Numerical Electromagnetic Modeling of Chemical Plants for the Assessment of Radio Frequency Ignition Hazards

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Abstract

In this work, electromagnetic simulation of electrically-large chemical plants is used to investigate RF ignition hazards. The proposed analysis is aimed at refining results and procedures detailed in the European Standard CLC/TR 50427, which foresees the use of elemental antennas (loops and half-wave dipoles) for the estimation, via closed-form approximated formulas, of the RF power induced by an impinging electromagnetic field.

1. Introduction

Radio-frequency (RF) electromagnetic fields may be considered as a hazard in industrial environments where flammable atmospheres may be present, particularly in chemical plants. Indeed, it has been proved that, in some unfavorable circumstances, a significant current can be induced by an RF electromagnetic field at the interface between two metallic structures which are parts of an industrial plant [1]. If the metallic structures initially in contact are then separated (this may happen for several different reasons, such as vibrations, or machinery operation) a so called "break spark" may occur, that is, the generation of an electric arc. In such conditions, the metallic parts of the apparatus act as unintentional antennas, extracting power from the electromagnetic environment and delivering it to a load, represented by the spark. This RF power could ignite a flammable atmosphere pervading the region of the spark, and therefore it could be the cause of an explosion, at least in the case of induced power levels above specific thresholds (depending on the chemical composition of the gas mixture) [1].

Evaluation and assessment of RF ignition hazards are addressed in the European Standard CLC/TR 50427 [2], originally issued in 2004 and based on considerable theoretical and experimental research activities carried out since the Eighties, in the United Kingdom [3-7]. This standard is structured as a guide, leading to estimation of the ignition hazard through a sequence of steps, which foresee: (a) identification of the RF sources illuminating the industrial plant (e.g., radio-broadcasting stations, radars, etc.), and the frequencies and level of the impinging electromagnetic field; (b) identification of unintentional antennas in the industrial plant; (c) estimation of the available power of the unintentional antennas; (d) comparison between the estimated available power and the ignition threshold. The available power $P_{\max}$ (i.e., the maximum power that can be extracted from a source) is considered instead of the actual power delivered to the load, in order to overcome the lack of knowledge on the characteristics of the break spark (which, actually, is a non-linear time-variant load).

Among the aforementioned steps, the most difficult and crucial are (b) and (c). In fact, from the electromagnetic standpoint, a chemical plant is a very complex system, and identification and assessment of unintentional antennas requires to simplify and to idealize the whole structure in order to extract significant configurations for the analysis. Additionally, it is worth noting that unintentional antennas may be either electrically-short or electrically large depending on the frequency/frequencies of interest in the range from 9 kHz to 60 GHz [2].

As an example, since loop-type geometries are considered as the most efficient unintentional antennas in the LF, MF and HF frequency bands (i.e., up to 30 MHz) [2, 5, 6], Standard CLC/TR 50427 gives general guidelines for the identification of loop geometries into typical plant structures (such as pipes, cranes, tanker-loading facilities, etc.). The loop perimeter is then used to estimate the RF available power induced by an impinging electromagnetic field via the following closed-form approximated formulas:

$$P_{\max} = 702\left(E_{rms}/f\right)^2\left(p/\lambda\right)^{3.5}, \text{ for } \; p/\lambda < 0.4, \tag{1}$$

$$P_{\max} = 28.4\left(E_{rms}/f\right)^2, \text{ for } \; p/\lambda \geq 0.4, \tag{2}$$

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where E_{rms} is the rms value of the incident electric field, f is the frequency (expressed in MHz), $\lambda = 300/f$ is the wavelength (expressed in meters), and p is the estimated perimeter of loop-type geometries. These expressions derive from investigations on lossy loop antennas operating above ground [5, 6].

A similar approach is adopted for frequencies greater than 30 MHz, by assimilating the electromagnetic behavior of the involved metallic structures to that of a half-wave dipole antenna (with some modifications accounting for ground effects and safety margins) [2] via the following closed-form expression:

$$P_{\max} = 124\, E_{rms}^2 /(f^2 + 3030)\,. \quad (3)$$

In the case of multiple excitation frequencies, Standard CLC/TR 50427 provides a method based on conventional weighting factors for summing up the available powers pertaining to different frequencies so to obtain the total available power [2, 7].

