calculated as $c_m = \sqrt{a_m^2 + b_m^2}$ and $\psi_m = -\arctan(b_m/a_m)$, where

$$a_m = \frac{-2(1 - (-1)^m)(v_{e0} + G\sin\alpha)\sin(m\alpha/N)}{m\pi}$$

$$b_m = -G\delta_{m,N} + \frac{2(1 - (-1)^m)(v_{e0} + G\sin\alpha)\cos(m\alpha/N)}{m\pi}$$

$$m = 1, 3, 5, \dots$$

where $\delta_{m,N}$ is the Kronecker Delta function; note that for even values of m both coefficients a_m and b_m are equal to zero. Following the standard complex notation for harmonic fields, we define the complex currents i_m as

$$i_m \equiv \frac{-e}{d} c_m e^{j\psi_m}, \quad m = 1, 3, 5, \dots \quad (5)$$

corresponding to the m th Fourier harmonic of frequency $f_m = m(f/N)$; thus, the instantaneous value of the equivalent multipactor current can be expressed as the real part of these complex forms

$$I(t) = \Re\left(\sum_{m=1}^{+\infty} i_m e^{jm\frac{\omega}{N}t}\right).$$

At this point of the formulation, we can use the classical radiation theory to study the power radiated by the time-harmonic multipactor currents i_m in the parallel-plate region.

B. Radiation of the Time-Harmonic Multipactor Currents in the Parallel-Plate Waveguide

We need to calculate the electromagnetic fields radiated by a uniform time-harmonic current of length d and frequency f_m placed in a parallel-plate region, as shown in Fig. 1; cylindrical coordinates will be used along this paper. In order to proceed, we will use the scalar and vectorial potentials formulation for time-harmonic fields in free-space, which is based on the calculation of both the electric scalar (ϕ) and the magnetic vector potentials (\vec{A}), satisfying the Lorentz gauge [13]. For the case of a current i_m oriented in the z axis, the vector potential will have only nonzero z component, denoted as A_{z_m} , which satisfies the Helmholtz differential equation

$$\nabla^2 A_{z_m} + k_m^2 A_{z_m} = -\mu_0 i_m$$

where $k_m = m(k/N)$ is the wavenumber of the m th Fourier harmonic, being $k = \omega/c$ the free-space wavenumber; note that c is the speed of light in vacuum, and the form $e^{jm(\omega/N)t}$

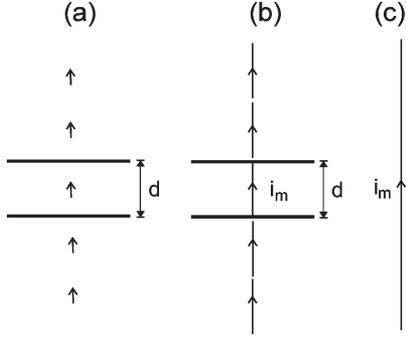


Fig. 2. Description of the multipactor current. (a) Infinite reflections of a point current between two parallel plates. (b) Uniform multipactor current is infinitely reflected in the parallel-plate region. (c) Multipactor current in the parallel-plate region is equivalent to an infinite wire uniform current.

has been omitted in the formulation. The solution of such equation can be expressed in integral form as a function of the z component of the vector potential Green's function $g_z(\vec{r}, \vec{r}')$

$$A_{z_m}(\vec{r}) = \mu_0 \int_0^d g_z(\vec{r}, \vec{r}') i_m dz' \quad (6)$$

with $\vec{r}' = z'\hat{z}$. The Green's function satisfies the scalar Helmholtz equation

$$\nabla^2 g_z(\vec{r}, \vec{r}') + k^2 g_z(\vec{r}, \vec{r}') = -\delta(\vec{r} - \vec{r}')$$

with the Neumann boundary condition.

The next step in the formulation is to obtain such a Green's function in a closed form for an easy integration of (6). The response of a z -directed infinitesimal current located at the source point $\vec{r}' = z'\hat{z}$ can be obtained using the classical theory of images [13]: The point current is successively reflected as an infinite images series in both metallic plates, as shown in Fig. 2(a). In this particular case, the multipactor current i_m is spatially uniform, which makes possible to directly transform the wire current, infinitely reflected in both plates, into an infinite uniform current radiating in free space, as shown in Fig. 2(b). As a consequence, the finite current of length d , radiating between the two conducting parallel plates, might be replaced by an infinite wire carrying the constant current i_m radiating in free space, as shown in Fig. 2(c). At this point, the well-known free space 3-D Green's function of the scalar Helmholtz equation $g_0(\vec{r}, \vec{r}')$ can be applied

$$g_0(\vec{r}, \vec{r}') = \frac{e^{-jkR}}{4\pi R} \quad (7)$$

being R the magnitude of the vector \vec{R} ($R \equiv \|\vec{R}\|$), which is defined as $\vec{R} \equiv \vec{r} - \vec{r}'$.