While the risk analysis described in the International Standard CLC/TR 50427 is simple and easy to follow, it involves certain simplifications which may have an impact on the estimated value of the induced RF power. Particularly, the following aspects are worth to be considered: (a) Application of closed-form formulas referring to simple canonical antennas weakens the correlation between the obtained estimates and the actual geometry (and related electromagnetic properties) of unintentional antennas identified in the chemical plant; (b) The analytical expressions used to build an estimate of the induced power neglect the actual incidence and polarization characteristics of the impinging plane-wave electromagnetic field (as a matter of fact, worst-case illuminating conditions are assumed); (c) The weighting curve used to sum up available powers at different frequencies stems from a conventional resonant circuit, usually showing different characteristics with respect to the actual equivalent circuit of the unintentional antenna under analysis. On the other hand, one has to recognize that the methodology proposed by the Standard, though extremely simplified, allows for carrying out hazard assessment with limited computational burden, and for easily coping with the complexity of real-world industrial plants via basic estimation principles.

Considering that the use of powerful and numerically efficient tools for electromagnetic simulation is widespread nowadays, and reminding that powerful hardware resources (not available when Standard CLC/TR 50427 was issued) are now within everybody's reach, there is now the possibility to refine the aforementioned procedure as regards characterization of the electromagnetic properties of the involved unintentional antennas. Namely, numerical electromagnetic modeling of metallic parts of a chemical plant can be used to estimate the gain, the radiation pattern and the input impedance, so to obtain complete information on its electromagnetic behavior as an unintentional antenna. In particular, it is possible to obtain a more accurate estimate for the available power induced by an external electromagnetic field. This work explores this specific issue by exemplifying the numerical simulation of a chemical reactor, and by comparing the outcome with the approximated results obtained by the closed-form formulas foreseen by the Standard. Potential and weaknesses of the proposed approach are discussed as well.

2. Estimation of the Available Power via Electromagnetic Simulation

In full-wave electromagnetic simulation, choice of the numerical method used to solve the Maxwell equations is a key issue. The main factors driving this choice are typically general characteristics of the electromagnetic problem under consideration. The problem here considered is characterized by the following properties: (a) simple materials (either perfect-electric or lossy conductors). Typically no dielectrics have to be considered in the simulation, (b) the geometry can be simply idealized as a set of metallic faces and wires elements, (c) a real or ideal ground may be present, (d) the electrical dimension of the involved structures could be small or large, depending on the frequency of interest, (e) the analysis is to be performed in the phasor domain (i.e., frequency by frequency in a quite large frequency range). All these considerations lead to the conclusion that the Method of Moments (MoM) and, in the case of very electrically-large structures, the Multilevel Fast Multipole Method (MFMM) are best suited to perform the proposed numerical analysis [8].

After identification of the unintentional antenna according to the guidelines given in [2], the first step of the analysis is idealization and definition of a simplified geometry to be implemented in the electromagnetic solver. In particular, the input port has to be clearly identified. In practice, this port represents the point where a break spark can occur due to the possible separation of two metallic parts (formerly in contact) [2]. Electromagnetic simulation of the structure, considered as a radiating antenna, is targeted to the computation of: (a) the gain $G(\vartheta,\phi)$ depending on the elevation angle ϑ and azimuth angle ϕ, and (b) the input impedance $\hat{Z}_A$. The available power of the unintentional antenna is then evaluated by means of the reciprocity theorem as

$$P_{\max}(\vartheta,\phi) = \frac{\lambda^2 E_{rms}^2}{4\pi\eta_0} G(\vartheta,\phi) \tag{4}$$

where η_0 is the intrinsic impedance of free-space. Note that, in (4), the available power $P_{\max}$ is associated with the incidence direction of the impinging plane-wave. This allows for characterizing the variability of the power extracted from the electromagnetic field. This information is by far more complete than the simple single-value estimation provided by the Standard in [2]. For example, if the parameters of the impinging wave are treated as unknowns, statistical analysis of (4) can provide information on the mean value, standard deviation, and distribution of the available power. This approach allows to formulate the RF ignition hazard in probabilistic terms.

It is also interesting to note that the equation in (4) inherently presumes that the polarization of the impinging plane-wave is equal to the polarization of the unintentional antenna. Since the latter could be elliptical and strongly dependent on ϑ, ϕ (since the antenna is unintentional), especially when the structure is electrically large, a more accurate approach can account for the mismatch between the polarization of the impinging wave and the antenna. This can be done by considering the complex radiation pattern and by applying the reciprocity theorem in general form.

Finally, the antenna impedance $\hat{Z}_A$ allows for derivation of the Thevenin equivalent circuit seen at the input port (see Fig. 1). This circuit can be used to evaluate the power P_L delivered to a specific load. Therefore, the problem of weighting and summing up the available powers at different frequencies can be consistently solved, overcoming the limitations of the conventional method adopted in [2, 7].