We now turn to proceed with the integration of (6), which is reduced to

$$A_{z_m}(\vec{r}) = \mu_0 i_m \int_{-\infty}^{+\infty} g_0(\vec{r}, \vec{r}') dz' \quad (8)$$

where the field and source points are $\vec{r} = r\hat{r} + z\hat{z}$ and $\vec{r}' = z'\hat{z}$, respectively. By substituting (7) in this integral, we obtain

$$\begin{aligned} A_{z_m}(\vec{r}) &= \frac{\mu_0}{4\pi} i_m \int_{-\infty}^{+\infty} \frac{\exp\left(-jk_m \sqrt{r^2 + (z - z')^2}\right)}{\sqrt{r^2 + (z - z')^2}} dz' \\ &= \frac{\mu_0}{4\pi} i_m (-j)\pi H_0^{(2)}(k_m r) \\ &= \mu_0 i_m \left(\frac{H_0^{(2)}(k_m r)}{4j} \right) \end{aligned} \quad (9)$$

where $H_0^{(2)}$ is the zeroth-order Hankel function of the second kind. Note that the term between brackets is typically referred as the free-space 2-D Green's function, remarking that our original 3-D problem has been converted into a 2-D one. In fact, the dependence with the z -coordinate has consequently disappeared. Then, the Lorentz gauge dictates that the electric scalar potential ϕ_m vanishes

$$\phi_m = j \frac{c}{k_m} \nabla \cdot (A_{z_m} \hat{z}) = j \frac{c}{k_m} \frac{\partial A_{z_m}}{\partial z} = 0. \quad (10)$$

The far-fields radiated by the multipactor current can now be easily evaluated utilizing the asymptotic expansion of $H_0^{(2)}$ for large arguments

$$H_0^{(2)}(x) \approx \sqrt{\frac{2}{\pi x}} e^{-j(x - \pi/4)}$$

just obtaining

$$\begin{aligned} \vec{E}_m &= -jk_m c A_{z_m} \hat{z} \approx -\eta i_m \sqrt{\frac{k_m}{8\pi r}} e^{-j(k_m r - \pi/4)} \hat{z} \\ \vec{H}_m &= \frac{1}{\mu_0} \nabla \times (A_{z_m} \hat{z}) \approx i_m \sqrt{\frac{k_m}{8\pi r}} e^{-j(k_m r - \pi/4)} \hat{\varphi}. \end{aligned}$$

Note that higher order terms of $r^{-1/2}$ have been neglected; η is the intrinsic impedance of the vacuum, $\eta = \sqrt{\mu_0/\epsilon_0}$. To get a suitable expression for the power radiated by the multipactor current in the parallel-plate region, we calculate the complex Poynting's vector of each Fourier harmonic

$$\vec{N}_m \equiv \frac{1}{2} \vec{E}_m \times \vec{H}_m^* = \eta |i_m|^2 \frac{k_m}{16\pi r} \hat{r}$$

where $*$ indicates complex conjugate. We remark that this vector only has radial component, which implies a net flow of energy in the radial direction. The final objective of this paper is to find such energy. The integration of the real part of the Poynting's vector in a cylinder of radius r and height d centered in the z axis, allows to get a simple formula for the total power radiated by the m th multipactor current, thus obtaining

$$P_m = \frac{\pi}{4} \mu_0 m \frac{f}{N} d |i_m|^2, \quad m = 1, 3, 5, \dots \quad (11)$$

Inserting (5) into (11) and using the value of the multipactor RF breakdown voltage (2), we have found, after simple algebraic

manipulations, the following formula:

$$P_m = \frac{\omega\mu_0 m e^2}{8Nd} \left[\delta_{m,N} \left(G^2 - \frac{8UQ(-2+WS)}{m\pi} \right) + \left(\frac{4U}{m\pi} \right)^2 \right] \quad (12)$$

where the terms Q , S , T , and U have been defined as follows:

$$Q \equiv \frac{\omega d - N\pi v_{e0}}{4 + N^2\pi^2}$$

$$S \equiv \sqrt{\frac{e^2 V_{RF}^2 (4 + N^2\pi^2)}{(\omega d - N\pi v_{e0})^2} - (m_e \omega d)^2}$$

$$T \equiv N\pi + \frac{2S}{\omega d m_e}$$

$$U \equiv v_{e0} + QT$$

$$W \equiv \frac{N\pi}{\omega d m_e}.$$

At this point, it is important to understand that (12) gives the power spectrum for a single electron, according to the proposed theory. However, since the multipactor current is directly proportional to the number of electrons involved in the multipactor discharge (5), the power emitted by n_e electrons in resonance would be simply given by $n_e^2 P_m$, thus being (12) universal and valid for any electron density. On the other hand, we want to emphasize that the radiated power by multipactor occurs at odd multiples of f/N , which means that harmonics will be generated at lower frequencies than the RF signal frequency f for multipactor orders $N > 1$. Moreover, the first term of (12), which is multiplied by $\delta_{m,N}$, will be different from zero when $m = N$, i.e., for the harmonic located at the RF frequency. For the rest of the harmonics, the formula predicts a decreasing power level with harmonic order following a $1/m$ behavior. Another interesting result is that (12) breaks up the traditional dependence of all multipactor parameters related with the prediction of the RF threshold voltage on the ωd product [5], [6]. In fact, the power level depends on ω/d for all the harmonics, if working with a fixed ωd . This implies, for instance, that the predicted harmonic levels for real low band waveguides (low frequency, large gap) would be lower than for high band ones, even if working with the same ωd . In addition, multipactor in typical large gap structures, such as bandpass filters, would considerably generate lower harmonics than other structures with shorter gaps, such as transformers or low-pass filters. Such implications should be also considered when measuring multipactor in real devices.

III. RESULTS

First, we present results for the convergence of the time-harmonic representation of the multipactor current. In Fig. 3, such a current is plotted as a function of the normalized time t/T ; these numerical results have been computed with both the exact (3) and the Fourier series (4) for multipactor order $N = 3$. Different number of odd terms have been considered in the summation, demonstrating that we need at least 200 odd harmonics to reach the convergence region. The data employed for

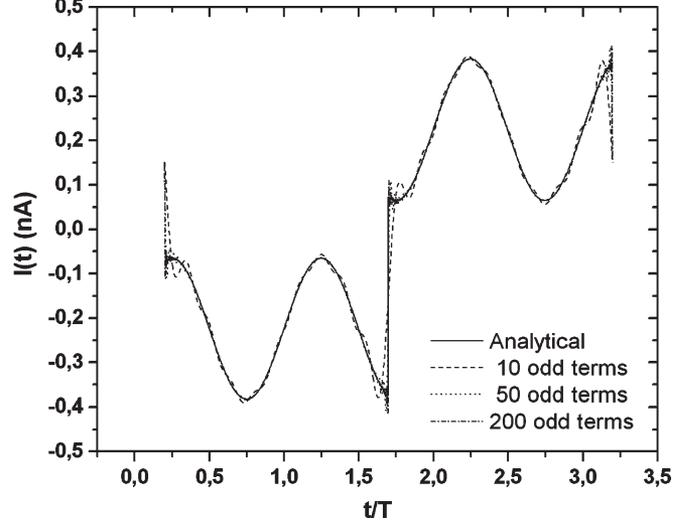


Fig. 3. Multipactor current as a function of the normalized time t/T for order $N = 3$. Comparison between the analytical expression (3) and the Fourier expansions evaluated with different number of odd terms (4).

these simulations in order to get perfect resonance conditions are the following: $f = 2$ GHz, $d = 2.5$ mm, $v_{e0} = 3.68$ eV, $V_{RF} = 442.9$ V, $\alpha = 72^\circ$.

In Fig. 4, the total radiated power of a multipactor current obtained with (12) is successfully compared to simulations performed with an electromagnetic PIC code based on a finite-difference in time-domain solver [14]. In order to check the presented algorithm, four cases have been analyzed for multipactor orders $N = 1, 3, 5, 11$. In the four cases, the RF frequency was $f = 1$ GHz, and the initial speed is $v_{e0} = 3.68$ eV. Other relevant parameters in the simulations are the following: For $N = 1$, we used $d = 1$ mm, $\alpha = 92.49^\circ$, $V_{RF} = 30$ V; for $N = 3$, we used $d = 5$ mm, $\alpha = 101.96^\circ$, $V_{RF} = 383.64$ V; for $N = 5$, we used $d = 7$ mm, $\alpha = 97.15^\circ$, $V_{RF} = 412.34$ V; for $N = 11$, we used $d = 15.65$ mm, $\alpha = 93.30^\circ$, $V_{RF} = 953.14$ V. The numerical results match perfectly the analytical predictions for both harmonic frequency and power level. The power levels of the results are extremely low (on the order of -200 dB · W) as corresponds to the emission of a single electron. In fact, as stated before, in real situations, the multipactor avalanche consists of several resonant electrons (n_e) that would increase the presented nominal power by a factor n_e^2 . For instance, for a typical avalanche of, for example, $n_e = 10^8$ electrons, all the curves in Fig. 4 would be shifted $+160$ dB upwards. These results verify, as predicted by (12), that the power level of the harmonics generated by a multipactor discharge decreases as $1/m$ for all the harmonics orders m except for the $m = N$ order, in which the maximum power is emitted.