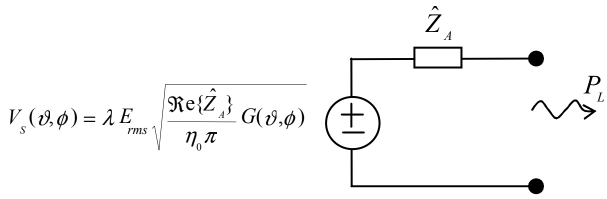
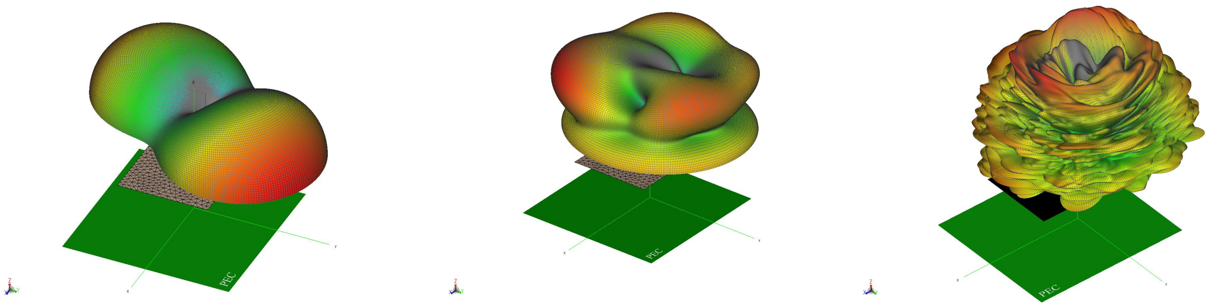


Fig. 1 Equivalent circuit of the antenna.

3. Example and Conclusion

The approach briefly described in the previous Section has been applied to metallic structures of a real chemical plant. A chemical reactor is briefly exemplified in the following. The geometry (not shown here for the sake of conciseness) has a typical dimension of 10 m, and includes ground planes (representing the earth and metallic floors), pipes, and the reactor capsule. According to indications provided in [2], the position of a flange along a pipe has been recognized as the input port of the unintentional antenna. The structure was simulated at four different frequencies: 3 MHz, 30 MHz, 300 MHz and 900 MHz (the first three are at the separation between the MF, HF, VHF and UHF bands; the fourth frequency is used for the operation of GSM cell phones in Europe).

The obtained 3D radiation pattern (gain) is represented in Fig. 2. One can note that, since the structure has loop-type geometry (the loop is formed by a pipe), the radiation pattern at low frequencies resembles that of a loop antenna [see Fig. 2(a)], thus confirming the analogy proposed in the Standard CLC/TR 50427 [2]. However, as the frequency increases, the radiation pattern becomes very complex and cannot be clearly associated either to a loop or to a half-wave dipole, as assumed in [2]. In Table I, the available power evaluated via (4) in the direction of maximum gain (worst-case) is compared with the results obtained by applying equations (1)-(3), as foreseen by the Standard. One can note that, in general, the simplified closed-form expressions underestimate power levels, especially at 30 MHz (between the HF and VHF band). Additionally, at 3 MHz two extreme values are reported for the Standard, due to uncertainty in the estimation of the parameter p involved in (1), whereas the available power obtained by numerical simulation close to the mean value between these two extremes.



(a) (b) (c)

Fig. 2 Radiation pattern of the unintentional antenna: (a) 3 MHz; (b) 30 MHz; (c) 900 MHz.

Even if the specific structure under analysis cannot be used to infer general conclusions, the aforementioned considerations suggest that the approach in [2] is consistent at very low frequencies, where the structure is electrically small. At these frequencies, unintentional antennas behave actually as loop antennas and their available power can be estimated by means of (1), even though a large sensitivity to the value of parameter p is to be expected. Conversely, if the wavelength approaches or exceeds the typical dimension of the system, the approach in [2] appears to be oversimplified. In any case, at the expense of a more complex and demanding analysis (from the viewpoint of the computational burden), numerical simulation has the ability to provide a detailed description of the system response, thus allowing for more accurate assessment of the RF ignition hazard.

Table I

Available power estimated via numerical simulation and according to CLC/TR 50427 ($E_{rms} = 1$ V/m)

Frequency	P_{max} (numerical)	P_{max} (CLC/TR 50427)
3 MHz	285 mW	193 ÷ 365 mW
30 MHz	151 mW	31.6 mW

Frequency	P_{max} (numerical)	P_{max} (CLC/TR 50427)
300 MHz	2.7 mW	1.3 mW
900 MHz	0.306 mW	0.153 mW

4. References

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