Finally, we want to make some remarks on the third-harmonic technique for multipactor detection [4], [11]. In the case of multipactor order $N = 1$, the mentioned third harmonic coincides indeed with the $m = 3$ harmonic, being detected at a frequency three times higher than the RF one. As it is well known, this is due to the fact that this harmonic is the one with highest level that appears for all the multipactor orders (apart from the main one at the RF frequency f , which is obscured by the carrier in an experiment). However, for higher order

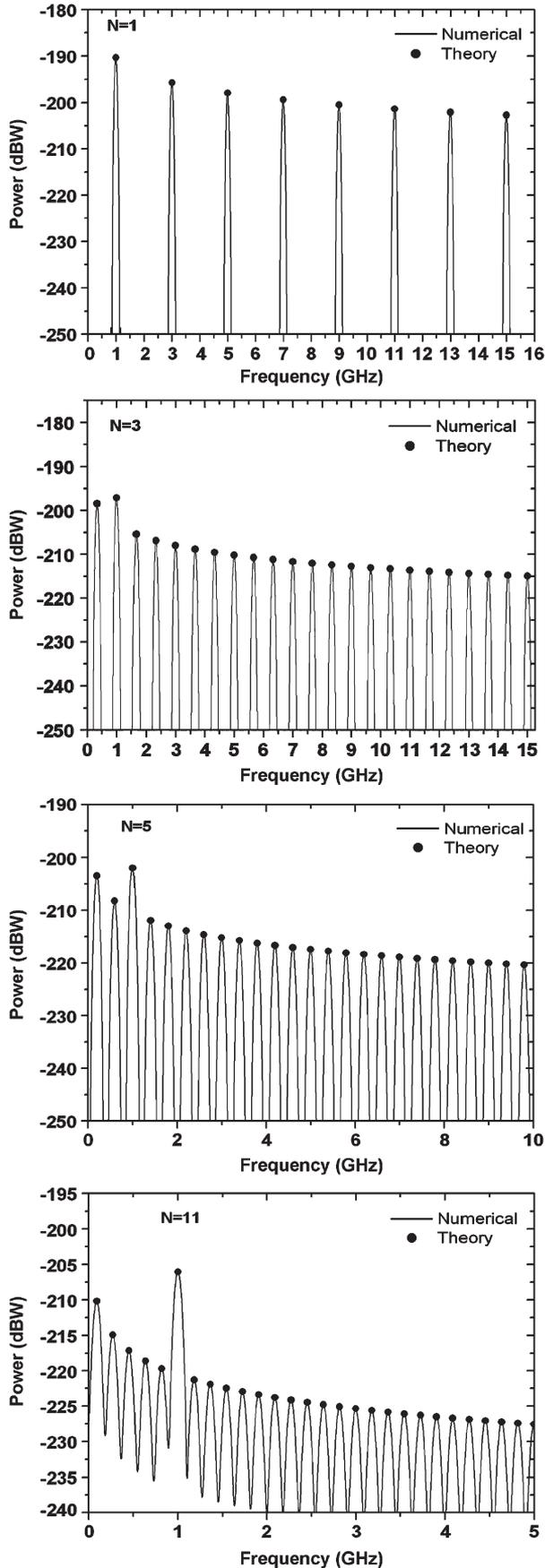


Fig. 4. Power spectrum generated by a multipactor discharge for different multipactor orders: $N = 1$, $N = 3$, $N = 5$ and $N = 11$.

multipactor orders $N > 1$, more harmonics appear to both sides of the RF carrier, at odd multiples of f/N , whose amplitudes are higher than the third-harmonic one (see Fig. 4). In the cases in which such harmonics are propagated and are not obscured by the carrier, they could give a more precise reference for detecting multipactor.

IV. CONCLUSION

In this paper, we present an analytic model to calculate the total radiated power by a multipactor current occurring in a parallel-plate waveguide region. The proposed formulation is based on the time-harmonic representation of the multipactor discharge current. A closed-form expression for the radiated power of each harmonic involving the relevant parameters of the phenomenon has been derived in detail. In order to check such expression, comparisons to numerical results obtained with a PIC code have been shown, obtaining excellent agreement, and fully validating the presented approach. The formulation derived might be easily used to predict the full radiated spectrum of a multipactor discharge, helping to correlate theoretical predictions with experimental results, and ultimately giving a more precise reference for multipactor detection.

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